A Framework for Micro Level Assessment and 3D Visualisation of Flood Damage to a Building

By

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“Floods are acts of God, but flood losses are largely acts of man”

White, G.F. (1945).
ABSTRACT

Flood Damage Assessment (FDA) is the key component of the flood risk management process. By highlighting the potential consequences of floods, FDA allows for an evidence-based risk management by employing optimal risk reduction measures in the community. FDA is generally performed in three main scales namely Macro, Meso and Micro. For assessing the potential flood damages at different levels, various categories of vulnerable elements (e.g. roads, people, buildings, etc.) are accounted for. Among these elements, buildings are the most notable and are considered in nearly all the current FDA methods due to their significance to the economy. In addition, with increasing risks of floods due to the climate change effects, the attention to improve the flood resilience of buildings is increasing. This leads to the need for a more profound understanding of the fluid-structure interactions and assessing the potential damages and risks to the building from floods in the early design and planning stages.

Amongst the FDA methods, in contrast to the aggregated land use as the inputs of Macro and Meso models, only those Micro level assessments can provide separate analysis for the buildings. However, the current micro-level FDA models cannot account for the distinct characteristics of each building and its unique behaviour against floods. Therefore, they are associated with high uncertainties. Additionally, the current models only account for either damage from the flood loads or those as the result of floodwater contacting with water-sensitive components. This leads to incomplete outputs and further increase in the uncertainty of the results. Moreover, the existing FDA models mostly focus on the quantitative assessment of damages and do not communicate the mode/type of damage to important decision makers (e.g. designers and engineers). This inhibits the optimal selection of measures for reducing the risk to buildings. While the need of larger-scale applications are well-satisfied by the existing FDA methods, the highlighted limitations hinder the use of these methods to effectively assess the damage and risks in situations where individual buildings are the focus of the analysis.

To address the aforementioned limitations of the previous models, in this multidisciplinary research by adopting the Design Science Research Methodology an FDA framework was developed. This framework allows for a detailed micro-level assessment and 3D visualisation of flood damage to a building and according to its unique characteristics and behaviour against floods. The proposed processes in the framework were designed in detail according to the well-established theories in a number of related domains. Moreover, by developing a new BIM-GIS integration method, rich inputs about a building and flood parameters could be provided for the framework to effectively overcome
the data input limitations of the current FDA models. The framework was realised by development of a prototype system and on the basis of the proposed guidelines. The dual evaluation of the framework using the internal validity checking as well as the use of a case study underlined the feasibility of implementation and the effective application of the framework for solving real-world problems. The benefits of the proposed framework for assessment and communication of flood damage at the building level was also highlighted to a variety of users. The framework can be employed as a complementary approach to the current FDA models for improving the resilience of the community towards floods and their adverse impacts.
DECLARATION

This is to certify that:

i. The thesis comprises only my original work towards the PhD;

ii. Due acknowledgement has been made in the text to all other material used;

iii. The thesis is fewer than 100,000 words in length, exclusive of references, tables, maps, bibliographies and appendices.

__________________________________________

Sam Amirebrahimi
Melbourne, Spring 2015
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TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. i
DECLARATION .......................................................................................................................... iii
ACKNOWLEDGEMENTS ........................................................................................................... v
TABLE OF CONTENTS ............................................................................................................. vii
LIST OF FIGURES ................................................................................................................... xiii
LIST OF TABLES ...................................................................................................................... xix
LIST OF ACRONYMS AND ABBREVIATIONS ........................................................................ xxi
LIST OF SYMBOLS ................................................................................................................. xxv
LIST OF PUBLICATIONS ........................................................................................................ xxvii
1 Research Overview ................................................................................................................ 1
  1.1 Research background ......................................................................................................... 1
  1.2 Research formulation ......................................................................................................... 3
    1.2.1 Problem statement ....................................................................................................... 3
    1.2.2 Research aim ............................................................................................................... 4
    1.2.3 Research questions and objectives ............................................................................. 5
  1.3 Research approach ............................................................................................................. 6
  1.4 Delimitation of scope and key assumptions ..................................................................... 9
  1.5 Thesis structure ................................................................................................................ 11
  1.6 Chapter summary ............................................................................................................. 13
2 Flood Damage Assessment (FDA) of Buildings: Principles and Methods ......................... 19
  2.1 Introduction ....................................................................................................................... 19
  2.2 Floods and the need for flood resilient community ........................................................ 19
  2.3 Flood Risk Management .................................................................................................. 24
  2.4 Flood damage assessment as a decision support tool ...................................................... 27
    2.4.1 Aspects of Flood Damage Assessment ...................................................................... 28
    2.4.2 Users of Flood Damage Assessment ........................................................................ 37
  2.5 Importance of FDA on Buildings .................................................................................... 38
  2.6 Micro-level methods for FDA on building ....................................................................... 39
    2.6.1 Ex-post methods ......................................................................................................... 40
    2.6.2 Ex-ante methods ....................................................................................................... 41
  2.7 Summary of past studies ................................................................................................... 59
  2.8 Summary of current knowledge gaps for detailed micro-level FDA of building ............... 61
  2.9 Chapter Summary ............................................................................................................. 63
3 Data Technology Review in Support of FDA of building at micro level ......................... 67
  3.1 Introduction ....................................................................................................................... 67
  3.2 Developments in Geospatial domain .............................................................................. 67
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview</td>
<td>351</td>
</tr>
<tr>
<td>Appendices</td>
<td>351</td>
</tr>
<tr>
<td>Appendix 1: Flood Disaster Statistics (source: EM-DAT)</td>
<td>353</td>
</tr>
<tr>
<td>Appendix 2: Personal Communication with Steven Tsikaris</td>
<td>357</td>
</tr>
<tr>
<td>Appendix 3: Damage curves for structural damage assessment</td>
<td>359</td>
</tr>
<tr>
<td>Appendix 4: Damage curves for direct monetary estimation of damage to building</td>
<td>365</td>
</tr>
<tr>
<td>Appendix 5: Summary of prominent data standards and specifications utilised in AEC/FM domain</td>
<td>367</td>
</tr>
<tr>
<td>Appendix 6: Structured interview questions</td>
<td>369</td>
</tr>
<tr>
<td>Appendix 7: Door Water Infiltration Equations</td>
<td>377</td>
</tr>
<tr>
<td>Appendix 8: Failed doors water infiltration equations</td>
<td>381</td>
</tr>
<tr>
<td>8 Prototype Implementation</td>
<td>251</td>
</tr>
<tr>
<td>8.1 Introduction</td>
<td>251</td>
</tr>
<tr>
<td>8.2 Prototype system for micro-level FDA on building</td>
<td>251</td>
</tr>
<tr>
<td>8.2.1 Functional overview</td>
<td>251</td>
</tr>
<tr>
<td>8.2.2 Implementation architecture</td>
<td>252</td>
</tr>
<tr>
<td>8.2.3 System processes</td>
<td>258</td>
</tr>
<tr>
<td>8.3 Chapter Summary</td>
<td>275</td>
</tr>
<tr>
<td>9 Framework Evaluation</td>
<td>279</td>
</tr>
<tr>
<td>9.1 Introduction</td>
<td>279</td>
</tr>
<tr>
<td>9.2 Case study</td>
<td>279</td>
</tr>
<tr>
<td>9.2.1 Case study setting</td>
<td>279</td>
</tr>
<tr>
<td>9.2.2 Damage assessment to a building in Maribyrnong</td>
<td>281</td>
</tr>
<tr>
<td>9.2.3 Summary of case study</td>
<td>297</td>
</tr>
<tr>
<td>9.3 Verification and Validation</td>
<td>297</td>
</tr>
<tr>
<td>9.3.1 Verification</td>
<td>297</td>
</tr>
<tr>
<td>9.3.2 Validation</td>
<td>298</td>
</tr>
<tr>
<td>9.4 Chapter Summary</td>
<td>305</td>
</tr>
<tr>
<td>10 Conclusions and Recommendations</td>
<td>311</td>
</tr>
<tr>
<td>10.1 Introduction</td>
<td>311</td>
</tr>
<tr>
<td>10.2 Addressing the research aim and objectives</td>
<td>311</td>
</tr>
<tr>
<td>10.2.1 Objective one</td>
<td>312</td>
</tr>
<tr>
<td>10.2.2 Objective two</td>
<td>314</td>
</tr>
<tr>
<td>10.2.3 Objective three</td>
<td>315</td>
</tr>
<tr>
<td>10.2.4 Objective four</td>
<td>316</td>
</tr>
<tr>
<td>10.3 Responding to the research problem</td>
<td>317</td>
</tr>
<tr>
<td>10.4 Main outcomes and the contributions to the knowledge</td>
<td>318</td>
</tr>
<tr>
<td>10.5 Recommendations for future research</td>
<td>320</td>
</tr>
<tr>
<td>References</td>
<td>327</td>
</tr>
<tr>
<td>Appendices</td>
<td>351</td>
</tr>
<tr>
<td>Appendix 1: Flood Disaster Statistics (source: EM-DAT)</td>
<td>353</td>
</tr>
<tr>
<td>Appendix 2: Personal Communication with Steven Tsikaris</td>
<td>357</td>
</tr>
<tr>
<td>Appendix 3: Damage curves for direct monetary estimation of damage to building</td>
<td>359</td>
</tr>
<tr>
<td>Appendix 4: Damage curves for structural damage assessment</td>
<td>365</td>
</tr>
<tr>
<td>Appendix 5: Summary of prominent data standards and specifications utilised in AEC/FM domain</td>
<td>367</td>
</tr>
<tr>
<td>Appendix 6: Structured interview questions</td>
<td>369</td>
</tr>
<tr>
<td>Appendix 7: Door Water Infiltration Equations</td>
<td>377</td>
</tr>
<tr>
<td>Appendix 8: Failed doors water infiltration equations</td>
<td>381</td>
</tr>
</tbody>
</table>
Appendix 9: Failed windows water infiltration equations .............................................................. 383
Appendix 10: Water infiltration equations through air bricks and vents to and from cavity space ....... 387
Appendix 11: Water infiltration equations for vents and air bricks.................................................. 389
Appendix 12: Wall-floor interface water infiltration equations.......................................................... 391
Appendix 13: XML schema for the design profile of GML to facilitate micro-level FDA on building .... 393
    Schema UrbanFloodBase.xsd .......................................................................................... 393
    Schema Terrain.xsd ............................................................................................... 399
    Schema Flood.xsd ................................................................................................. 402
    Schema Valuation.xsd ............................................................................................ 407
    Schema MaterialDomain.xsd .................................................................................. 409
    Schema Building.xsd ............................................................................................ 415
    Schema Utility.xsd ............................................................................................... 449
    Schema Connection.xsd ........................................................................................ 457
Appendix 14: Process for extracting the point and surface-based flood information from MIKE output in the ArcGIS ModelBuilder ........................................................................ 461
Appendix 15: Plans of the building in the case study ..................................................................... 462
LIST OF FIGURES

Figure 1.1: Research approach and link to the research objectives .............................................................. 7
Figure 1.2: The structure of the dissertation .................................................................................................. 11
Figure 2.1: Schematic summary of the content of the chapter .................................................................... 19
Figure 2.2: (a) Number of flood occurrences per year since 1980; (b) the total reported economic damage from floods around the world since 1980 (source: CRED) ......................................................... 20
Figure 2.3: Flood Risk as a function of probability and consequences .......................................................... 23
Figure 2.4: Flood risk management cycle ..................................................................................................... 24
Figure 2.5: An example of damage-probability curve .................................................................................. 25
Figure 2.6: Scale of FDA analysis ............................................................................................................... 31
Figure 2.7: (a) Number of flood occurrences per year since 1980; (b) the total reported economic damage from floods around the world since 1980 (source: CRED) ......................................................... 20
Figure 2.8: Clausen damage criterion for brick and masonry structures ..................................................... 49
Figure 2.9: (left) USACE Collapse curve for class D steel building; (right) Expected flood damage surface from combined effects of depth and velocity in slow-rise riverine flood ........................................................................... 50
Figure 2.10: Partial collapse curves of Roos (2003) for one- (TB) and two-storey typical building (TB2), concrete (CC) and prefabricated (PF) buildings .......................................................................................... 50
Figure 2.11: structural load path in simple wood-frame structure (left); Criteria for fill, collapse, float failures (right) ........................................................................................................................................ 51
Figure 2.12: A schematic representation of the building damage variability that are not reflected by curves .... 53
Figure 2.13: Failure pathway of flood impacts on building ........................................................................... 54
Figure 2.14: Building Resilience Rating Tool (BRRT) by ICA (2013) ............................................................ 59
Figure 3.1: BISDM representation of floor plans and walls in ESRI ArcGIS .................................................. 69
Figure 3.2: Representing flood depth and velocities using raster and vector ................................................ 70
Figure 3.3: Voxel geometry (right), swept solid geometry (middle) and boundary representation (left) ........ 72
Figure 3.4: Photo-realistic and COLLADA models of buildings in KML format ........................................ 75
Figure 3.5: Modular structure of the CityGML ......................................................................................... 78
Figure 3.6: Complex object with fully coherent spatio-semantic structure ............................................... 78
Figure 3.7: Building representation in different LODs of CityGML .......................................................... 79
Figure 3.8: CityGML Building Model in UML ......................................................................................... 80
Figure 3.9: Building component representation using surfaces CityGML ................................................ 80
Figure 3.10: (top) CityGML water body 3D representation using surfaces (bottom-left) the waterGroundSurface; (bottom-right) WaterSurface ................................................................. 82

Figure 3.11: (left) visualisation of flood and the building using 3D models .................................................. 83

Figure 3.12: IFC data model’s schema and layers .................................................................................. 91

Figure 3.13: Representation of building using IFC objects ..................................................................... 92

Figure 3.14: BIM/ABV integration for damage assessment against earthquake (left) the BIM model (right) the colour coded damage status of assemblies ............................................................. 94

Figure 3.15: B-rep in GIS vs. Constructive Solid Geometry in BIM ..................................................... 96

Figure 3.16: Semantic CAD/GIS Web Services Vision .................................................................................. 98

Figure 3.17: System Architecture of AFESM ......................................................................................... 101

Figure 3.18: GeoBIM ADE for CityGML (adopted from Van Berlo and De Laat, 2010) ............................. 102

Figure 3.19: Geo-analysis of utility network using NIBU model in a web-based GIS (adopted from Hijazi, 2011) ................................................................................................................................. 104

Figure 3.20: UML diagram of UBM ........................................................................................................ 105

Figure 3.21: BIM-3D GIS integration for Indoor evacuation ........................................................................... 106

Figure 4.1: The overall chapter structure ................................................................................................. 113

Figure 4.2: Conceptual design framework ............................................................................................... 115

Figure 4.3: Design Science Research Methodology (DSRM) process model ............................................. 117

Figure 4.4: The selected Design Research model .................................................................................... 119

Figure 4.5: The application of Hevner's model for this research ............................................................. 121

Figure 4.6: Research design ....................................................................................................................... 124

Figure 4.7: Offsetting design flood overlay and the LGA information for Melbourne metropolitan area .......... 127

Figure 4.8: Example of analysis output for wall types, number of stories, attached/detached type for houses in various LGAs in Victoria (left) and Queensland (right) (source: NEXIS) ................................................................. 129

Figure 4.9: Data modelling process for this research .............................................................................. 130

Figure 4.10: Schematic flow of the adopted tasks in prototyping methodology ........................................... 131

Figure 4.11: Case study area in Maribyrnong (left) and the survey of 282 buildings in areas at risk of flood (right) ............................................................................................................................................. 134

Figure 5.1: Typical Brick veneer system with timber frame construction (left); elements in the external veneer wall (middle); cross section of brick veneer wall system adopted from Australian Standard AS3700 (2011) (right) ................................................................................................................................. 148

Figure 5.2: schematisation of typical wall framing system ......................................................................... 149

Figure 5.3: Slab on ground foundation and its connection to the frame and cladding ..................................... 149

Figure 5.4: Vulnerability of building components to flood actions ............................................................ 152
Figure 5.5: Damage levels to a typical brick veneer house from different inundation intervals ....................... 153

Figure 5.6: (left) Failure mechanisms of brick veneer wall against lateral loads; and (right) Failure of internal lining of the wall against the hydrostatic pressure ....................................................................................... 154

Figure 5.7: (left) according to low depth of water, only the bottom half of the lining is removed due to damage; (right) extreme damage to internal wall frame. ........................................................................................................ 156

Figure 5.8: Problems arisen in ceiling from flood immersion ................................................................. 159

Figure 6.1: (left) hydrostatic pressure from only water level outside of the building component; and (right) depth difference between inside and outside of a building component (window). ......................................................................................... 179

Figure 6.2: (Left) combined pressure from hydrodynamic and hydrostatic; (right) magnitude of hydrodynamic load/force on the building component .............................................................................. 181

Figure 6.3: Water infiltration through weepholes, airbricks and the wall-floor interface; ................................ 183

Figure 6.4: The infiltration pathways from doors and windows to inside the house .................................... 188

Figure 6.5: Comparing leakage of rendered and non-rendered brick face walls ........................................... 188

Figure 6.6: The division of wall area in case of presence of openings .......................................................... 190

Figure 6.7: Infiltration through wall-flood interface according to the water depth inside house (h''), and inside cavity (h') ................................................................................................................................. 194

Figure 6.8: Water contact evaluation against building components ........................................................... 196

Figure 6.9: Yield line configuration for unreinforced masonry walls of different sizes and supports ............ 198

Figure 6.10: Damage analysis to the cladding and frame of the external veneer wall system ...................... 199

Figure 6.11: Division of wall panels to sub-panels; (left) panel with opening with 2 or 3 restraining edges (left); panel without opening with 4 restraining edges (right). ...................................................................................... 200

Figure 6.12: The bending moment from the generated point forces at the location of the connection of ties to studs (for the situation that ties are not failed); and the reactions at top- or bottom-plates with stud. 201

Figure 6.13: Variables required for FE model construction for analysis of failure of window glass .......... 206

Figure 6.14: Setting the dimensions of the glazing panel ............................................................................. 207

Figure 6.15: The water levels and hydrodynamic pressures setting in ANSYS ........................................... 207

Figure 6.16: Results of solving the FEM in ANSYS software ........................................................................ 208

Figure 7.1: Use cases for the micro-level FDA on building ........................................................................... 214

Figure 7.2: The proposed framework for micro-level FDA on a building ................................................... 216

Figure 7.3: Different representation of buildings in the flood simulation ................................................... 218

Figure 7.4: Physical damage assessment .................................................................................................. 220

Figure 7.5: The data model's high level packages ......................................................................................... 229

Figure 7.6: Core package .......................................................................................................................... 231

Figure 7.7: Terrain package ....................................................................................................................... 232
Figure 8.21: Export process for building elements to GIS ShapeFiles ............................................................... 272
Figure 8.22: Tabular damage cost export for the building and its damaged elements ........................................ 274
Figure 9.1: The case study area .......................................................................................................................... 281
Figure 9.2: The BIM model of the house ............................................................................................................ 282
Figure 9.3: South boundary rating curve (left) and the north boundary river discharges for the case study area (right) ........................................................................................................................................ 283
Figure 9.4: The boundary (in red) for flood simulation ........................................................................................ 284
Figure 9.5: The generated mesh with buildings blocked out of the elevation model for the entire study area ... 285
Figure 9.6: Details of the generated mesh with buildings blocked out of the elevation model ......................... 285
Figure 9.7: Flood model set up in MIKE 21 ........................................................................................................ 286
Figure 9.8: Modelling the flood without (left) and under the influence of buildings (right) ............................ 286
Figure 9.9: Visualisation of the output of the flood simulation using ArcGIS: MIKE 21 output and comparison with MW flood study (left); velocity vectors around the building under investigation (right) ........................................................................ 287
Figure 9.10: The Voronoi diagram of the flood parameters point distribution around the building ................. 288
Figure 9.11: Flood parameters for individual facade elements of the building ................................................. 288
Figure 9.12: Water depth outside and inside cavity for each wall and for different time steps of infiltration modelling .......................................................................................................................... 289
Figure 9.13: Real-time report of the infiltration and depths of water outside .................................................. 290
Figure 9.14: Water depths and levels outside and inside the building ........................................................... 290
Figure 9.15: Example of the damage assessment log file .................................................................................. 291
Figure 9.16: The flooded case study area in 3D, visualised in ArcScene ......................................................... 292
Figure 9.17: Flood parameters around the building using (top) 3D point and (bottom) surface representation . 292
Figure 9.18: A 3D Visualisation of Damaged Walls (top left), Doors (top middle), Flooring (top right), moulding and skirting (bottom left), electrical elements (bottom middle) and windows (bottom right) .... 294
Figure 9.19: Querying damaged assemblies using “identify” tool in ArcScene for doors and wall linings ....... 295
Figure 9.20: Summary of response of the participants on the importance and relevance of the problem ....... 300
Figure 9.21: Summary of participants’ responses regarding the framework structure and logic .................... 300
Figure 9.22: Responses of the participants for the damage assessment methods and their assumption .......... 301
Figure 9.23: Summary of responses for validating the appropriateness of damage threshold for assemblies .... 302
Figure 9.24: Summary of responses for inclusion of the key flood and building parameters in the framework 303
Figure 9.25: Summary of responses on the value of BIM together with GIS as input for a detailed FDA ...... 304
Figure 9.26: Summary of participants' responses for the outputs of the framework ...................................... 305
### LIST OF TABLES

Table 2.1: Typical floodplain risk management measures ............................................................... 26
Table 2.2: The aspects of Flood Damage Assessment........................................................................ 28
Table 2.3: Classification of damage categories .............................................................................. 29
Table 2.4: Uncertainty sources in the damage assessment models .................................................... 37
Table 2.5: A range of flood risk management decisions and their requirements .............................. 38
Table 2.6: Flood actions on buildings .............................................................................................. 44
Table 2.7: Advantages and disadvantages of damage model construction methods .......................... 46
Table 3.1: Comparison of 3D exchange standards within geospatial domain .................................. 84
Table 4.1: Model validation methods ............................................................................................... 135
Table 4.2: General assessment guidelines for Design Science Research (the left two columns) and the discussion on how this research meet these criteria (right column) ................................................................. 142
Table 5.1: The summary of impacts of flood actions on the components of the building under investigation ................................................................. 166
Table 6.1: Drag coefficients for ratios of component width (facing the flow) to water height (w/h) .... 180
Table 6.2: Leakage characteristics for walls ..................................................................................... 190
Table 6.3: Leakage characteristics for doors .................................................................................... 193
Table 6.4: Leakage characteristics for wall/window and door/window frame ................................ 193
Table 6.5: Damage states for external veneer wall components (insulation and internal lining rows can also be applied to internal walls) ....................................................................................... 203
Table 6.6: Damage states for internal and non-sliding external doors ............................................. 204
Table 6.7: Damage states for window or external sliding doors ...................................................... 208
Table 6.8: Damage states for floor covering .................................................................................... 209
Table 7.1: The result of data requirements analysis .......................................................................... 225
Table 7.2: Mapping between the proposed data model's concepts and classes and IFC 4 classes .......... 246
Table 7.3: The data model packages' corresponding XML Schema files ........................................ 247
Table 9.1: Summary of damage to the building ................................................................................. 293
Table 9.2: Mapping between the designed questionnaire and the face validity criteria .................. 298
Table 9.3: List of participants in the framework evaluation ................................................................. 299
## LIST OF ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two dimensional</td>
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<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
<tr>
<td>AAD</td>
<td>Average Annual Damage</td>
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<tr>
<td>ABCB</td>
<td>Australia Building Code Board</td>
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<tr>
<td>ABS</td>
<td>Australian Bureau of Statistics</td>
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<tr>
<td>ABV</td>
<td>Assembly-Based Vulnerability</td>
</tr>
<tr>
<td>ADE</td>
<td>Application Domain Extension</td>
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<tr>
<td>AEC/FM</td>
<td>Architecture, Engineering, Construction and Facility Management</td>
</tr>
<tr>
<td>AS</td>
<td>Australian Standard</td>
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<tr>
<td>AS/NZS</td>
<td>Australian/New Zealand Standard</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<td>BCA</td>
<td>Building Code Australia</td>
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<td>BIM</td>
<td>Building Information Model</td>
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<td>BISDM</td>
<td>Building Interior Space Data Model</td>
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<td>BL</td>
<td>Business Layer</td>
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<td>B-Rep</td>
<td>Boundary Representation</td>
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<td>CAD</td>
<td>Computer-Aided Design</td>
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<td>CAM</td>
<td>Computer Aided Modelling</td>
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<tr>
<td>CBA</td>
<td>Cost-Benefit Analysis</td>
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<td>CDMP</td>
<td>Centre for Disaster Management and Public Safety</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>City Geographic Markup Language</td>
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<td>COLLADA</td>
<td>COLLAborative Design Activity</td>
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<td>CRED</td>
<td>Centre for Research on the Epidemiology of Disasters</td>
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<tr>
<td>CSDILA</td>
<td>Centre for Spatial Data Infrastructures and Land Administration</td>
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<tr>
<td>CSG</td>
<td>Constructive Solid Geometry</td>
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<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<td>CSV</td>
<td>Comma Separated Values</td>
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<td>Data Access Layer</td>
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<td>DCLG</td>
<td>Department for Communities and Local Government (in UK)</td>
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<td>DL</td>
<td>Data Layer</td>
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<td>DSRM</td>
<td>Design Science Research Methodology</td>
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<td>EAA</td>
<td>Emergency Architects Australia</td>
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<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
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<tr>
<td>ETL</td>
<td>Extract, Transform, and Load</td>
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<td>FDA</td>
<td>Flood Damage Assessment</td>
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<td>FEM</td>
<td>Finite Element Method/Modelling</td>
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<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
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<td>FHRC</td>
<td>Flood Hazard Research Centre</td>
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<td>FIR</td>
<td>Flood Infiltration Rate</td>
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<td>FRM</td>
<td>Flood Risk Management</td>
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<td>FRR</td>
<td>Flood Rise Rate</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GA</td>
<td>Geoscience Australia</td>
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<td>GABT</td>
<td>Geoscience Australia Building Type</td>
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<td>GIS</td>
<td>Geographic Information System</td>
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<td>GML</td>
<td>Geographic Markup Language</td>
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<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air Conditioning</td>
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<td>IBC</td>
<td>International Building Code</td>
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<td>ICA</td>
<td>Insurance Council of Australia</td>
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<td>IDM</td>
<td>Information Delivery Manual</td>
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<td>IFC</td>
<td>Industry Foundation Classes</td>
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<td>Information System</td>
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<td>International Standards Organisation</td>
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<td>KML</td>
<td>Keyhole Markup Language</td>
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<td>LGA</td>
<td>Local Government Area</td>
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<td>LoA</td>
<td>Level of Abstraction</td>
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<td>LoD</td>
<td>Level of Detail</td>
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<td>LS</td>
<td>Limit States</td>
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<td>LSD</td>
<td>Limit State Design</td>
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<td>MEP</td>
<td>Mechanical, Electrical, and Plumbing</td>
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<td>Mpa</td>
<td>Mega Pascal</td>
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<tr>
<td>MSC</td>
<td>Monte Carlo Simulation</td>
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<td>MV</td>
<td>Model View</td>
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<td>MW</td>
<td>Melbourne Water</td>
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<td>NEXIS</td>
<td>National Exposure Information System</td>
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<td>NSW</td>
<td>New South Wales</td>
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<td>OGC</td>
<td>Open Geospatial Consortium</td>
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<td>OO</td>
<td>Object Oriented</td>
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<td>PDF</td>
<td>Portable Document Format</td>
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<td>PL</td>
<td>Presentation Layer</td>
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<td>RAM</td>
<td>Rapid Appraisal Method</td>
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<td>ROI</td>
<td>Return on Investment</td>
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<td>RS</td>
<td>Remote Sensing</td>
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<td>SCM</td>
<td>Semantic City Model</td>
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<td>SDI</td>
<td>Spatial Data Infrastructure</td>
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<td>SensorML</td>
<td>Sensor Modelling Language</td>
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<td>SIG3D</td>
<td>Special Interest Group</td>
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<td>SLA</td>
<td>Statistical Local Area</td>
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<td>SLS</td>
<td>Serviceability Limit State</td>
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<td>SOA</td>
<td>Service Oriented Architecture</td>
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<tr>
<td>SPH</td>
<td>Smoothed Particle Hydrodynamics</td>
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<tr>
<td>STEP</td>
<td>Standard for the Exchange of Product model data</td>
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<tr>
<td>TIC</td>
<td>Terrain Intersection Curve</td>
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<tr>
<td>TIN</td>
<td>Triangulated Irregular Network</td>
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<td>UBM</td>
<td>Unified Building Model</td>
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<td>UIM</td>
<td>Urban Information Model</td>
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<td>ULS</td>
<td>Ultimate Limit State</td>
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<td>Acronym</td>
<td>Description</td>
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<td>UML</td>
<td>Unified Modelling Language</td>
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<tr>
<td>UN</td>
<td>United Nations</td>
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<td>UNCSD</td>
<td>United Nations Conference on Sustainable Development</td>
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<td>UNISDR</td>
<td>United Nations International Strategy for Disaster Reduction</td>
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<td>URM</td>
<td>Unreinforced Masonry</td>
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<tr>
<td>USACE</td>
<td>United States Army Corps of Engineers</td>
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<td>VRML</td>
<td>Virtual Reality Modelling Language</td>
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<td>Water Modelling Language</td>
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<td>Web Coverage Service</td>
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<td>Web Feature Service</td>
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<td>WMS</td>
<td>Web Mapping Service</td>
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<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
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</table>
LIST OF SYMBOLS

ω  A particular building assembly

$P_s$  Hydrostatic pressure

g  Gravity acceleration (m/s)

$\rho$  Mass density of water (kg/m$^3$)

h  Depth of water outside (m)

y  Elevation in the y-axis that the pressure is calculated for (m)

$f_{diff}$  Depth differential (m)

b  Height above ground of the bottom of a the component [m]

s  Height above ground of the top of the component [m]

$P_d$  Hydrodynamic pressure

$v$  Floodwater Velocity (m/s)

$C_{drag}$  Drag coefficient

F  Force (N/m)

$\theta$  Angle between the building external and the force vector

$dh$  Equivalent increase in the depth of water from velocity

$P_{dh}$  Equivalent hydrostatic pressure due to low velocity flood flows (kg/m$^2$)

C  Coefficient for the power law in crack flow

n  Exponent for the power law in crack flow [no units]

W  Width of building component

$\Delta P$  Pressure difference

Q  Discharge (Volume of infiltrated water) m$^3$/s

$\Delta t$  Time interval (seconds)

$h'$  Depth of water inside the house [m]

$I(T)$  Total FIR for all components (m$^3$/s)

$I(n)$  FIR for component n (m$^3$/s)

T  Period of time (seconds)

A  Area of component (m$^2$)

$M_d$  Design bending capacity of component
\( M_x \) Maximum generated moment in a component

\( \sigma \) Stress in the glazing component (MPa)

\( R \) Resistance of building component against water contact

\( t_{c_0} \) Reference time step that water contact was first initiated with a component

\( t_i \) Specific time step in the simulation

\( t_c \) Water contact duration (seconds)

\( D(A_n) \) Damage to assembly \( n \) (in dollars)

\( DS \) Damage state

\( D_B \) Building damage cost (in dollars)
LIST OF PUBLICATIONS

The following list includes the publications that were produced as part of this thesis:

i.  

Journal articles


ii.  

Book chapters


iii.  

Conference proceedings


Part 1: Introduction
Chapter 1

Research Overview
1 Research Overview

1.1 Research background

Floods are the most common and costliest natural disasters around the globe (Kourgialas and Karatzas, 2012; Jha et al., 2012; CRED, 2014). The severe flooding in the recent years and the predicted increase in the frequency and intensity of future events have highlighted the need for establishing flood resilience in the community and the effective management of floods towards mitigating their adverse impacts (Brody et al., 2008; Yerramilli, 2013; Jalayer et al., 2013).

The traditional method for flood management, also referred to Hazard-based method, focuses solely on containing and controlling floods via structural measures (e.g. dams and levees). However, the limited focus of this method and its shortcomings to account for other aspects of flood risk (refer to Section 2.2) have resulted in a shift in attention towards the more comprehensive Flood Risk Management (FRM)\(^1\) framework for ensuring the overall success of the flood management (Samuels et al., 2006; Merz et al., 2010b; Birkmann et al., 2013). By using a multi-tier analysis of risk, FRM intends to identify and treat risks at different levels in an integrated way by (a) minimising the hazard levels and (b) reducing the potential damages (Buchele et al., 2006; Bubeck et al., 2011). A major advantage of FRM over hazard-based approach lies in its holistic view towards risk and consideration for flood damages as evidence for decision making. This underlines the significance of the concept of Flood Damage Assessment (FDA) as the key component of the FRM for estimating the possible damages for the crucial decisions in this context (Penning-Rowsell et al., 2003; Pistrika and Jonkman, 2010; Meyer et al., 2013). FDA can generally be performed in three major scales (i.e. Micro, Meso and Macro) in support of the different tiers of risk assessment in FRM (Apel et al., 2009; Merz et al., 2010b). While Macro and Meso models usually target large-scale applications with less detailed outputs, the Micro-level methods are employed for high resolution object oriented analysis on individual elements at risk at a small spatial stretch (Merz et al., 2010b; De Risi et al., 2013b).

Buildings have significant importance to the economy and usually their damages contribute significantly to the total community damage from a flood event (Messner et al., 2007; Dewals et al., 2008). Accordingly, in the majority of the methods in the current FDA practice, the focus is solely on buildings as the representative of the total flood damage to the community (Cannon et al., 1995; Ten Veldhuis and Clemens, 2010). On the other hand and more specifically at a building level, recent emphasis on the safety of people and the performance-based design of buildings against flood require

\(^1\) It is also referred to as risk-based method for flood management.
evidence-based decision support to a range of decision makers to ensure the flood resilience of buildings at their design and planning stages (Van de Lindt and Taggart, 2009; Dewals et al., 2008; ABCB, 2012a). This calls for an effective assessment of the potential flood impacts at building level for understanding of the buildings' behaviour against floods in this process and identifying the potential areas of improvement/retrofitting (CSIRO, 2000). FDA at this level also enables a cost-benefit analysis of various design alternatives for a building. This facilitates the adoption of effective risk reduction measures to mitigate possible damages from flood, and shortening the recovery time and efforts following an event (Lamond and Proverbs, 2009; Joseph et al., 2011). These drivers underline the importance of assessment of the potential damages to a building at the Micro-level and at its early stages of planning/development process for making sound decisions for improving its flood resilience.

Amongst the numerous FDA models proposed at different scales, only the Micro level methods can allow for the assessment of damages at a building level (Messner and Meyer, 2005; Apel et al., 2009). However, the current Micro-level FDA methods have limitations for taking into account the distinct behaviour of buildings against damaging effects of floods (Smith, 1994; Merz et al., 2010b). The generalisations and assumptions about building information inputs - and in the majority of cases ignoring the interior of the building - results in the misrepresentation of the unique characteristics of the building and consequently a significant increase in the uncertainty of the outcomes (Apel et al., 2009; Maqsood et al., 2014; Merz et al., 2004). With a direct link to the model complexity and its predictive capability, the current data input concerns have resulted in the dominance of simpler methods with higher level of uncertainty (Messner et al., 2007; Merz et al., 2010b). On the other hand, the damage is generally assessed solely against approximated flood parameters and in many cases only the depth of water. Since no direct relationship exists between the damage and the water depth alone, the uncertainties and consequently errors increase in the outputs (Smith, 1994; Merz et al., 2004; Thieken et al., 2005; Pistrika and Jonkman, 2010). Moreover, the damage estimation in the current practice is undertaken for the worst-case scenarios and against the simultaneous occurrence of maximum flood parameters (e.g. depth and velocity) which may be rare in reality. Without accounting for the spatiotemporal dynamism of the flood parameters, the intermediate flood impacts on a building that may influence its damages are ignored.

On the other hand, where complex flooding situation can affect a building by imposing various types of loads or causing damage to their materials according to their contact with water, yet the investigation of the current FDA methods shows that they exclusively focus on either water contact damage or estimation of damage from flood loads; without considering the coupled effects of both
together. Furthermore, the existing FDA models are developed according to the local conditions and therefore are difficult to transfer to another location or time. The outputs provided by these methods are limited to a single number for the overall building damage cost or only an indication of whether the building collapses or not for certain level of water and velocity. Other than these, no further information about the details and the location of damage at the building level is provisioned. Such details are important to reveal the sources of risk for a building for their treatment (Kelman, 2002; Mazzorana et al., 2014). Lastly, the current FDA methods generally cannot provide an effective presentation of the details and mode of the flood damage to a building and its components. Therefore, crucial information about the underlying factors for the damage cannot be communicated using these methods.

Despite the benefits of the current FDA methods to evaluate the damage for applications like comparative risk analysis or risk and vulnerability mapping at larger-scale, due to their aforementioned drawbacks and scope of analysis, they are inadequate at individual building level to support applications like flood resilient building design and planning (by engineering design firms, councils or referral authorities); and there still exists a research gap in addressing the requirements of such applications. These limitations hinder the necessary shift from the traditional and limited code-conforming approaches to the performance-based methods for building design and engineering. This results in the dominance of the code-conforming methods in many countries (including Australia) that are normally designed to address the wind and earthquake [and not flood] hazards (Van de Lindt and Taggart, 2009; Christodoulou et al., 2010). Therefore, a need is highlighted for further research to develop a method that by adopting a comprehensive input datasets about a building and the flood parameters, it can incorporate the uniqueness of the building for a complete analysis and communication of its potential damages. By linking such method to the early stages of the planning process for a building, FDA can possibly facilitate a flood resilient design of buildings in flood prone areas. This, in addition to the other regional and local flood risk reduction strategies, can improve the overall flood resilience of the community and reduce the cost of damage from such events.

1.2 Research formulation

1.2.1 Problem statement

According to the provided research background, the existing FDA methods can reasonably support larger-scale applications and by considering aggregated land use as their inputs. However, their capabilities fall short at the building level for evaluation of building design against flood where
detailed analysis of potential impact of a given flood on a specific building and according to its unique construction is required. Accordingly, the problem in this research can be formally formulated as follow:

"Despite the need for FDA at a building level (and consequently risks analysis) at the design and planning stages, by not taking into account the uniqueness of buildings in the analysis the current micro-level FDA approaches cannot provide an adequate assessment and presentation of potential damage to a building".

The above problem can be an impediment for effective decision making at the lower-tiers (local) of risk management at a building level and a barrier for optimised adoption of evidence-based solutions for improving the building resilience.

A variety of technical developments from data point of view have been observed in the literature. A thorough evaluation of these technologies in various domains (refer to Chapter 3) highlighted the potential benefit of an integrated use of Building Information Modelling (BIM) and Geographic Information Systems (GIS) for enriching the FDA process towards overcoming their underlined issues. While BIM contains detailed information about all aspects of a building and currently is being mandated for use in the land development process in many countries (Zeiss, 2013; McGraw Hill Construction, 2014a), GIS and geospatial information can provide geographically extended features like flood and spatial analysis capabilities for damage assessment. Despite the theoretical discussions on potential use of this integrated method and its value for FDA (Isikdag and Zlatanova, 2009a; Dakhil and Alshawi, 2014), no research or practical evidence exist in the literature that provides a methodology for taking advantage of this opportunity in the FDA context.

1.2.2 Research aim

According to the defined problem, this research, as part of a broader ARC project (grant number LP0990135), aims to

"Design and develop a new framework for a detailed micro-level analysis and communication of damage to a building based on its unique characteristics and behaviour against floods."

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2 Australian Research Council.
1.2.3 Research questions and objectives

To address the research problem and achieving the aim of this research, several research questions must be answered that include:

1. What is the current practice and research status of FDA on building at micro-level in the world? And what are limitations of the existing methods?

2. Can an approach for FDA be designed to support the appraisal of damage to a building by accounting for its unique characteristics and behaviour against floods? How this approach can be designed?
   a. What analytical processes and components are required for this purpose?
   b. What technical developments can be used to support these identified processes and how?

3. Can the developed FDA method overcome the limitations of the existing methods and provide an effective assessment and communication of damage to a building?

   In this context, 'effectiveness' is defined as the reliability of the model predictions and the quality of presentation of the damage to the building and its components.

To achieve the aim of the research and answering the research questions, and according to the scope of this research (refer to Section 1.4), a number of objectives were defined which are outlined below. Each of these objectives may answer one or more of the abovementioned questions.

1. To investigate and understand the
   a. Current status of FDA on buildings in support of the flood risk management;
   b. State-of-the-art technologies that can potentially benefit FDA by providing a more effective data input covering all the requirements for a detailed micro-level FDA of a building;

2. To design a framework for a detailed assessment and visualisation of flood damage to a building for allowing the analysis of the building damage based on its unique characteristics;
   a. To understand the potential impacts of flood on different aspects of a building;
b. To identify the required analytical methods for assessment of the damage to a building and its components;
c. To extract the data requirements for the designed processes in (2b); and
d. To outline the design of the damage assessment framework;

3. To develop a prototype system; and
4. To demonstrate the designed framework and evaluate its effectiveness for analysis of potential building damage from floods.

The research approach for achieving the objectives and further the aim of this research is provided next.

1.3 Research approach

This research is designed according to the "Design Science Research Methodology" (Hevner et al., 2004) for addressing the research problem put forward earlier in Section 1.2.1. According to the selected methodology, the adopted research approach in here consists of five main phases namely conceptualisation of research, design, development, evaluation, and synthesis and communication which are presented schematically in Figure 1.1.

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3 The selected type in this research is the most common Australian house type - One-storey Brick Veneer with slab on ground foundation. As Maqsood et al. (2014) discuss, within the research of Geoscience Australia, this building type is equivalent to class FCM7 of buildings that GA research on.
Conceptual phase

In the first phase, the theoretical background for the research is established which consists of two sub-tasks. In the first, in correspondence to the "awareness of the problem" phase in Design Science methodology (refer to Chapter 4), a thorough and exhaustive review of the relevant literature in the "problem domain" - flood risk management and flood damage assessment - is undertaken to address the objective 1(a) of the research. For this purpose, a wide range of books, journal articles, conference papers, reports, guides and other relevant resources such as discussions with experts as well as the Internet were utilised to understand the problem and the research gap.

As part of the Design Science methodology, new perspectives and insights to the problem that leads to development of a better solution should also be investigated in those potential "reference disciplines" (Hill, 2009). This constitutes the second sub-task in this phase and for this purpose, a similar literature review is undertaken in the Geospatial as well as the Architecture, Engineering, Construction and Facility Management (AEC/FM) domains to address the research objective 1(b).
Design phase

Subsequent to conceptualisation of the research, by addressing the sub-objectives 2(a-d), a framework for assessment and visualisation of flood damage to a building at a micro-level is designed. As part of this phase, according to the limitations of the current methods for the BIM-GIS integration (refer to Chapter 3), a new method is presented that can bring together the heterogeneous information from BIM and GIS for realisation of the framework.

Development phase

Once the FDA framework is designed, in the third (development) phase, by employing a series of suitable technologies it is further implemented in a prototype system. This development was specifically undertaken to address the research objective 3 in correspondence to the second phase in the Design Research methodology, namely the 'development' (Geerts, 2011).

Evaluation phase

In the fourth and last phase of the research, a twofold evaluation of the designed framework is undertaken to (a) demonstrate the framework; and (b) verify and validate its design and effectiveness for overcoming the limitations of the previous methods.

The part (a) of the evaluation, the prototype is demonstrated in a case study to assess and visualise the potential flood damage to a building in an Australian context. This case study is conducted in collaboration with a local council in Melbourne and the Melbourne Water, the responsible floodplain management authority in the Melbourne metropolitan region. A design flood\(^4\) was simulated using MIKE 21 simulation software (DHI, 2015) and the output of the model was adopted for evaluation of the damage to a proposed building in Melbourne.

For the Part (b) on the other hand, a formal evaluation is performed using the Face Validity method (see Law, 2008; Eddy et al., 2012). A set of questions as part of face-to-face interviews is used to acquire the experts' opinion on different aspects of the framework for testing its validity. The results were further compared with the original identified problem in the FDA domain to test if the aim of the research was achieved. Furthermore, the potential areas of improvement are highlighted and presented.

\(^4\) A flood with particular return period (usually 1-in-100 year) that is used for building design and planning in the land development process.
**Synthesis and communication phase**

In the final phase, the problem of the research, solution and its novelty as well as its findings are presented to other researchers and relevant audiences using a dissertation, a number of academic publications as well as presentations to the key relevant industry bodies.

**1.4 Delimitation of scope and key assumptions**

This research focuses on the ex-ante FDA with the ability to predict the potential damages to answer what if questions (see Section 2.4.1.1). As floods can be in different forms and with specific characteristics, due to the context of this research (Australia), the focus was on the riverine floods which constitute one of the most common types of flooding in the country as well as around the globe.

Furthermore, this research assesses the damage to a building at a Micro level where each building (and its components) is separately (and not in an aggregated way) analysed. In this analysis, only the direct tangible flood damages to a building are considered and the other damage types (e.g. indirect or intangible) are regarded beyond the scope of this dissertation. In addition, amongst the direct tangible damages, only the first-order damages are considered within the scope and those secondary damages generated from the cascading impacts of damage to one or more components are not included.

As will be discussed in Chapter 2, hazard assessment (flood simulation) is an important prerequisite for FDA and provides crucial information about floods for analysis of their potential impacts on a building. Such assessment is complex and there is a field of knowledge dedicated to it. Although as part of the presented research a flood simulation is performed, an improvement in the quality of such assessment is not the focus of this research.

Depending on their type of construction, buildings may have different resistance and failure mechanisms against floods (see Chapter 2). Due to the limited time and resources provided for this research, it only focuses on one construction type, a single storey brick veneer house with slab-on-ground foundation and integral garage. This building type is the most common type in Australia. Further justification for selection of this type is provided in Section 4.5. On the other hand, according

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5 First-order damage in this dissertation refers to damages that occur during the specific time-frame of the flooding and are caused directly from the interaction of building components and the flood actions. The first-order damages do not consider the cascading impacts of the flood or failure of specific components on others. In addition, their scope does not include those that occur as the result of other natural phenomena (e.g. mould growth) and human intervention during the drying or recovery process.
to the type of the flood under investigation, only its relevant flood impacts are considered within the scope of this research (see Chapter 5 for more details).

The research in here only considers the flood damage to the building components and excludes the analysis of damage to the building content (e.g. furniture) from the scope. In addition, the following influencing factors are not considered in this research:

- impact of changes in ambient conditions (e.g. freeze/thaw);
- damage from moisture-induced growths (e.g. toxic mould);
- flooding from internal sources (e.g. burst water tank or boiler) or sewer flooding; and
- problems caused by inadequate or defective roof drainage.

In addition, although the property-level factors like fences and other risk reduction measures at this level can reduce the damage to a building, the evaluation of their influence is beyond the scope of this research. In here it is assumed that the building components are not previously affected by the adverse impacts of aging, weathering or damage from other hazards. This assumption is sensible for new buildings which are the focus in this research. For those aged buildings however, these factors can be included.

This research focuses only on the design of a new framework to address the formulated problem in Section 1.2.1. Due to the specific aim of this research, answering further questions regarding "how to implement" for specific organisations and their assessment for "usefulness" of the framework is beyond the scope of this research. Therefore, evaluation of the framework is particularly performed for testing its internal validity and the feasibility of its implementation (see Chapter 4 for more details). In the evaluation of the proposed method in this research, as discussed in Chapter 4, the face validity and expert judgment are used. This was due to inaccessibility to and the absence of empirical damage data that fits the abovementioned assumptions about the building. This issue is repeatedly discussed in the literature in various countries (Messner et al., 2007; Merz et al., 2010b). Face validity has been regarded in the literature as the first step for evaluation of a method. Due to the limited resources and time provided in this research, only face validity was considered which adequately provides answers to the research questions put forward in Section 1.2.3.
Lastly, the sole purpose of the technical developments (e.g. prototype system) in this research is to demonstrate the proposed framework. Therefore, optimisation of the used algorithms for performance improvement of this system is beyond the framed scope in this research.

This section provided the overall and general assumptions of the presented research in this dissertation. However, for the design and implementation of the framework discussed in Chapters 7-9, other assumptions for its various components are also made which will be further discussed in their relevant sections in this thesis.

1.5 Thesis structure

This dissertation is structured in four parts namely *introduction, background, research, and synthesis* each of which may contain one or more chapters as illustrated in Figure 1.2. The order and overall contents of each chapter are briefly explained in here.

![Figure 1.2: The structure of the dissertation](Image)
Chapter 2 provides an overview of the overall process of FRM and the importance of FDA as its crucial component. Further, it presents the different aspects of the FDA and the importance of damage evaluation to a building. Thereafter, a critical review of the application of micro-level flood damage assessment to buildings is presented and a number of limitations and major research gaps are highlighted.

Chapter 3 critically reviews numerous technological developments in the Geospatial and AEC/FM domains from a data structure point of view. It further provides insights to the current methods for integration of BIM and GIS and their potential application in support of a new framework to overcome the highlighted gaps in Chapter 2.

Chapter 4 outlines the selected research methodology (the Design Science) in this research to answer the questions put forward in Section 1.2.3. In addition, the required steps in this methodology are presented and the details of how they are fused with different aspects of this research are explained.

Chapter 5 intends to provide an understanding of the possible vulnerability of the building to floods and refine the scope of the damage analysis in this research.

Based on the information provided in Chapter 5, a number of suitable analytical/engineering methods for damage estimation for various building components are provided in Chapter 6. This chapter further formalises the processes for the selected damage evaluation methods.

In Chapter 7, the design of the framework and its different components are explained. In this chapter, integration of various identified processes into an integrated framework and the development of a new BIM-GIS integration method to construct a data foundation for those processes are explained in detail.

Chapter 8 details the implementation of the framework into a proof-of-concept prototype system. It explains the overall architecture of the prototype system and the adopted technologies in it.

Chapter 9 presents a case study to demonstrate the prototype system and the application of the framework to assess and visualise the damages and risks to a real building. In this chapter, the simulation of the flood using MIKE 21 package and use of this information along with the extracted building data from BIM is explained and the damage evaluation and visualisation process for this

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6 The one under investigation in this research (refer to Section 1.5).
building according to the presented framework in Chapter 7 is provided. This chapter further presents the result of the framework evaluation and summarises the provided experts' feedback.

Finally in Chapter 10, the achievements in the presented research are reflected, the concluding remarks are presented, and the recommendations for future research directions are proposed.

1.6 Chapter summary

In this chapter, the foundation of the research presented in this dissertation was laid using the provided background to the existing issues in the current practice of flood damage assessment. The problem statement, the aim of the research, the essential questions that are required to be answered to achieve this aim, and the objectives and scope of the research were also formalised and discussed. A brief overview of the adopted research approach was also provided and its various phases were linked to the presented objectives. This chapter was concluded by delineating the overall structure of this dissertation to guide the reader throughout this document.

The next chapter provides a background to the problem domain, the flood damage assessment, and presents a thorough investigation of its different aspects, the current FDA methods and their limitations for damage evaluation to buildings at a micro level.
Part 2: Background
2 Flood Damage Assessment (FDA) of Buildings: Principles and Methods

2.1 Introduction

For addressing the objective 1(a) of this research, this chapter provides an overview of the principles and current status of the research on micro-level FDA on buildings. This chapter, as Figure 2.1 illustrates, first discusses the importance of resilience in the community against the flood and highlights the crucial role of FRM in this context. The role of FDA as a decision support for FRM is highlighted next and its important applications and users are discussed. Due to the complexity of the FDA domain, knowledge about its different aspects is necessary for the reader and they are explained in detail accordingly. The scope of the discussion is further restricted to damage evaluation of the building and in particular at micro level (where individual buildings are recognised in the damage evaluation). This is followed by a categorical overview of the current methodological frameworks and tools for micro-level flood damage assessment of buildings. Subsequently, a critical summary of these methods is presented and the chapter is concluded by revealing a number of knowledge gaps in this context that further form the basis for the presented research in this dissertation.

![Figure 2.1: Schematic summary of the content of the chapter](image)

2.2 Floods and the need for flood resilient community

A flood is "a body of water that rises to overflow lands which are not normally submerged" (Ward, 1978). Similarly, FEMA (2014) defines it as "a general and temporary condition of partial or complete inundation of normally dry land area or of two or more properties". Depending on their "source" or "speed of onset", floods can be in different forms and may have very different characteristics. The speed of onset of a flood determines how quickly it develops. On this basis, floods are classified into rapid onset (e.g. flash floods and urban floods) and slow onset (semi-permanent and slow-rise riverine floods) (Becker, 2008). On the other hand, based on their source, floods can be (Sterna, 2012):
Floods account for 20-30% of the global economic losses from natural hazards (Douben and Ratnayake, 2006). According to the published data by CRED (2014)\(^7\), this is nearly 18.5 billion US dollars worldwide damage per year. With over 3800 occurrence of floods since 1980 (see Figure 2.2a), they have been responsible for approximately 40,000 fatalities or injuries and have affected nearly 95 million people every year. This makes floods the most common and costliest natural hazard around the globe (Bhanumurthy and Behara, 2008; Kourgialas and Karatzas, 2012; CRED, 2012; Jha et al., 2012).

![Figure 2.2: (a) Number of flood occurrences per year since 1980; (b) the total reported economic damage from floods around the world since 1980 (source: CRED) ](image)

\(^7\) This data is for the period of 1980 to 2014. For detailed records, refer to Appendix 1.
A consensus exists amongst experts that, as Figure 2.2(b) shows, the number of floods and their damages are increasing (Plate, 2002; Brody et al., 2008; Jha et al., 2012; Yerramilli, 2013). A variety of underlying factors are considered for this issue. On one hand, the frequency, intensity and magnitude of flood events are increasing mainly because of the alterations in the meteorological patterns associated with global warming. On the other hand, the vulnerability of human settlements is increasing due to the population growth, intense urbanisation and poorly managed developments in floodplains (Jongman et al., 2012). This is majorly caused by the pressure to land resources and other socioeconomic and political agendas (Williamson et al., 2010; Ezemonye and Emeribe, 2011; Jha et al., 2012). These issues are of greater concern for urban flooding where high density of population and assets and tangled economic dependencies exist (Hammond et al., 2013).

Uncertain future outlook and the growing risks of floods require communities to be prepared and resilient. This has been reflected repeatedly in a variety of national and international strategic documents such as Hyogo Framework for Action (UNISDR, 2005), Sendai Framework for Disaster Risk Reduction (UN, 2015), Policies for Sustainable Development (UNCSD, 2012), European strategy on Adaption to Climate Change (European Commission, 2013) and the Australian National Strategy for Disaster Resilience (COAG, 2011). Resilience as an internal property of systems, is based on three common notions; i.e. resistance, recovery and adaptive capacity (Thieken et al., 2014). Resistance reflects the strength of the community to withstand the impacts of hazard while maintaining its functions (Dovers and Handmer, 1992). Recovery, on the other hand, illustrates how quickly the community can regain an acceptable level of functioning or return to its original state (Nyström et al., 2000). Learning from the past should also be incorporated into the recovery process to improve the coping capacity of communities beyond their pre-disaster state. This is reflected by the notion of adaptive capacity of the community that encompasses its willingness and ability to accept and adjust to change (Watts and Bohle, 1993).

Accomplishing resilience requires long-term investments in different aspects of the community and carrying out a wide range of activities prior to, during and following a disaster. These activities are commonly classified into three overlapping clusters, i.e. prevention, response and recovery (Zevenbergen et al., 2008; Flood Victoria, 2014). The partnerships between the key players and a successful integration of these activities at national, regional and local levels as part of the flood management process enables the community to absorb and resist the disturbances caused by the flood hazard and promptly and effectively recover from its consequences (Lamond and Proverbs, 2009; SES, 2012b).
The World Bank (ADB, 2012) and Deloitte (2013) highlight the importance of mitigation/prevention activities suggesting a $4-10 savings in disaster recovery for every dollar spent for these activities\(^8\). Similarly, it has been discussed that up to 50% of disaster response cost can be avoided by proper investments in preventative activities/measures (Deloitte, 2013). However, national statistics show a deficiency in investments in these activities as for example in case of Australia, only a very small portion (2-5%) of the national disaster funding is allocated for these activities (Tsikaris, 2014; Productivity Commission, 2014)\(^9\). On the other hand, a new paradigm has been emerged in the recent years that promotes a necessary shift of focus from the management of "disasters" to managing "risks" (UN, 2013). This also puts a strong emphasis on the prevention/mitigation activities of flood management with intention to reduce risks and prevent a disaster to happen rather than responding to it. These activities mainly lie in the specific scope of floodplain management which involves managing people, infrastructure and the environment in areas at risk of flood (QRA, 2011). Floodplain management aims to minimise the flood impacts on public and private properties and maintain the safety and security of the community while preserving the natural processes within the floodplain (CSIRO, 2000).

Traditionally, floodplain management in many countries was dominated by "hazard-based" method. By adopting structural measures such as dams and levees, this method aims to protect the community against the risks of one or a handful of "design floods"\(^10\) (Keys, 2006; Samuels et al., 2006; Merz et al., 2010b). In hazard-based method, the focus is only on the hazard, intending to exclude the risk by controlling the flood and reducing its probability of occurrence. However as Figure 2.3 illustrates, risk is commonly defined as a function of both hazard and the vulnerability of elements at risk (Alexander, 1991; Helm, 1996; Blong, 1996; Granger et al., 1999; Crichton, 2001; Sayers et al., 2002; Merz and Thieken, 2004; European Floods Directive, 2007; Dewals et al., 2008; Hoa et al., 2008; Jonkman et al., 2008; Smith, 2013; Klijn et al., 2015). In this way, the hazard-based methods tend to ignore the latter component of risk and the observations over the years show that the sole focus on hazard-based method is insufficient to build effective resilience towards flood impacts (Birkmann et al., 2013; Merz et al., 2010b).

\(^8\) Also see the discussed output of Australian Business Roundtable for Disaster Resilience and Safer Communities at http://www.theage.com.au/national/flirting-with-disaster-20140511-383ju

\(^9\) See Appendix 2 for the details of the communication.

\(^10\) Design flood is a flood with specific probability of occurrence that its exposure parameters and magnitude is used as the basis for design and planning. Common design flood for urban planning in Australia (and many other countries around the globe) is 1-in-100-year flood.
Scholars like Sayers et al. (2002), Merz et al. (2010a), Lofstedt (2011) and Chakraborty (2012) discussed this inefficiency in terms of mainly three limitations of this method:

a) Prevention of design flood in here is only effective up to certain probability of occurrence and limited beyond this point for higher magnitude events. Therefore, this limited focus ignores the residual risks and can cause unintended and unforeseen consequences and may potentially increase risks in other ways.

b) The structural measures adopted in this method are fragmented and designed separately and therefore, fail to provide a holistic approach needed for managing flood risks.

c) Since the consequences of flood are left open for interpretation in the decision making, the adoption of risk-reduction measures in hazard-based method is based on assumptions and not testing and therefore, not scientific.

The above limitations and the emerging global and local economic and financial bottlenecks restrict the capacity of public and private investments on only costly structural protection measures (Mazzorana et al., 2012a); therefore, in the last decade or two, floodplain management has undergone a paradigm shift from hazard-focused method to a comprehensive management of risk, taking into account both hazards and vulnerabilities in FRM method (Samuels et al., 2006; Merz et al., 2010a). The new paradigm is developed to support the notion of “live with flood risk” as a trade off between the benefits of establishing human settlements in floodplains and accepting and dealing with the risks of floods (HNFMSC, 2006; Glavovic, 2014). Due to the importance of FRM for floodplain management, it is explained in more detail in the next Section.
2.3 Flood Risk Management

Flood risk management involves the identification, assessment, evaluation and treatment of flood risk using suitable floodplain management measures (Hall et al., 2003). The focus of the FRM is on minimising the flood risk to an acceptable level by reducing the hazard and/or minimising the potential damages (European Commission, 2004; Buchele et al., 2006; Merz et al., 2010a; Bubeck et al., 2011). The overview of the FRM concepts is schematically illustrated in Figure 2.4.

![Figure 2.4: Flood risk management cycle (adopted from Hall et al., 2003)](image)

A variety of guidelines and standards (e.g. DEFRA, 2000; Hall et al., 2003; NSW Government, 2005; AS/NZS ISO, 2009; USACE, 2013; EU Flood Directive mentioned in Thieken et al., 2014) have described the FRM cycle and its details. In this cyclic process, after defining the scope and the context of the FRM (e.g. objectives, stakeholders and acceptable levels of risk), the information about the current and past performance of the system is obtained by observation and monitoring that forms the databases to develop models of systems. Risk analysis (as part of risk assessment) at the heart of this method provides an indication of the performance of the system (e.g. the national economy, a river catchment, or a risk-reduction measure for a building) for evaluation and quantification of the risk. This analysis can be performed for the present state of the floodplain or under scenarios of change and/or intervention (Hall et al., 2003; Ten Veldhuis and Clemens, 2010).

11 Interchangeably used by “risk-based” method for floodplain management.
Risk analysis, depending on the needs and purpose of the investigation, it can be undertaken using one or a combination of qualitative, semi-qualitative or quantitative techniques (AS/NZS ISO, 2009) and can be in three major tiers; i.e. high-level at national scale, intermediate level at regional and catchment scale; and detailed analysis at local level and sometimes project level to assess if a project (e.g. a building) contributes to its intended design (Hall et al., 2003). The nature of the decision is another influencing factor for the analysis and determines the required analysis models and the resolution of the outputs. Messner et al. (2007) discuss that risk analysis, as a holistic approach, may take into account the risk of all flood types and a full range of probability of occurrence in the study area. It combines the likelihood and the potential damage of all possible events into a single figure, known as the "damage-probability curve" (see Figure 2.5). This diagram illustrates the level of damage for events with different probabilities. The area under the curve is referred to as "Average Annual Damage (AAD)" and illustrates the average of expected flood damages per year. It is also an indication of risk (Solin and Skubincan, 2013) and is commonly used for comparison between the effectiveness of risk-reduction measures\textsuperscript{12} for decision making.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{damage-probability_curve.png}
\caption{An example of damage-probability curve (adopted from Messner et al., 2007)}
\end{figure}

Subsequent to the assessment of the potential risks, they are evaluated against the acceptable risk levels and if interventions for risk reduction are required, then risks are further prioritised for treatment. Then the risk-reduction measures are considered, compared based on their AADs, prioritised and selected by the responsible people and organisations in the FRM framework. AS/NZS ISO 31000 (2009) classifies these measures into risk avoidance, elimination of the source of risk or changing its likelihood, reducing the consequences, sharing (or transferring) risk with other stakeholders (e.g. risk financing) and controlling the risk by awareness and informed decisions. CSIRO (2000) and NSW Government (2005) further classify these in either categories of flood

\textsuperscript{12} For development of the damage-probability curve and AAD, see Messner et al. (2007)
modification, response modification and property modification measures. Table 2.1 explains these categories and provides some examples for each.

Table 2.1: Typical floodplain risk management measures (NSW Government, 2005; Hall et al., 2003)

<table>
<thead>
<tr>
<th>Definition</th>
<th>Example of measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flood modification</strong></td>
<td>Flood control dams, retarding basins, levees, bypass floodway, channel improvements and floodgates</td>
</tr>
<tr>
<td><strong>Response modifications</strong></td>
<td>Community awareness and readiness, flood forecasting and warning, local flood plans, evacuation planning and management, recovery planning</td>
</tr>
<tr>
<td><strong>Property modification</strong></td>
<td>Zoning and land-use planning, voluntary purchase, voluntary house raising, development controls, building flood proofing, flood access, etc.</td>
</tr>
</tbody>
</table>

Once the suitable measures are selected, they are planned and implemented to treat the identified risks. DCLG (2009), Jha et al. (2012) and Ashley et al. (2012) underlined the planning and development process as the most sustainable channel for implementing the selected measures for managing the flood risks. As treatment plans have no statutory basis, according to the influence of statutory planning system on factors like location, type, design and function of the development, inappropriate proposals in the flood prone area can be forced to be avoided or their risks to be reduced via adoption of suitable measures (CSIRO, 2000; White and Richards, 2007). Due to such benefits, the FRM has been integrated with planning and development process in different parts of the world like US, UK, Australia, etc (CSIRO, 2000; DCLG, 2009; ABCB, 2012a; Grech and Bewsher, 2014).

Within the FRM framework, monitoring and review of the performance of the measures as well as the residual risks is carried out regularly by the responsible authorities to ensure the achievement of the goals of the risk reduction measures or if necessary, reassessing the risks that might require further treatment. The cycle is restarted according to the modification and the new setting of the floodplain.

FRM is central to the success of floodplain management process towards achieving the flood resilience in the community (CSIRO, 2000; NSW Government, 2005). The major advantage of this method over the traditional hazard-based method, as discussed previously, lies in its holistic view towards risk and consideration for consequences of flood for informed decisions for reduction of risks. Having different aspects of FRM explained in this section, the crucial role of damage
assessment in this framework is emphasised here again. The influence of damage analysis element cascades throughout different phases of FRM and without it, such evidence-based method towards a sustainable floodplain management would not be achievable. This further underlines the significance of FDA as the key component for estimating the consequences of flood in this context (EMA, 2003; Penning-Rowsell et al., 2003; Merz et al., 2010b; Meyer et al., 2013). In the following section, FDA is discussed in detail and its different aspects are explored.

2.4 Flood damage assessment as a decision support tool

At different levels of FRM, a variety of stakeholders must work together in a coordinated way to realise an integrated FRM. Decisions for adoption of individual or a collection of them together as a "floodplain management option" should consider their economic feasibility as well as their soundness from technical point of view. The immediate question in the selection of any of these measures is that whether the investment in its adoption can be justified in the presence of other alternatives.

By calculating the average damage per-year using AAD, and taking into account for costs of different risk-reduction measures, decision support and invaluable information can be provided to the decision maker for an effective investment in the most suitable measures (Meyer et al., 2013). By predicting the outcomes of decisions and facilitating risk communication via suitable metrics, FDA allows for evidence-based decisions according to the "what if" questions asked by the decision maker. The need for such decision support at different levels of FRM and its benefits for increasing the overall system effectiveness have been previously acknowledged in the literature (ICE, 2001; Hall et al., 2003; Wicks et al., 2011; Van Ree et al., 2011).

The benefits of FDA are not limited to the optimal selection of risk-reduction measures. It is an important tool for identification of elements at risk in flood prone areas, assessment of vulnerabilities, flood risk mapping, community awareness, comparative risk analysis, cost-benefit analysis of the required investments in flood reduction measures, and setting the research priorities (Roos, 2003; Meyer and Messner, 2005; HNFMSC, 2006; Merz et al., 2010b; Middelmann-Fernandes, 2010; Jongman et al., 2012; Meyer et al., 2013). Moreover, FDA supports rapid or even comprehensive appraisal of damage to the community for situational awareness for facilitating a more effective disaster response or funding arrangements for recovery and reconstruction (Mark and Djordjević, 2006).

All these drivers illustrate the importance of FDA to the risk-based method for floodplain management (Pistrika and Jonkman, 2010; Thieken et al., 2005; Kreibich and Thieken, 2008). Green
et al. (2011) and Hammond et al. (2013) further underlined the strong link between FDA, sustainable development and establishing resilience in the community. The evaluation of damage within FRM is usually specific to the objectives of a particular study in regards to how quick and comprehensive it is required to be. These objectives dictate the underlying assumptions, characteristics of the FDA model and the required outputs of the damage assessment (Meyer et al., 2013).

2.4.1 Aspects of Flood Damage Assessment

The diversity of requirements of the aforementioned applications has resulted in the development of a variety of FDA methods. The review of literature shows that the distinction between the current methodological frameworks for evaluation of damage is mainly related to the context of FDA (purpose, required reliability, available data, available resources, etc.), timing of assessment, spatial scale and precision level, exposure parameters and damage categories considered in assessment, cost base, and the type of model (EMA, 2003; Messner et al., 2007; Merz et al., 2010b; Molinari et al., 2014a). Similar dimensions are adopted by Meyer and Messner (2005) and Jongman et al. (2012) as the basis of the comparison between different FDA methods. Referring to these dimensions in this chapter as the "aspects of FDA", they are summarised in Table 2.2 and are briefly explained in the following subsections.

Table 2.2: The aspects of Flood Damage Assessment

<table>
<thead>
<tr>
<th>Timing of study</th>
<th>Type of assessment</th>
<th>Scale</th>
<th>Damage categories</th>
<th>Exposure parameters</th>
<th>Damage valuation method</th>
<th>Damage model construction method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex-Ante</td>
<td>Economic</td>
<td>Macro</td>
<td>Buildings (residential or non-residential)</td>
<td>Extent</td>
<td>Replacement cost</td>
<td>Empirical</td>
</tr>
<tr>
<td>Ex-Post</td>
<td>Financial Insurance</td>
<td>Meso</td>
<td>Infrastructure</td>
<td>Depth</td>
<td>Depreciated cost</td>
<td>Synthetic</td>
</tr>
<tr>
<td></td>
<td>Physical Environmental</td>
<td>Micro</td>
<td>Agriculture</td>
<td>Velocity</td>
<td></td>
<td>Combination</td>
</tr>
<tr>
<td></td>
<td>Public health</td>
<td></td>
<td>Traffic disruption</td>
<td>Duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Businesses</td>
<td>Debris</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>People</td>
<td>Waves</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Contamination</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4.1.1 Timing of FDA study

Flood damage evaluations are considered for either estimating the "actual" damages in the aftermath of an event (referred to as ex-post) or used for assessment of "potential" consequences of probable future floods (ex-ante). The actual damages, in contrast to potential ones, incorporate the
temporary resistance parameters (e.g. flood warning or deployment of sandbags); hence, a more realistic estimation of damage can be provided. The evaluated damages in ex-post method are commonly utilised for facilitating response and recovery activities and their funding (Meyer et al., 2013), or adopted for development and/or calibration of ex-ante FDA models. In contrast, the ex-ante studies are beneficial for assessment of damages as part of the previously discussed intervention scenarios in risk management.

2.4.1.2 Typology of flood damage

According to the type of flood, the extent and types of damages vary in space and time and may span across a variety of hardships and a spectrum of impacts on the community (Thieken et al., 2005; Green et al., 2011). They can encompass the harm to human health and their belongings, infrastructure, buildings (residential and non-residential), the environment, cultural heritage as well as industrial, social and economic activities. Despite the occasional discrepancies in terminology and interpretations of damage types, flood damages are commonly classified into tangible and intangible on the basis of if they can be expressed in monetary or economic terms (Cochrane, 2004b; Rose, 2004; Merz et al., 2010b). Tangible and intangible damages are further classified into direct and indirect. Direct damages are those resulted from the immediate physical contact of floodwater, whereas indirect damages refer to any impacts of flood such as disruption of economic or social activities that is induced by the direct damages. Indirect damage may or may not occur in space and time of the actual event (Kourgialas and Karatzas, 2012; Meyer et al., 2013). Examples of these damage categories are illustrated in Table 2.3:

Table 2.3: Classification of damage categories (adopted from Jonkman et al., 2008; Merz et al., 2010b)

<table>
<thead>
<tr>
<th>Form of damage</th>
<th>Tangible</th>
<th>Intangible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>Buildings and content, infrastructure, roads, agriculture, Business interruption (inside the flooded area), Clean up costs, vehicles.</td>
<td>Loss of life, injuries and health effects, Historical and cultural losses, environmental damage.</td>
</tr>
<tr>
<td>Indirect</td>
<td>Production loss from losses of suppliers or flooded factory, Temporary housing of evacuees.</td>
<td>Societal disruption, Psychological trauma, inconvenience of post-flood recovery activities.</td>
</tr>
</tbody>
</table>
The direct and indirect flood damages can also be discussed in terms of primary and secondary damages according to their importance to a particular sector (Joy, 1993; Smith, 1994; Dutta and Herath, 2001; Messner et al., 2007).

2.4.1.3 Type of assessment

Referring back to Section 2.3, on the basis of the type of decision, the performance of the system under the flooding situation is valued differently by the stakeholders. The economic evaluation of damage to the elements at risk as the basis for many decisions in FRM has been dominant in the FDA literature. This type of assessment evaluates damage to the elements at risk based on their economic value in the present market. Hall et al. (2003) criticise the exclusive reliance on economic analysis and highlight the importance of other assessment types for supporting a multivariate evaluation of damage for different activities within FRM.

The other types of damage analysis may include financial, insurance\textsuperscript{13}, physical, environmental and health assessments (EMA, 2003; Kamruzzaman, 2008; Jonkman et al., 2008; Meyer et al., 2013). The financial assessments focus on the financial impact of flood on an entity which is directly affected by the flood and can be used for investigation of possible Return on Investment (ROI) from a specific mitigation measure (BTE, 2001). On the other hand, an evaluation of flood damage based on the analysis of insurance claims for a particular event constitutes the insurance assessment. As opposed to the other assessment types, insurance assessments only consider the insured damages and disregard those uninsured as well as those elements at risk that are not covered by the insurance. Environmental and public health assessment focus on the intangible aspects and describe the damages to the environment and people. Physical assessment has been identified as the basis and the starting point for all the other assessments and includes the evaluation of the physical damage to the elements at risk (Pistrika and Jonkman, 2010; Blanco-Vogt and Schanze, 2013; Mazzorana et al., 2014).

2.4.1.4 Scale of assessment

A direct relationship has been established between the risk analysis and its spatial specifications including the area of interest and the resolution of the study (Apel et al., 2009). Scale is an additional source of complexity in the evaluation of flood damage (Downton et al., 2005b). Many researchers (Gewalt et al., 1996; Messner and Meyer, 2005; Messner et al., 2007; Merz et al., 2010b) discussed

\textsuperscript{13} Financial, insurance and economic loss estimations are different. EMA (2003) provides a comprehensive comparison between them.
that the damage evaluation is commonly undertaken in three spatial scales to support the tiered risk analysis discussed in Section 2.3:

- **Macro** studies for high level decision making at (inter-)national and sometimes regional levels;
- **Meso** studies at regional extent down to local government levels, analogous to intermediate level risk analysis; and
- **Micro** studies with small spatial stretch from local government area down to individual elements like building which serve the needs of detailed analysis for risk assessment.

This classification not only indicates the size of the study area but also implicitly details the expectations in terms of precision and the level of aggregation of inputs and outputs of the study (see Figure 2.6). In contrast to the use of Object-Oriented method for the evaluation of damage to individual elements at micro level, the Macro and Meso studies are usually based on aggregated land use and do not recognize individual elements at risk for the assessment (Messner and Meyer, 2005; Apel et al., 2009). While an approximate damage assessment may be sufficient for Macro and Meso scales, for those carried out at Micro level, the demand for precision is high and small errors may result in misjudging the risks and unprecedented outcomes.

![Figure 2.6: Scales of FDA analysis (adopted from Messner et al., 2007)](image)

Merz et al. (2010b) and Meyer and Messner (2005) underlined the blurry boundaries between these scales that results in different definition of these scales in various studies creating intermediate methods with possible combination of characteristics of multiple scales.
2.4.1.5 Exposure parameters included

Flood damage is the consequence of effects of flood characteristics (the exposure parameters) on the flood susceptible elements. Messner and Meyer (2005) discuss the two crucial components of ex-ante damage estimation: determination of hazard and exposure parameters and then the evaluation of damage using damage models. Every FDA model therefore takes into account at least one flood exposure parameter\textsuperscript{14} for evaluation of damage.

Various studies have discussed these parameters on the basis of the nature and size of the flood (Kreibich and Thieken, 2008; Sterna, 2012). These parameters may encompass *inundation extent*, *flood depth*, *velocity*, *debris*, *rate of rise*, *duration*, *waves*, *contamination*, and *frequency* (Smith, 1994; Dutta et al., 2003; Dewals et al., 2008; Apel et al., 2009; Elmer et al., 2010). In addition, the theoretical contribution of a number of other parameters such as *salinity*, *temperature*, *density* and *sediments* is often discussed (USACE, 1996; Kelman, 2002). For a comprehensive picture about the losses from flood, Kelman and Spence (2004) and Jonkman et al. (2008) underline the importance of the inclusion of a complete set of all exposure parameters in an integrated assessment approach. The inclusion of more exposure parameters can allow the realisation of complex flood damage models\textsuperscript{15} towards improving their predictability (Kreibich and Thieken, 2008; Middelmann-Fernandes, 2010; Schroter et al., 2014). In contrast, many scholars argue that the inclusion of too many parameters result in increase in the uncertainty of the analysis as there is insufficient empirical evidence about the damage-generation mechanisms for the majority of these parameters (McBean et al., 1988; Merz et al., 2010b). This is mainly related to the heterogeneity of these parameters in space and time, limited knowledge about the exact contribution of these parameters as well as difficulty in the prediction of their occurrence and effects on the damage (Kelman and Spence, 2004; Kreibich et al., 2009; Elmer et al., 2010; Merz et al., 2013). The review of literature shows that the multi-parameter models usually either remain at conceptual level or are very location-specific and currently no comprehensive FDA method exists that takes into account all these parameters for a comprehensive analysis of damage (Thieken et al., 2005; Merz et al., 2010b; Jongman et al., 2012).

Inundation extent is basically an indication of the affected elements at risk by the flood and beside this, does not have any effect on the magnitude of damage. Middelmann-Fernandes (2010), Messner et al. (2007), Kreibich et al. (2009), Merz et al. (2010b) and many others acknowledge the widespread use of flood depth as the sole parameter in a large number of current FDA models for evaluation of damage.

\textsuperscript{14} Also known in the literature as ‘flood parameters’ or ‘impact parameters’.

\textsuperscript{15} Model complexity refers to the number of damage explanatory variables in the model.
damage. Velocity of water, on the other hand, is influential on the level of damage and has been repeatedly discussed in a variety of studies (Sangrey et al., 1975; Clausen, 1989; USACE, 1998; Roos, 2003; Thieken et al., 2008a; Kreibich et al., 2009; EAA, 2011). Velocity is occasionally used separately alongside the depth for damage evaluation. In some cases, instead of two separate factors, a combination of depth and velocity called "depth-velocity product" - an indicator for intensity and magnitude of flood - is used (Clausen, 1989). On the other hand, Penning-Rowsell et al. (2003), Thieken et al. (2005) and Messner and Meyer (2005) discussed the important effects of different duration and contamination on the magnitude of flood damage. While depth and occasionally the floodwater velocity are considered in the majority of the FDA methods, the use of duration and other parameters of flood such as debris, waves, frequency and contamination is not common.

The review of literature shows that the number of exposure parameters included in an FDA study is directly linked to the scale of analysis. In large scale analyses (i.e. Macro or Meso), an approximate damage evaluation commonly suffice and therefore, extent and approximate depth at each location suffice for the purpose of the analysis. This is due to the less importance and difficulties in prediction of the impacts of the aforementioned parameters on aggregated information used at these scales. In contrast, for more detailed studies at micro level that individual elements at risk or damage to their components are considered, the use of more flood parameters is commonplace.

In the ex-ante damage evaluation studies, these parameters are usually obtained from "Hazard Assessment" using hydrodynamic simulation tools. On the other hand, for ex-post methods, observations from field survey or using remote sensing technologies are common tools for obtaining these parameters. The majority of these parameters (e.g. debris or contamination) are extremely difficult to obtain in a post-flood survey.

### 2.4.1.6 Damage categories

A major distinction between the current flood damage evaluation studies lies in the number and type of damage categories in direct, indirect, tangible and intangible damages (see Table 2.3) that are incorporated in them. It is generally argued that all damages (including those indirect and intangible ones) must be included in the analysis (Green et al., 1983; NRE, 2000; Penning-Rowsell and Green, 2000; Lekuthai and Vongvisessomjai, 2001; Thieken et al., 2005; Jonkman et al., 2008). Yet, Messner et al. (2007) discuss that a more pragmatic approach is to focus on the most important categories of

16 See Pistrika and Jonkman (2010) for detailed discussion about the meaning of this factor.
damage to avoid very extensive and costly analyses. It is therefore up to the decision maker (or analyst) to decide on the inclusions as well as the exclusions (Hammond et al., 2013). Cochrane (2004a; 2004b) summarises the methods that can deal with estimation of indirect and intangible damages. However, the review of literature shows that the majority of methods of the FDA literature focus on estimation of direct tangible damages of flood (Merz et al., 2004; Merz et al., 2010b; Messner and Meyer, 2005; Thieken et al., 2005). This is mainly due to:

- Bigger risks from direct flood impacts and therefore, general perception of the importance of these categories over indirect or intangible ones (Jha et al., 2012);

- Contribution to significant proportion of the total damage (Merz et al., 2004; Messner et al., 2007);

- Difficulty in the assessment of indirect and intangible damages, both conceptually and practically, due to possible reliability issues of models or inadequacy of empirical data about these damages (Penning-Rowsell et al., 2003; Messner and Meyer, 2005); and

- Direct tangible damages are more tractable for systematic quantification and communication (Downton et al., 2005b).

The damage categories considered are also influenced by the nature of flood as well as the scope, scale and the objectives of the study. The comparison of included damage categories in a variety of studies in different countries by Meyer and Messner (2005) shows that the most common direct tangible damage categories encompass residential and non-residential buildings and their content/inventory, vehicles and cars, public infrastructure (e.g. roads and railways, other urban infrastructure), and livestock and agriculture. Examples of other damage categories are presented in Table 2.3.

2.4.1.7 Damage model construction method

Damage models are procedures or tools for evaluating the damage to one or more categories of damage against the considered flood exposure parameters. These models are generally developed in different levels of complexity and using three methods (Merz et al., 2010b); i.e. empirical, synthetic or their combination.

The empirical models are based on the analysis of actual damage data collected in the aftermath of a flood event (e.g. data from surveys or insurance claims). This data is about real damage by
considering many additional parameters such as flood warning, flood experience of people, etc. In this method, past observations from the damage data are generalised in a model for use in the estimation of future damages in ex-ante methods. In contrast, synthetic models are based on expert judgment or hypothetical analysis to answer ‘what if’ questions (e.g. how much damage to building if depth of water is 1.5 meters?). These damage models are generally created for potential flood damages to typical elements at risk and not an actual one (Sterna, 2012; Maqsood et al., 2013). On the other hand, coupled synthetic and empirical methods can also be used to develop, extend or to calibrate the damage evaluation model. This method is suggested to provide the most accurate damage assessment (McBean et al., 1986).

The construction method of the damage models can affect their transferability (Smith, 1994). Transferability indicates how effectively these models can be applied to other situations than those they were developed for (Jongman et al., 2012). It can be in time, space, elements at risk and spatial scale (Merz et al., 2010b); underlining to how extent a model is effective for an event in another time or location. In addition, the applications of the same model to another scale of analysis or for other elements at risk constitute the latter two transfer-abilities.

2.4.1.8 Damage valuation method

In the appraisal of the direct tangible flood damage, in particular for those like economic or financial assessments where monetary presentation of the damage is required, two methods for valuation have been dominantly used in the FDA domain; i.e. full replacement value and the depreciated value (Geldermann et al., 2008; Jongman et al., 2012). While old items can be damaged in a flood event, it is reasonable for the damage valuation to consider their depreciated present value rather than their replacement cost as the latter might result in overestimation of the damage. In many cases, and particularly for the economic estimation of damage, the use of the depreciated value is more appropriate (Howe et al., 1991). However, this is significantly different for the insurance assessment purpose. In here, usually full replacement cost is adopted as the value of elements at risk because the insurance policies commonly promise the replacement of the damaged items (Van der Veen and Logtmeijer, 2005). Further discussion regarding the benefits and disadvantages of the abovementioned valuation methods is presented by Cannon et al. (1995).
2.4.1.9 Uncertainty

Most damage assessments are based on assumptions and decisions of the users in regards to the input data and the modelling technique which propagate through the assessment process and affect the results (Merz and Thieken, 2005). Uncertainties describe the likelihood of particular outcomes in situations where full knowledge about the system (or model) is not present. Therefore, elevation in uncertainties level can increase the possibility of errors and resulting in deviation of predictions from the reality and significant effect on the investment decisions (Wagenaar et al., 2015). These uncertainties have been related to both flood hazard and damage calculation components (Apel et al., 2009). Although flood hazard has been discussed in the literature as the major source for uncertainty (Tate et al., 2014), recent research has shown new insights that other aspects of damage calculation (in particular damage models) have uncertainties as large as the hazard parts (Apel et al., 2009; De Moel and Aerts, 2011, 2012; De Moel et al., 2014). It is suggested that a balanced attention to be paid to both sources, although the attention is generally and mostly skewed towards the hazard assessment uncertainties.

Uncertainties as shown in Table 2.4 are either natural (Aleatoric or statistical uncertainties) or epistemic (systematic); and may be related to the model and/or the input data (Meyer et al., 2013; Barbato et al., 2013). The natural uncertainties are inherent in the nature of the analysis and are irreducible. In contrast, epistemic uncertainties lie in the understanding and measurement of the system under investigation and can significantly affect the outcome of damage assessment (Merz et al., 2008). Despite the considerable model improvements over the last few decades, epistemic uncertainties are still significant (Meyer et al., 2013). This is due to inadequate or aggregated data sources, lack of knowledge about the processes leading to damage and lack of appropriate models. The first issue is supported by Handmer (2003) which considered lack of sufficient, detailed, comparable and reliable data as one of the major sources of uncertainty in assessment of damages and their costs. Provision of a more detailed data inputs for reduction of epistemic uncertainty can be a solution here (Maqsood et al., 2013; Maqsood et al., 2014). However, Messner et al. (2007) and Sterna (2012) discuss that this depends highly on the level of potential gains over the costs and efforts for uncertainty reduction.
Having different aspects of the FDA discussed, it becomes important to underline the areas and the users that may benefit from FDA. These users are briefly discussed in the next section.

2.4.2 Users of Flood Damage Assessment

As discussed previously in Section 2.4, FDA may be used for a variety of purposes. In addition to those mentioned in Section 2.3, the other areas that damage evaluation outcomes might be beneficial include the *decision making for risk-reduction measures, policy development, civil protection, spatial planning, emergency response and planning, disaster relief, (re-)construction, insurance, and damage evaluation research* (CORFU, 2014). The applications of FDA relate to the interests, concerns, and the scope of responsibilities of the user that can be a person or an organisation. Two types of users in general may be interested in information about the flood damages. One includes those that require taking actions for reducing the damages and risks and requiring cost benefit analysis of possible options; and the other encompasses those that may be affected by floods and need to be aware of possible impacts. While Table 2.5 highlights some of the users of FDA in the risk management framework, the users of FDA in general can be national government and ministries, state and local governments, emergency planners, insurance companies, engineers and designers, private firms and house owners (Messner et al., 2007). As discussed in Section 2.4, according to their needs, the damage evaluation may vary for one user to another.
Table 2.5: A range of flood risk management decisions and their requirements (adopted from Hall et al., 2003)

<table>
<thead>
<tr>
<th>Decision</th>
<th>Precision of information</th>
<th>Spatial scope of decision</th>
<th>The involved decision maker(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>National policy</td>
<td>Approximate</td>
<td>(Inter)national</td>
<td>Politicians advised by civil servants</td>
</tr>
<tr>
<td>Catchment and shoreline management planning</td>
<td>Approximate</td>
<td>Regional, catchment</td>
<td>Technical officers, but a range of non-technical stakeholders</td>
</tr>
<tr>
<td>Development control</td>
<td>Detailed</td>
<td>Local and regional development plans</td>
<td>Planners</td>
</tr>
<tr>
<td>Project appraisal and design</td>
<td>Very Detailed</td>
<td>Local, though impacts may be wider</td>
<td>Engineering designers</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Detailed</td>
<td>Local, regional prioritisation</td>
<td>Maintenance engineers and operatives</td>
</tr>
<tr>
<td>Operation</td>
<td>Very detailed</td>
<td>Local</td>
<td>Flood defence engineers and operatives</td>
</tr>
<tr>
<td>Flood warning</td>
<td>Very detailed</td>
<td>Regional</td>
<td>Flood warning specialists</td>
</tr>
<tr>
<td>Risk communication</td>
<td>Detailed</td>
<td>Local to national</td>
<td>General public</td>
</tr>
</tbody>
</table>

2.5 Importance of FDA on Buildings

Buildings have special importance to the economy and a significant portion of the economic damage of a flood event (over 60% of total damage) can be attributed to the damage to residential and non-residential buildings and their content (Joy, 1993; Messner et al., 2007; Dewals et al., 2008). Similarly, they are considered as the most important elements in the direct tangible category of damage and have been suggested to be prioritised and included in any estimation of direct tangible damages of flood (DEFRA, 2004; Messner et al., 2007; Ten Veldhuis, 2011). For the same reason and those explained in Section 2.4.1.6, in many cases, FDA focuses solely on damages to buildings to represent the overall economic damage for the cost-benefit analysis purposes (Cannon et al., 1995).

In recent years, local governments and the national building codes require designers/engineers to design buildings in accordance to the performance requirements against flood impacts (e.g. Van de Lindt and Taggart, 2009; or Australian building code standards in ABCB, 2012a). Moreover, buildings have been recognised crucial for the safety of people (Dewals et al., 2008). Past studies have established a link between a percentage of fatalities from floods and the failure of structures (Grundy et al., 2005); and therefore, there has been a recent call for higher safety standard for buildings to protect both the structure and people in such situations (ABCB, 2012a; Xiao and Li, 2013). Considering the long tradition of use of flood and response modification measures in FRM (refer to Section 2.3), yet the use of building/property level mitigation measures is quite recent and have been
paid little attention towards in the past (Keys, 2006; Samuels et al., 2006; Lamond and Proverbs, 2009; Golz et al., 2015). Becker et al. (2011) discuss a need for detailed analysis of response of homes against floods for better understanding of their behaviour in such events. Such detailed studies - in the expense of developers or local governments - can allow for the identification of non-conforming developments and potential areas of improvement/retrofitting towards a more flood resilient building design (CSIRO, 2000). This analysis enables engineering designers and owners to use Cost-Benefit Analysis (CBA) to explore different flood resilience technologies/measures at property scale (Van de Lindt and Taggart, 2009; Joseph et al., 2011). By adopting proper flood-resilient designs and suitable mitigation measures in FRM at early stages, flood resilience of buildings can be significantly improved and costly retrofitting and redesign at later stages would be avoided (Matthew, 2005). Moreover, flood resilient buildings not only are more resistant to floodwater, but are also less costly to restore after a flood and their reinstatement is much quicker. They allow their residents to settle back in a shorter timeframe after a flood with minimum expenses and stress (Lamond and Proverbs, 2009).

All the above drivers underline the importance of the buildings and motivation for evaluation of damage to them at different levels and development phases. In the next section an overview of the current methods for damage assessment of buildings is provided. Recalling from Section 2.4.1.4, the aggregated data inputs and outputs at Macro and Meso levels cannot accommodate the local heterogeneity of objects within the land use classes (e.g. built-up areas or residential land use) and their adoption for buildings would result in misjudging the risks; therefore are not suitable for the majority of the aforementioned applications discussed in this section. For this reason, the focus of the next section is limited to those methods for the evaluation of direct tangible damage to building(s) at Micro scale where the analysis of damage to each building can be performed separately from the others.

**2.6 Micro-level methods for FDA on building**

The review of literature shows that four general categories of methods exist that can be appropriately utilised for assessment of damage to a building at a micro level. They are namely ex-post methods, averaging, damage curves, and the detailed analytical approaches.
2.6.1 Ex-post methods

As previously discussed in Section 2.4.1.1, ex-post methods intend to estimate the actual damages in the aftermath of a flood event. This method may use different channels for primary data collection to evaluate the building damage. These may include field survey and interviews, remote sensing, and crowd sourced information.

The detailed building surveys is conducted by on-site inspection of buildings or interviews by experts and trained personnel. Post hurricane Katrina survey (Friedland et al., 2008b; Franco et al., 2010), damage survey of 2002 Germany floods (Thieken et al., 2006), Nyngan and Brisbane in Australia (Joy, 1993; EAA, 2011), and major floods of 2013 in Norway (Berg et al., 2014) and Italy (Molinari et al., 2014c) are some examples in here. Although a building-specific damage evaluation is provided in this method (Thieken et al., 2005; Apel et al., 2009), yet post-flood damage data collections are not common. They are generally costly and labour-intensive (Jordan and Rogers, 2012) and the quality and reliability of this method is often questioned (Smith, 1994; Thieken et al., 2005; Molinari et al., 2014b). This has been mainly related to the discrepancies regarding the purpose of the damage data collection (e.g. economic damage or insurance), the heterogeneity of data collection methods, and inconsistencies in damage perception and human error in recording the data about exposure parameters as well as the building damages (Downton et al., 2005a; Thieken et al., 2005). These issues can be compounded by legal barriers or dangers of full inspection of damaged buildings (Friedland, 2009).

Remote Sensing (RS) method for ex-post FDA involves tracing the physical damage signatures in high resolution imagery by employing intensive analysis using image interpretation algorithms. Some instances of this method for per-building damage analysis for different flood types include Magsud et al. (2005), Feng et al. (2005), Pesaresi et al. (2007), Adams et al. (2009) and Gong (2014). These methods are designed for rapid damage assessment for response and relief activities and therefore, not all aspects of the building damage are captured. While RS methods can estimate the damage to buildings to certain accuracy, they are generally unsuitable for identification of damage magnitude of buildings that do not experience total collapse (Magsud et al., 2005; Miura et al., 2005). Therefore, they cannot fully capture intermediate damage levels to buildings and commonly underestimate the damage (Friedland, 2009, pp 108).

Goodchild (2007) highlighted the benefits of use of crowd-sourced information for a variety of applications. Crowd-sourced methods incorporate observations of citizens collected by phones or personal computers to expand the knowledge of the situation. Poser and Dransch (2010) specifically
discusses the potential and usefulness of this information channel for rapid flood damage assessment. Although crowd-sourced information can be considered as an inexpensive damage assessment method, concerns about the quality and reliability of such information still exists. Poser and Dransch (2010) discuss that this information should be heavily tested to filter out those erroneous and biased inputs.

2.6.2 Ex-ante methods

Despite the previously discussed benefits of the ex-post methods, they do not have predictive capacity to evaluate damages from possible future events. In the subsequent sections, ex-ante models with such decision support capabilities are discussed. Ex-ante FDA on building, as Figure 2.7 illustrates, generally involves (1) the evaluation of physical damage and (2) its valuation (Jonkman et al., 2008; Pistrika and Jonkman, 2010). This process is independent from modelling of the flood. However, as explained in Section 2.4.1.5, flood hazard assessment is an essential prerequisite of this procedure since the damage from flooding fundamentally depends on the flood exposure parameters (Kelman and Spence, 2004; HNFMSC, 2006).

Figure 2.7: Scheme of Ex-ante FDA to built environment (adopted from Pistrika and Jonkman, 2010)

The estimation of physical building damage at micro level is a complex task and requires knowledge about the damage influencing parameters encompassing (a) resistance parameters like the structural and construction method as well as the materials of individual building(s); and (b) impact parameters from floodwater that can have impact on different aspects of a building (Nicholas et al., 2001; Jordan and Rogers, 2012; Jongman et al., 2012). Building damage is caused by the interaction between the generated "actions" from flood impact parameters (Kelman and Spence, 2004; Arrighi et al., 2013). Actions are "acts in which flood could directly impose on a building, potentially causing
damage or even structural failure" (Kelman and Spence, 2004; Kreibich et al., 2009). The consequences of actions are called "mechanisms" that are required to be defined and investigated for damage assessment. Mechanisms may vary from one building to another due to their different resistance characteristics (Roos, 2003; Becker, 2008). Limited knowledge about the physical causes of flood damage beyond the description of the discussed flood parameters in Section 2.4.1.5, forces damage estimation models to rely only on these parameters and their actions (Kelman and Spence, 2004).

In addition to the flood characteristics, resistance parameters also influence the magnitude of damage. Building characteristics constitute the most important of the resistance parameters (Pistrika and Jonkman, 2010). Important factors here include the geometry of the building, its location and orientation, number of stories, construction type, location of building elements and their material, foundation type, floor elevation, layers of soil supporting the building, building contents, etc (Johnson, 1985; Kelman, 2002; Nadal et al., 2010; Pistrika and Jonkman, 2010; Merz et al., 2010b). These characteristics are distinct for each structure and variations in the overall and specific construction characteristics of the buildings results in variability in their resistance against flood impacts (Merz et al., 2004; Mason et al., 2012). Long or short-term (temporary) emergency measures before or during a flood, flood warning, and flood experience of people also affect the resistance of buildings (Thieken et al., 2005; Sterna, 2012) and can reduce the level of losses (Wind et al., 1999; Penning-Rowsell and Green, 2000; Kreibich et al., 2005).

Kelman and Spence (2004) discuss the flood actions applied to buildings in terms of seven different categories. They include water contact (that includes action chemical actions, nuclear actions, and biological actions), hydrostatic and hydrodynamic actions, buoyancy, debris (static and dynamic) action, erosion action, and wave action (see Table 2.6). They may cause destruction of foundation or destabilization of the building, failure in its components (e.g. walls and windows), corrosion of walls or foundation materials, and damage to wooden floors or panelling, HVAC systems, wall finishes and so on (FEMA, 2006; Kreibich and Thieken, 2008). In the following section, the existing ex-ante FDA methods will be reviewed and discussed.

2.6.2.1 Averaging

The simplest ex-ante method for evaluation of damage to building is 'averaging'. This technique quantifies the damage based on 'the mean damage cost per building' for all buildings. An example of this method is the Rapid Appraisal Method (RAM) in Australia (NRE, 2000). As discussed by Barton
et al. (2003), the RAM method may also incorporate two simple building classes of non-residential larger than 1000m$^2$ and all other buildings (including residential and non-residential) for damage cost estimation. RAM applies to all building types that fall into the extent of the inundation with no requirements for knowledge about the water depth above the floor level where most damages to building start to occur.

Despite the simplicity and cost-effectiveness of this method for quick estimation of damage, averaging is found to be unrealistic for micro-level studies due to its limitations in distinguishing between different buildings and accounting for their damageability differences. In addition, there exist significant uncertainties in this method as flood extent, the only parameter used for damage assessment which as discussed previously in Section 2.4.1.5, is not a strong factor for damage assessment.
Table 2.6: Flood actions on buildings (compiled from Kelman and Spence, 2004; Nadal et al., 2010; Mason et al., 2012)

<table>
<thead>
<tr>
<th>Flood action</th>
<th>Definition</th>
<th>Relevance</th>
<th>Predictability</th>
<th>Flood parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water contact</strong></td>
<td>As the primary source of damage (HNFMSC, 2006), affects those water-sensitive components of the building which only contact with water is sufficient for them to be damaged. It involves chemical, nuclear and biological effects on the building components and their damage.</td>
<td>High</td>
<td>Relatively predictable</td>
<td>Above-floor inundation, Duration of contact, Presence of contaminants</td>
</tr>
<tr>
<td><strong>Hydrostatic</strong></td>
<td>Lateral forces imposed on building and its components by the mass of still water and created by the depth-differential on two-sides of a vertical component like wall. At any point, hydrostatic force is equal in all directions (irrespective of building or component orientation).</td>
<td>High</td>
<td>Relatively predictable</td>
<td>Depth</td>
</tr>
<tr>
<td><strong>Hydrodynamic</strong></td>
<td>Lateral forces that are generated by the flowing floodwater. These forces generate five forms of actions which three of them are related to velocity - i.e. lateral pressure, localized changes, and turbulence - and the other two are wave-related (breaking and non-breaking waves). Hydrodynamic forces can push or drag building and its elements depending on the local velocities.</td>
<td>High</td>
<td>Relatively predictable</td>
<td>Depth, velocity</td>
</tr>
<tr>
<td><strong>Buoyancy</strong></td>
<td>Also known as upward-direction hydrostatic force, buoyancy is an uplift force as a function of submerged volume of the object which results in a floating of the building or parts of it.</td>
<td>Varies</td>
<td>Difficult</td>
<td>Depth</td>
</tr>
<tr>
<td><strong>Debris</strong></td>
<td>The forces generated by flood-borne solids (debris) in the water or sediment deposition and aggradations against building components. These include the dynamic (former) and static (latter) debris actions.</td>
<td>Varies</td>
<td>Difficult</td>
<td>Water velocity, Debris velocity, weight, geometry, impact height and duration</td>
</tr>
<tr>
<td><strong>Erosion</strong></td>
<td>The scouring of the soil away from the side or bed along by moving water.</td>
<td>Varies</td>
<td>Difficult</td>
<td>Depth, flow velocity</td>
</tr>
<tr>
<td><strong>Wave</strong></td>
<td>Specific to coastal floods and include forces generated by impacts of waves. Damage to building components is highly variable from non-breaking, breaking and broken waves.</td>
<td>Varies</td>
<td>Difficult</td>
<td>Depth</td>
</tr>
</tbody>
</table>

17 Capillary rise is another flood action which may occur in building elements. The water reaches to higher building floors and damage building elements without requiring the depth of water at that level. However, Kelman and Spence (2004) discussed that capillary rise is not a phenomenon to be included in flood damage assessments.
2.6.2.2 Damage curves

In comparison with averaging approach, a more sophisticated ex-ante method for covering a broader range of impact and resistance parameters is provided by damage curves (or functions). Damage to a building in this method is evaluated by pooling the building stock into homogenous classes by considering only limited characteristics of the building (e.g. construction type, age or occupants income) and applying a generic pre-established damage curve for any building in each class. Curves represent the susceptibility of the building (and its resistance) to flood and are generalised relationships between the level of damage to a building class and one or few flood parameters. They have a long tradition since 1960s (White, 1964) and are still the internationally accepted standard approach to assess flood losses (Smith, 1994; Thieken et al., 2005; Merz et al., 2010b).

Empirical vs. Synthetic damage curves

Much effort has been put in the development of a wide variety of damage curves that serve different purposes. Damage curves\(^\text{18}\) may range from simple linear functions like the ones by Boettle et al. (2011) to more complex curves. The majority of the developed curves use depth as the only flood parameter and are referred to as "stage-damage curves"\(^\text{19}\). They, as discussed in Section 2.4.1.7, may be constructed using empirical, synthetic or their combination. Empirical curves such as HAZUS-MH (Scawthorn et al., 2006), MERK (Reese et al, 2003), FLEMOps and FLEMOps+ (Thieken et al., 2008b; Kreibich and Thieken, 2008), curves developed by Jonkman et al. (2008) and Black and Evans (1999) are derived from the analysis and generalisation of the post-flood damage surveys data and observation records in different damage databases like HOWAS in Germany. Jonkman et al. (2008) developed some curves according to the collected damage data in the aftermath of 1953 Netherlands flooding as well as other local floods by river Muse in the 1990s. A similar exercise was used to develop FLEMOps curves from empirical damage data collected in the aftermath of 2002, 2005 and 2006 Germany floods for assessing the damage to residential buildings. Five classes of depth and three classes of building quality are used to classify buildings for estimating the damage. An extended method in this tool (called FLEMOps+) accounts for water contamination and precautionary measures by employing the adjustment factors also empirically derived from the same

\(^{18}\) As a reminder, damage curves discussed here refer to those at micro level only.

\(^{19}\) Or "depth-damage curves".
damage database. A more specific version of the software, FLEMOcs deals with commercial buildings. These models are extensively validated using different damage data sets at micro level.

In contrast, synthetic curves like ANUFLOOD (Greenaway and Smith, 1983), Multi Coloured Manual (Penning-Rowsell et al., 2003; FHRC, 2013), Geoscience Australia curves (Maqsood et al., 2014), Mason et al. (2012) and HOWAD-PREVENT (Neubert et al., 2009; Neubert et al., 2014) are derived from the analysis of "what if" flood situations (e.g. range of depths) to derive curves for representatives of different classes of buildings. For example, as the most complete suite of curves, Multi-Coloured-Manual (MCM) includes over 900 damage curves in UK which have been created synthetically by the opinion of experts and loss assessors for a variety of building types in UK (Penning-Rowsell et al., 2003; FHRC, 2013). These curves, in addition to the depth of flood, take into account long and short flood duration for evaluation of damage in absolute monetary terms. Similarly, the Geoscience Australia curves (Maqsood et al., 2014) are derived according to the analysis of different water depth intervals and water contact action on the representatives of 19 building classes in Australia. Expert judgment is used to evaluate the level of damage from water contact only. The general advantages and disadvantages of the aforementioned synthetic and empirical flood damage curves are presented briefly in Table 2.7.

Table 2.7: Advantages and disadvantages of damage model construction methods (adopted from Black and Evans, 1999; EMA, 2003; Merz et al., 2010b)

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empirical</strong></td>
<td></td>
</tr>
<tr>
<td>Greater accuracy of empirical than synthetic data.</td>
<td>Models can be based on possibly poor damage data from uncommon detailed damage surveys after flood.</td>
</tr>
<tr>
<td>Considering the effects of damage mitigation measures in damage modelling.</td>
<td>Scarcity of actual data about different magnitude floods and lack of damage records required for extrapolations.</td>
</tr>
<tr>
<td>Taking into account for variability within each damage category rather than averaging all buildings similar to averaging method.</td>
<td>They are location-specific and transferability in time and space is difficult.</td>
</tr>
<tr>
<td><strong>Synthetic</strong></td>
<td></td>
</tr>
<tr>
<td>Different levels of flood exposures (particularly water depth), even for those that previously never happened can be obtained.</td>
<td>High effort for database development or large surveys for obtaining sufficient data for each building type</td>
</tr>
<tr>
<td>Application of model to other locations is improved as the method is independent from real damage data.</td>
<td>Subjective damage estimates may result in uncertain estimation of damage</td>
</tr>
<tr>
<td>Provision for higher level of standardisation and comparability of damage estimates.</td>
<td>Large variations within each category exist which are not reflected in the data as typical elements are considered only.</td>
</tr>
<tr>
<td>Tendency for overestimation of damage because of not accounting for mitigation measures and warning time in models.</td>
<td></td>
</tr>
</tbody>
</table>
Monetary damage curves

The review of the literature shows that the majority of damage curves for buildings are developed for the estimation of the "monetary" damage. These curves can be differentiated into absolute and relative (Messner et al., 2007; Apel et al., 2009; Middelmann-Fernandes, 2010; Merz et al., 2010b). Absolute damage curves include those that directly provide a dollar value estimation of damage by including the value of damage in the curve (see Figure 2.8 bottom). In contrast, the relative curves provide the damage level as a percentage of the total building value\(^{20}\) (see Figure 2.8 top).

Merz et al. (2010) provide a comparison between the advantages and disadvantages of relative and absolute curves. Acquiring building values is a challenging and uncertain task in FDA domain. Absolute curves do not require this input and can provide a direct monetary estimation of damage for

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\(^{20}\) In some cases, a ratio of repair cost to replacement cost of the building is used.  
\(^{21}\) GABT: Geoscience Australia Building Type
a given scenario. However, they are generally not transferable in space and time. On the other hand, the relative curves require building value and do not need for constant updating of curves in the way that absolute ones require. Additionally, they can provide better transferability in space and time (Messner et al., 2007).

A review of damage curves for estimation of direct monetary damages to buildings at a micro level is provided in Appendix 3. Although these curves can provide the monetary estimation of damage, they are incapable of indicating the mode of damage. Therefore, several studies focused on the development of damage curves to evaluate physical failure of the building to provide such information. They will be presented in the next section.

**Structural damage curves**

It is often crucial to understand the nature of the risk for its treatment. As discussed in the previous section, this is beyond the capabilities of the monetary damage curves. For this reason, Black (1975) developed a number of curves for determining the potential collapse and/or transport (moving off foundation and drag) of North American light wood-frame houses from the depth-velocity product\(^{22}\) (see Section 2.4.1.5). These curves distinguish between "survived" and "destroyed" buildings due to the effects of buoyancy and horizontal forces from depth and velocity. Sangrey et al. (1975), RESCDAM (FEI, 2001), NSW Government (2001), Dale et al. (2004), CH2M-Hill (1974), and Smith et al. (2014) developed similar criteria for evaluation of collapse or transport of the building due to combined depth and velocity effects.

Clausen (1989) and Clausen and Clark (1990) defined a criteria for three different damage types for masonry and brick houses based on the empirical data from 1864 Dale Dyke dam break (see Figure 2.9). According to the depth and velocity of water these criteria can determine the boundaries between "inundation", "partial collapse" and "total destruction" damage.

\(^{22}\) In different literature, it is expressed as "\(d \times V\)", \(d\) representing depth and \(v\) the velocity.
Clausen (1989) discusses that the above criteria only provide a primitive approximations for use where more reliable results do not exist. In addition, although $d \times V$ can be related to the momentum (Pistrika and Jonkman, 2010), Kelman (2002, pp 28) argues that no physical meaning can be assigned to the $d \times V$ product and therefore the physical mechanisms applied to the building structure by flood cannot be discussed using this term. Pistrika and Jonkman (2010) applied the depth-velocity product by Clausen (1989) for damage estimation in case of Hurricane Katrina. They found significant difference between the model predictions and the observed damages and therefore, according to the empirical evidence, proposed an adjustment to Clausen’s work that improved the predictions of the model for their case study.

Gallegos et al. (2012) compared some of the aforementioned curves and investigated the effectiveness of these models. They concluded that although some curves like McBean et al. (1988) perform better in extreme events, others like Black (1975) and Dale et al. (2004) are more suitable for moderate events. They further discussed that these models often tend to overestimate the damage.

As quoted in Roos (2003), Vrouwenvelder and Waarts (1994) developed a primitive model to predict the probability of collapse of several building types from waves and according to their construction materials. This model is very generic and frequent absence of data about loads and strength of buildings suggests its unreliability. USACE (1985) on the other hand developed the total of 9 collapse curves for three building types namely concrete, steel and wood for the Portland District in US. An example of curves for a steel building is illustrated in Figure 2.10 (left). Based on its empirical tests, USACE (1988) further suggests that any depth difference of 0.9m between inside and outside the house would result in collapse of masonry walls.

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**Figure 2.9: Clausen damage criterion for brick and masonry structures (adopted from Clausen, 1989)**

![Damage Criterion Diagram](image-url)
Roos (2003) developed a number of synthetic partial collapse curves for concrete, brick (solid and with cavity) and prefabricated houses (see Figure 2.11). These curves were developed according to the comparison of the applied bending moments and shear forces from the hydrostatic, hydrodynamic, scouring, waves and probable impacts of debris with the resistance capacity of only building walls and foundation to assess their failure. The flood actions were calculated on typical buildings in those types and curves were developed according to the building type and its date of construction.

The load vs. resistance analysis method in Roos (2003) was also adopted by Nadal et al. (2010) to develop a number of synthetic relative damage surfaces (see Figure 2.10[right]) for concrete buildings for different floods types. These curves were developed using a stochastic method and the Monte Carlo Simulation (MCS) for the analysis of failure mechanisms of various building assemblies. Damage to elements like reinforced concrete frame, concrete block walls, foundation, doors and windows was calculated using a comparison between the applied actions and the load capacity of
elements (details are provided in Nadal, 2007). The water contact damage for utilities and finishes was assessed based on the pre-established damage curves by USACE (1985) with assumption that no velocity was present. In MCS, the averaged flow velocities from 8 sides (45 degree interval) were considered to take into account the direction of flow in the analysis of damage.

Becker et al. (2011) developed a number of combined curves for typical one- and two-storey Canadian houses against hydrostatic, hydrodynamic and buoyancy actions to assess breaching of the building envelope (fill), building floatation resulted by failure of foundation anchors (float) or its structural collapse from failure of at least three load-bearing elements (collapse) as illustrated in Figure 2.12. HNFMSC (2006) mentioned that float effect only occurs in case of light wood-frame buildings. For heavier types like brick veneer on timber-frame or concrete buildings, floatation is unlikely and this model would not provide desirable results.

The above curves and many other structural damage curves are summarised in Appendix 4. Although these curves provide structural damage to building(s), the description of intermediate building damage where collapse does not occur cannot be clearly presented. Moreover, these curves cannot provide any monetary indication of damage for use in cost-benefit analysis process. Schwarz and Maiwald (2008) adopted a method from earthquake damage assessment to improve the understanding of other types of damage to the building in these situations. Instead of relative or absolute damage presentation by curves, a number of empirically derived damage grades are used to convey information about different damage states of the building. However, these curves were derived only for low resolution applications and broad building classes, differentiated only by their general

Figure 2.12: Structural load path in simple wood-frame structure (left); The criteria for fill, collapse, float failures (right) (Adopted from Becker, 2008)
construction materials (e.g. concrete, masonry, etc.). For this reason, further investigation of these and the other discussed curves at individual building level has been suggested (Gallegos et al., 2012).

The method by Kelman (2002) was found as the only attempt to bridge the gap between the above curves to provide both qualitative (physical) and quantitative (monetary) measurement of the damage. In his work, Kelman (2002) evaluated the vulnerability of residential buildings in the east coast of England. By evaluating the hydrostatic and hydrodynamic actions on walls and openings (windows and doors) of the buildings according to the depth difference inside and outside, he developed a series of synthetic damage profiles that provide an indication of the damage state of the building. These profiles are similar to those discussed in the work by Schwarz and Maiwald (2008); however, Kelman provides an additional step for translating these damage grades to their equivalent building damage percentage (similar to relative curves). These percentages yet, were highly variable and assigned on the basis of the Kelman's judgement.

**Importance of Geographic Information Systems for damage curves**

Flood impact (exposure) and building resistance parameters discussed previously are functions of space and possibly time (Kreibich and Thieken, 2008). As a platform for managing and presenting spatially referenced information, GIS has been identified a useful tool for supporting the ex-ante evaluation of flood impacts to building (Dutta and Herath, 2001; Eleutério et al., 2010). Boettle et al. (2011), Betts (2002), Kamruzzaman (2008), HAZUS-MH (Scawthorn et al., 2006), SEMENTA GIS toolbox for FDA (Neubert et al., 2009), Eleutério et al. (2010) and Dutta and Herath (2001) are some of the numerous FDA methods/tools that benefit from GIS for their purpose. By offsetting the aforementioned parameters in GIS and adoption of a suitable damage curves, it allows for spatially-aware estimation of damage to the buildings and the visualisation of their spatial distribution in the investigation area. Chen and his colleagues in project CORFU (2014) used GIS for a building-by-building damage estimation and visualisation in a 2D map.

Damage curves are beneficial for damage assessment in support of decision making in micro-level studies like appraisal of damage at precinct or local government levels where large number of buildings are included. Yet, as discussed by Merz et al. (2004), their use is limited and uncertain for building-specific damage assessment since curves are created for a particular building class and ignore the large variations of buildings (and consequently as Figure 2.13 illustrates, their damage) within that class.
Building-specific FDA may be crucial for adoption of risk-reduction measures at building level (and those previously discussed applications in Section 2.5) which the decisions for them are increasingly made on a basis of cost-benefit analysis of alternatives (De Risi et al., 2013a; Maqsood et al., 2014). Additionally, Maqsood et al. (2013) highlighted the need for more detailed assessment inputs and analysis of buildings at a higher spatial resolution for supporting such applications. Careful consideration for details of the distinct characteristics of the building and flood parameters as the input of analysis can determine the patterns of water intrusion through different building components (e.g. openings) and facilitate the evaluation of the overall structural and non-structural response of a building (Totschnig et al., 2011). In agreement with this statement, Schroter et al. (2014) discuss that complex models with more detailed inputs can incorporate the local characteristics of the buildings and the flood to overcome the deficiency of curves neglecting the variability of buildings in each class.

In the next section, a review of the past efforts for more detailed analysis of flood damage to buildings using analytical and detailed engineering methods are provided.

2.6.2.3 Detailed analytical/engineering models

From the theoretical perspective, rigorous approaches to damage computation for structures can be derived from the physical and numerical analysis of the fluid-structure interaction (Mazzorana et al., 2014). These models, in contrast to limited computational resources in the past, can be considered more feasible in today’s computationally intensive environment and are capable of producing results in the highest level of detail (Friedland et al., 2008a).
From fluid-structural coupling and load-resistance analysis perspectives, various methods have been developed in the last few decades. Thomalla et al. (2002) and Kelman and Spence (2003a) provided similar flowcharts which illustrated the building failure pathways from floodwater's hydrostatic and hydrodynamic actions (see Figure 2.14). Although these works have been the pioneering attempts to illustrate the impacts of depth difference on the building, they only accounted for failure of walls and windows and ignored the other aspects of the building. Additionally, the outputs are qualitative indication of potential severity of the flood impacts on the structure (e.g. minor, moderate or major) and no further quantitative or more detailed qualitative illustration of impacts or damages on the building were presented.

A similar method was presented by Kelman (2002) for the analysis of potential damage (and vulnerability) to unreinforced masonry buildings. Although the aim in this study was to develop a number of damage profiles, it is considered as a good example of detailed damage analysis at individual component levels of a building. The results of the model included six damage states to provide general indications of what may occur to the building. The inputs included the averaged flood depth for all walls and the approximated building characteristics according to the survey of only the externally observable features of the buildings without consideration for internal aspects. Kelman (2002) also developed a theoretical model for consideration for infiltration of water to inside the house for calculation of hydrostatic pressure.
Nadal et al. (2006) also applied engineering mechanics for comparing the load vs. resistance of a number of components of the building to estimate the damage. They introduced vulnerability matrices to present the damage to building components according to the combination of depth and velocity of floodwater. A simple 1-dimensional flood modelling tool, HEC-RAS, was used to obtain flood information. This tool does not consider the obstacles (e.g. buildings) on the floodway for estimating the flow changes around the buildings; and accordingly velocities and the depth of water may have high uncertainties. Additionally, inconsistencies existed in the analysis of damage. Where loads and damage on structural components were considered for no inside water, the damage assessment to materials and finishes was according to the equalised depth of water inside and outside and application of damage curves.

The theoretical model of Becker et al. (2011) is another example of detailed building damage analysis. Although the main aim of the study was to develop curves for typical simple buildings, their model provided good insight into the behaviour of simple wood-frame house against the flood. In this study, the houses were typical rectangular-shaped structures where their dimensions, materials, location and elevation, and resistance were assumed from a range of values in Canadian building code. In addition, the assemblies of the same type (e.g. windows or doors) were all treated the same which is not always the case. This study focused solely on the structural failure for assessing the building safety and did not consider water contact damage.

Some of the detailed studies of damage to a specific building adopted Finite Element Method (FEM) to calculate the flood loads and the damage to buildings. Chidambarathanu and Retnan (2013) evaluated the potential damage to reinforced concrete structures subjected to hydrostatic, hydrodynamic pressures and the duration of loading. In this study, a SAP model (finite element modelling software) of the building was used to evaluate the impacts of flood loads on three different scenarios for different frame configurations. The bending moments from dynamic loads for the duration of load was used as criteria of damage. The vulnerability index for different flood loadings on structural frame was computed and compared. In that study, non-structural components of the building were ignored. Similarly, Xiao and Li (2013) presented a computational method for the use of the time-series of pressure from flood parameters obtained from their in-house flood simulation model. They evaluated the damage on a rural unreinforced masonry house via FEM simulation. Every brick and mortar joint and the openings in the single-leaf load-bearing walls were modelled in detail in a finite element model program. They investigated the stress, deformation and destruction processes of the masonry walls and further discussed that the failure of the walls occurs as the result of mortar element failure. This method is too detailed and expensive to set up and simulate for
evaluation of damage to the building walls. In addition, many aspects of the buildings are ignored in the evaluation of damage.

De Risi et al. (2013a) proposed a GIS-based platform for analysis of damage in a homogeneous environment without sufficient data about buildings. Three Limit States (LS)\(^\text{23}\) were considered in this study for collapse, life safety and serviceability (where household activities are disrupted). The collapse was evaluated by an analytical wall failure fragility curves (with different probable configuration of openings in walls of different sizes). The serviceability and life safety limit states are determined by the critical water depths inside the house as the result of either collapse of walls or the water tightness probability for the house. The platform includes the data about buildings in a probabilistic way using decision trees. The hazard parameters are presented in approximation and are determined for the centroid of the building. While this method suits studies where homogeneous and a large number of buildings are investigated; yet it fails when FDA on a building-specific basis is required.

Friedland et al. (2008a) proposed a model to estimate the possibility of collapse of buildings. This method uses load-resistance analysis to provide discrete building damage states (e.g. collapse or no collapse). Due to data availability issues, typical buildings were used in this work while acknowledging the existence of significant variability in the building classes. For no collapse case, the failure of other individual components like walls, cladding, opening (including windows and doors), repairable foundation damage and damage from inundation within the building is investigated further. This work provides no details of the calculation of damage to these components. In addition, the validation of the model using the empirical damage data also shows large deviation of the predictions from actual damage data.

Van de Lindt and Taggart (2009) discuss that none of the previously explained methods enable building owners and designers to make educated decisions based on flood damage probabilities for their specific structure and location. For this reason, a methodology was presented by Taggart and Van de Lindt (2009)\(^\text{24}\) which adopts the Assembly-based Vulnerability (ABV) for the case of flood damage to a building. ABV is a methodology proposed by Porter et al. (2001) for estimation of earthquake losses to a building on the basis of damage costs to its individual assemblies. The damages considered here were only pertinent to the water contact damage from particular depth and a range of flood durations. Although not explicitly specified, equalised water depth inside and outside of the

\(^{23}\) The limit states are conditions which the building or part of it can no longer fulfil its intended function (McCormac, 2008).

\(^{24}\) Similarly in Van de Lindt and Taggart (2009).
house was assumed and accordingly, the possible damages to individual components (with no differentiation within each; e.g. no difference is accounted for different window types in the house) were calculated. Taggart and Van de Lindt (2009) successfully illustrated an application of this method for decision making between six mitigation measures and/or their combination.

Park et al. (2014a) similarly used the developed methodology by Van de Lindt and Taggart (2009) for storm surge and rain intrusion damage to the non-structural aspects of the building in a hurricane event. This method accounted for the structural aspects; but only for roof damage from the wind-induced pressure/suction which is usually not considered in ex-ante FDA models. This is due to the dominance of damages from flood actions to lower parts of the building (Kelman, 2002; HNFMSC, 2006). On the other hand, water damage is analysed separately as "rainwater damage only" or "storm surge damage only".

Barbato et al. (2013) on the other hand, proposed a method that by considering the flood and wind interactions, evaluates the damage to buildings in a probabilistic way. In here, each building, its resistance as well as the repair costs of its assemblies are probabilistically described for damage analysis. Three performance levels (i.e. comfort and safety of occupants, damage to non-structural components, and structural integrity) were included in this conceptual framework and the damage analysis on different components of the building was performed using their specific fragility curves. Using the probabilistic derivation of repair costs of the damaged components, the losses were further quantified. Although the feasibility of the framework was evaluated by an example application, the damage to windows, glass doors, walls and roof panels were only evaluated from wind actions and no flood impacts were considered in this implementation.

**Static vs. dynamic evaluation**

The nature of the vulnerability of the elements at risk (and accordingly damage) in the discussed damage assessment frameworks in this section is 'static'. This means that the spatiotemporal dynamism of the hazard and building resistance is rarely considered in the damage analysis. Mazzorana et al. (2012a) introduced and conceptualised the "dynamic vulnerability". They discussed the crucial role of the analysis of time-varying vulnerability in a variety of management processes. By considering the step-by-step identification of the risk-amplifying triggers throughout the period of the event using engineering mechanics, one can consider or define risk reduction strategies according to

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25 Hurricane has two effects: wind and rainfall damage seeping in the house from damaged roof; and the flood damage from storm surge from hurricane.
such knowledge (Mazzorana et al., 2012b). In this way, the application of FDA can go beyond a simple risk analytic tool for identification of optimal management options, and be used further as an "exploratory planning toolkit in the crucial design phases" (Mazzorana et al., 2012a).

Mazzorana et al. (2014) recently adopted the dynamic vulnerability analysis procedure and developed a sophisticated approach for assessment of physical vulnerability followed by the economic evaluation of damage to a residential building from a debris-flow in European mountainous areas. By considering the time-varying load-resistance analysis and fluid-structure interactions, this model focused on the evaluation of the physical structural damage from external loading on the building envelope using Finite Element Modelling and Limit-State concepts. The economic evaluation of damage was further performed by calculating the depreciated cost of reinstatement of damaged objects. Although this method provides an excellent attempt for a detailed building-specific flood damage evaluation, it ignored the water contact damages as well as the internal aspects of the building and the damage analysis phase has been remained at a conceptual level.

2.6.2.4 Other relevant initiatives

In addition to the discussed ex-ante FDA methods in Section 2.6.2, other methods/tools were developed for improving the resilience of buildings by illustrating their possible vulnerabilities. The Insurance Council of Australia (2013) developed "Building Resilience Rating Tool" (see Figure 2.15) based on the existing knowledge in guidelines for construction of houses in flood prone areas (e.g. HNFMSC, 2006; Bowker et al., 2007; FEMA, 2008; Snow and Prasad, 2011; Growth Management Queensland, 2011; CDCP, 2012). This tool provides a report to the house owner containing information about the risks of flood damage to the individual building components with suggestions for alternative materials/assemblies. The analysis is purely based on the susceptibility of the building assemblies' material without considering the flood parameters. Although this tool is a good first step for increasing the awareness of house owners about their property risks, it is still in its infancy stage and is limited to water contact damage only.
2.7 Summary of past studies

An overview of existing methods for evaluation of floods damages to a building at micro level was presented in Section 2.6. It was shown that the ex-post methods are generally associated with high level of uncertainty and are strictly used for post-flood damage evaluation. On the other hand, averaging was discussed to be a useful method for rapid ex-ante evaluation of approximate damage to buildings. Yet, its outputs are found to be unrealistic due to overlooking the flood parameters as well as the unique building characteristics.

In addition, the damage curves were discussed as the standard method for FDA. Despite the simplicity and general applicability of this method for larger number of buildings for economic damage appraisal, the review of existing curves revealed that their application for individual buildings can be extremely problematic and associated with high level of uncertainty (Merz et al., 2004). This is a well-understood issue in the literature and a major source of uncertainty in micro-scale FDA on buildings. Many factors are involved as the source of this problem. They include:

- Curves are generally created for a building class and ignore the large variations of buildings in it (Smith, 1994; Merz et al., 2004; Maqsood et al., 2014). Although this issue is negligible for large population of buildings where this variation is evened out (Pistrika and Jonkman, 2010; Merz et al., 2010b; Mason et al., 2012), yet the effectiveness of curves becomes poorer in smaller spatial scales to the point that the utilisation of curves at the individual building level becomes inadvisable (Merz et al., 2004; Pistrika and Jonkman, 2010). Such generalisation and the assumptions about building information inputs result in
misrepresentation of the unique characteristics and resistance of the building and consequently significant increase in the epistemic uncertainty (Apel et al., 2004);

- Classification of buildings for associating damage curves to them is also subjective and uncertain. It brings additional challenges to the use of curves (Apel et al., 2004; Messner et al., 2007; Sterna, 2012);

- Stage-damage curves are the most common type of curves and express the susceptibility of the building and its potential losses in relation to only the depth of inundation. As no one-to-one relationship exists between the level of damage and the depth of water alone (Smith, 1994; Merz et al., 2004; Thieken et al., 2005; Pistrika and Jonkman, 2010), the use of depth in these curves can only explain a portion of possible damages and excluding other parameters which results in uncertain damage evaluation (Middelmann-Fernandes, 2010; Merz et al., 2013); and

- Although in some curves other parameters (e.g. velocity) are used, they are normally averaged or only one value is used for them. This can be problematic as velocity can have significant variations in small spatial distances and therefore result in an increase in the epistemic uncertainty in the outcomes of damage evaluation for buildings of similar type but with different shapes and orientations (Merz et al., 2010b).

In addition, beside the monetary estimation of damage or general indication of whether collapse or inundation damage occurs, curves can provide little or no information about 'how' and 'where in the building' the damages may occur. They also ignore the underlying damage-generating mechanisms in the presentation of losses. This limits the application of the curves/functions for design evaluation and planning for flood resilient buildings (Mazzorana et al., 2014). Furthermore, many curves are developed for local conditions and types of buildings. Therefore, general transferability concerns exist for damage curves, and in particular empirical ones.

It was discussed previously in Section 2.6.2.3 that the detailed analytical methods emerged to overcome some of the aforementioned limitations of curves in supporting FDA on a building-specific basis. Their review highlighted that they can provide a more detailed damage evaluation to the buildings and in contrast to damage curves, in many instances some information about 'what damages in the building may occur' and 'how' can be provided to the decision maker. However, these methods are still immature and also tend to disregard the distinct characteristics of the building and its components as they either average these resistance parameters or use probabilistic representation of these components and their location in the building. Similar to damage curves, the assumptions about
the flood parameters and averaging them (both magnitude and direction) for the building still exists in many of these models. Other limitations of detailed analytical methods may include:

- They largely ignore the interior of the building which with no doubt have influence on the overall building resistance. For example, Roos (2003) underlines the importance of the perpendicular interior walls to provide extra support to the external ones;

- Flood is a complex hazard causing damage to a building by applying loads and also by the water contact. Limited analysis of damage by focusing exclusively on one of the water contact damage or structural analysis was observed in engineering/analytical models. Only the use of both together can provide the proper evaluation of damage from complex flood phenomenon;

- Finite element methods are generally too costly and computationally intensive; both in setting up as well as the calculation time. In addition, the knowledge of the software - that is normally complex and very specialised - would be required;

- In most approaches, the spatiotemporal aspects of flood and resistance parameters (dynamic vulnerability) are not considered in the analysis;

- In addition to the above points, the water intrusion analysis was rarely accounted for except in the case of Kelman (2002). This is particularly important for dynamic vulnerability concept discussed in Section 2.6.2.3;

- These models mostly remain at conceptual level with partial demonstration for limited hypothetical cases.

In addition, the rare validation of the models is one of the repeatedly discussed concerns in the FDA literature (Thieken et al., 2008a; Apel et al., 2009; Merz et al., 2010b; Meyer et al., 2013). Such validations are crucial for testing the reliability of predictions of the models for evaluation of damage (Meyer et al., 2013; Tate et al., 2014). The next section discusses the identified knowledge gaps in this chapter to support a detailed FDA on building at micro level.

### 2.8 Summary of current knowledge gaps for detailed micro-level FDA of building

The extensive review in this chapter illustrates a number of knowledge gaps in the existing FDA literature. In spite of the development of a diverse range of FDA models and success in satisfying
some of the applications discussed earlier in this chapter, other important areas like design evaluation by engineers/designers or checking the appropriateness of a development in flood prone areas by councils/referral authorities in support of planning process cannot be supported by the existing methods. This is due to the high level of uncertainty of the current state-of-the-art methods discussed earlier in Section 2.7 that limits the adoption of performance-based methods for building design and approval according to the building performance against the defined criteria like flood actions (Van de Lindt and Taggart, 2009; Christodoulou et al., 2010). To support these applications, despite many previous attempts, a number of unresolved research gaps still exist that should be further investigated and addressed. These gaps are outlined below:

- Dispersed efforts without consideration for coupled structural and water contact damage. No effective framework currently exists that provides a combined investigation of impacts of flood on buildings considering both structural stability of the building as well as the damage from water contact;

- Issue of data inputs about one building (e.g. its structural resistance and non-structural materials) and the lack of consideration of unique characteristics of a building for its detailed evaluation of damage at Micro-level. This gap, in terms of building information describing its shape, size, orientation and materials and their resistance has been highlighted in a variety of previous literature (Handmer, 2003; Friedland et al., 2009; Merz et al., 2010b; Barbato et al., 2013; Hammond et al., 2013). The data input is directly linked with the complexity of the FDA model and its predictive capability (Messner et al., 2007). Where more detailed input data is available, more complex models can be developed to evaluate the potential damage to a building. However, as discussed by Merz et al. (2010b), the current issue with input data has resulted in the dominance of simple methods like damage curves in the FDA domain; even for micro level applications which their suitability is questionable. For this reason, Douglas (2007) underlined the need for further research to make use of more comprehensive input datasets about the building;

- Despite its benefits, the dynamic vulnerability concept is still immature and except in a few limited cases, it has not been effectively implemented in FDA domain and further need exists to apply this concept for a coupled load-resistance as well as water contact damage evaluation.

- Multipurpose methods with capability to assess and present the physical and monetary damages together are extremely rare in the context of FDA;
• The presentation of location of damaged elements in the building is generally not provided. Such information can allow for a better understanding of the nature of risks and facilitate their treatment.

As highlighted in the aim of this research in Chapter 1, some of the aforementioned knowledge gaps form the basis of the research framework in this dissertation and are further investigated and addressed.

2.9 Chapter Summary

This chapter provided an overview of FDA domain and its importance in flood risk management towards achieving flood resilience in the community. The principles and aspects of FDA were reviewed and the importance of damage evaluation to building within the risk management cycle for ensuring the flood resilience of buildings was highlighted. The chapter further presented a critical review of the existing methodological frameworks and tools for evaluation of flood damages to building at micro level and underlined a number of gaps. A major gap here is that due to the lack of availability of data and the type of data inputs in current methods, mostly the simple approaches like damage curves (with various limitations discussed in this chapter) dominate in this domain. Simple methods ignore the uniqueness of buildings in the analysis and therefore generate high level of uncertainty and errors in the outputs. In addition, no existing model was found that could account for both load-resistance and water contact damage and provide the detail of damage in the building. These limit the application of existing FDA for use in the performance-based engineering or approval process of buildings in flood prone areas that is necessary for ensuring their resilience and overall damage mitigation to the community. A need is highlighted in here for further research to develop a framework (or model) that makes use of more comprehensive input datasets about the building in a dynamic analysis of both flood loads and water contact actions on the building to address these limitations.

The next chapter will explore the potential use of the recent technological developments like 3D building models in virtual city models or BIM from the Geospatial or the AEC/FM domains for FDA. These technological developments will be investigated in support of implementing an FDA framework that can represent the unique characteristics of buildings in the damage evaluation and overcome the highlighted knowledge gaps discussed in this chapter.
Chapter 3

Data Technologies in support of FDA of Buildings at Micro Level
3 Data Technology Review in Support of FDA of building at micro level

3.1 Introduction

This chapter aims to explore the technical developments for representing buildings and flood parameters within the built environment to identify opportunities for enriching the FDA process towards a more effective damage evaluation to a building at micro level. As discussed in the previous chapter (see Section 2.6.2.2), GIS in the Geospatial domain play a crucial role in managing and overlaying the spatial information about buildings and flood parameters for the evaluation and visualisation of damage to buildings. Therefore in this chapter, the investigation begins with the Geospatial domain and explores the important and relevant developments from data point of view in this area. The investigation is further extended to other relevant domains (e.g. Architecture, Engineering and Construction/Facility Management; AEC/FM) and even overlaps between these areas are considered and explored.

3.2 Developments in Geospatial domain

The reliance of many of the analyses and decisions nowadays (such as those discussed in Chapter 2) on the location of elements underpins the importance of the Geospatial information (Zlatanova et al., 2002a; Mignard et al., 2011; Zhang et al., 2009). This information is referred to the [geographic] representation of the observed or measured above- or below-ground man-made or natural physical features that are commonly managed and presented by GIS (Maguire, 1991). GIS was initially developed and launched in the 1960s and is described as “a system for capturing, storing, checking, manipulating, analysing, and displaying data which are spatially referenced to the Earth” (DOE, 1987; Maguire et al., 1991). The main power of GIS is related to its spatial analysis functionalities (Zhang et al., 2009). The analyses of geospatial data in GIS tools are highly dependent to the format that the information is stored and represented in the system. In the subsequent sections, the common data models and representations in the Geospatial domain are thoroughly discussed. A brief discussion on the application of these models for a detailed micro level FDA on building will also be provided.

The digital representation and geometrisation of the physical world in GIS systems were traditionally projected in various ways on the planar two-dimensional digital maps (Isikdag and Zlatanova, 2009b). In such 2D digital representations, geographic features are commonly characterised by either Vector or Raster (Couclelis, 1992; O'Sullivan and Unwin, 2003; Karimi and Akinci, 2010b).
3.2.1 Vector vs. Raster

The vector model\(^{26}\) is the representation of the physical entities using *points*, *lines* and *polygons* and described by a number of attributes attached to them. Some examples of vector data formats include the ESRI ShapeFile (.shp), Mapinfo's TAB files, GeoJASON, etc. The Shapefile is the most common and widely accepted vector data format in the Geospatial domain and based on open specifications (ESRI, 1998; Zlatanova et al., 2012). Shapefiles provide support for geometries (i.e. point, line and polygons) basic semantics\(^{27}\), and simple textures. However, no topology or relationships between objects are accounted for in this format. Also, the semantics are handled at the feature layers than objects themselves. The representation of the building using any of the aforementioned shapes along its attributes constitute the common data inputs for current practice of FDA (damage curves) which as discussed previously in Chapter 2, it is ineffective for representing the complex building structure.

ESRI Building Interior Space Data Model (BISDM) (ESRI, 2011) is a vector-based conceptual data model for 2D representation of a building and its floors and spaces. This data model is developed by ESRI for practical modelling of the indoor spaces that their thematic and semantic information as well as the relationships are modelled. The BISDM objects are represented using ESRI features and cannot provide an open standard for building representation. Although by knowing the ceiling height at each floor, a 3D view of the spaces using extrusion can be provided, this data model is limited to 2D representation of the building, its floors and ceiling (and their materials) and interior spaces, and other aspects of the building are not included. In addition, using the floor-plan lines and the ceiling height information, the walls as extruded lines can be represented (see Figure 3.1). For considering routing applications, BISDM 3.0 further provides a graph-based conceptualisation of the indoor routes.

\(^{26}\) It is also referred to as the object view of the world.

\(^{27}\) *Semantics* indicate the possibility to assign thematic meaning to an object or a group of objects (Zlatanova et al., 2012)
In contrast to vector representation, raster\(^29\) is a continuous representation of the real world entities using regular (or even irregular) grid cells called 'pixels' (O'Sullivan and Unwin, 2003). In this format, only one value can be associated to each pixel that represents the characteristics of the geographically extended entity/phenomenon (e.g. flood depth or ground elevation) at that location. The most common raster file formats may include ESRI Grid file, JPEG, GeoTIFF (Tiff files with GIS related metadata), etc. The use of these formats for representation of buildings is very limited; however, its adoption for the flood extent and depth using different colours is commonplace in 2D GIS. The representation of multiple flood parameters using one raster is not feasible and as Figure 3.2 illustrates, a combination of multiple raster and/or vector is usually employed for presenting flood depth and velocity together. On the other hand, the accuracy of the raster information is highly dependent on its pixel-size that may be a limiting factor for proper representation of the building footprint and the flood parameters around it (Apel et al., 2009).

\(^{28}\) http://www.credospb.com/ArcReview/number_68/otras.htm

\(^{29}\) Also referred to as the field view of the world.
3.2.2 Interoperability in geospatial domain

Although nearly all GIS software support the vector and raster models, the inadequacy of software for exchange of information between vendor-specific tools/formats and therefore interoperability amongst them, has been a significant challenge. Interoperability is the ability of systems to work together and exchange information (IEEE, 1990; ISO/IEC, 1993). In the Geospatial domain, Open Geospatial Consortium (OGC) as the responsible body for establishing interoperability uses standards or services like Web Mapping Service (WMS), Web Feature Service (WFS) and Web Coverage Service (WCS) for this purpose (Peachavanish et al., 2006; Karimi and Akinci, 2010a, p.43). The interoperable standard data formats are generally open specifications that in contrast to vendor-specific formats, can be used in software by any vendor.

Geographic Markup Language (GML) by OGC (2007b) is the most comprehensive modelling language and an XML-based ISO standard\textsuperscript{30} for storing and exchanging geographic information and the underlying data structure for the aforementioned geographic services. GML implements the ISO

\textsuperscript{30} ISO 19136
19107 (ISO, 2003) for modelling the geometrical and topological features. Previously, GML only supported 2D vector-based geo-information. In its most recent version, GML 3, the 3D geometrical representation of features, raster data as well as topological relationships are also included. A GML document also supports coordinate systems, temporal dimensions, and possibly map styling rules to represent the physical world; however, it does not contain semantics of the geographic features. Therefore as described previously by OGC (2007a), many users or developers take advantage of its modular structure and create community-specific "GML application schemas". Hence, instead of referring to generic GML features like points and polygons, actual labelled real world entities like schools, roads or buildings can be stored along with their descriptive properties and geometries in a GML document as objects (Peachavanish et al., 2006).

An example of GML application schema for exchange of 2D flood data is the Water Modelling Language (WaterML) (OGC, 2012a). WaterML is used for encoding, storing and exchange of the spatiotemporal hydrological information. It is mainly structured according to GML's "coverage" concept and allows for storage of 2D spatial distribution as well as the time-series of water observations. LandGML (OGC, 2015b) for management of land information, SensorML (OGC, 2007d) specifically for sensor measurement data, and Weather Information Exchange Model (WXXM) constitute some other examples of 2D GML application schemas.

Despite the significant research and many practical developments in the 2D geo-information and GIS (Borrmann, 2010), the 2D data are limited for describing and representing the complexity of the 3D world in urban context in support of essential analysis for multifaceted urban management processes (Cheng et al., 2013; Duncan and Abdul-Rahman, 2013). Some of these limitations are summarised in the work of Hijazi et al. (2009) and Kwan and Lee (2005) for buildings and utility objects. Such issues also exist for the case of floodwater modelling and visualisation (Stoter and Zlatanova, 2003). The review of the literature suggests a paradigm shift in the analysis and visualization from the traditional 2D approaches into sophisticated 3D methods for a variety of applications in the complex urban environments; e.g. sustainable development, land administration, disaster management, environmental modelling and visualising, training simulations, urban planning, navigation, tourism, etc. (Kwan and Lee, 2005; Kolbe et al., 2008; Kolbe, 2009; El-Mekawy, 2010; Amirebrahimi and Rajabifard, 2012; Alam et al., 2013; Shojaei et al., 2014). Some of the underlying drivers for this shift include (Zlatanova et al., 2002b; Hijazi et al., 2009):

- Increasing demand for 3D urban data and visualisation (Shiode, 2001; Dollner et al., 2006b);
• Significant developments in 3D data acquisition techniques and reducing the costs of 3D geospatial data collection and therefore, increase in availability of 3D geo-information (Stoter and Zlatanova, 2003; Li et al., 2013; Jazayeri et al., 2014); and

• Improvements in techniques for storage, manipulation and access to detailed 3D and 4D geo-information and the development of tools for their analysis (Cheng et al., 2013; Alam et al., 2013);

In the next section, 3D GIS and the relevant developments in 3D digital representation of the physical world will be presented and discussed.

3.2.3 Three-dimensional GIS

Due to an exponential increase in the complexity of geo-information from 2D to 3D, specialised and extended GIS software are required to manage and visualise such data. 3D GIS shares similarities with 2D GIS functions, but is mainly used for handling the 3D geospatial data (Zlatanova et al., 2002a). More realistic and detailed 3D geo-information and cyber 3D worlds have increased the popularity and the use of 3D GIS (Bandrova and Bonchev, 2013).

From geometry point of view, the accepted 3D modelling techniques as the basis of most file formats in the Geospatial domain include the "Boundary Representation (B-Rep)" or "swept solid geometry" (or extrusion) (Zlatanova et al., 2012; Isikdag and Zlatanova, 2009b). While in the former, complex geometries are constructed via a series of connected 3D surfaces/polygons based on what humans perceive from objects (Zlatanova et al., 2012), the latter is created as the result of sweeping a 2D shape along a simple or complex path in space (see Figure 3.3[left] and [middle]).

Figure 3.3: Voxel geometry (right), swept solid geometry (middle) and boundary representation (left)
Isikdag and Zlatanova (2009b) discuss that in the ISO standard for Geographic Information (ISO 19107) as the basis of GML geometry and topology, nearly all 3D objects (even complex ones) are represented using the previously discussed 2D representations or either of these 3D representation methods. On the other hand, Zlatanova et al. (2012) discussed the applications of "Voxel", a three-dimensional equivalent of raster format for representation of 3D continuous geographic features (see Figure 3.3(right)). Next, the data formats in the realm of 3D GIS and interoperability amongst the software in this domain are discussed.

### 3.2.4 Standards and exchange formats for 3D geospatial information

A variety of 3D data formats and standards have been developed by the standardisation organisations or particular vendors in the Geospatial domain. While some of these data formats were developed as standards, some others became accepted standards due to their widespread use. The majority of these data formats are goal-specific and their variation may be in terms of their presentation, usage and applications which they serve (Zlatanova et al., 2012; Duncan and Abdul-Rahman, 2013). In here, an overview of the most prominent data formats/models for exchange of 3D geo-information is provided. Nagel (2014) classifies the representation of the building in those geospatial information models into Geometric and Graphical building models (e.g. VRML, X3D, COLLADA, 3D PDF, KML), and urban information models (e.g. CityGML and IndoorGML).  

**VRML and X3D**

VRML\(^{32}\) (W3C, 1995) and its successor, the X3D\(^{33}\) by the Web 3D consortium were developed in the 1990s. They are the most widely used formats for exchange of graphics over the web (Web3D, 2015) and are 3D computer graphics standards specific to 3D visualisation. In spite of the support of VRML for a variety of geometries and texturing techniques, it requires large storage capacity and does not support for XML. These shortcomings resulted in the introduction of X3D which is an XML-based ISO standard and an extension/enhancement to VRML for representing 3D computer graphics in applications in Computer Aided Design (CAD), GIS, etc (Silvestre et al., 2015). Beside the geometric representation in these file formats, they provide no semantics for the objects; and the relationships and topology between them are not accounted for. Therefore, although providing

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\(^{31}\) The classification by Nagel (2014) also includes the Building Information Model (BIM) in AEC/FM which will be discussed in Section 3.3.4.

\(^{32}\) ISO/IEC 14772-1 and ISO/IEC 14772-2

\(^{33}\) ISO/IEC 19775-1
excellent tools for 3D visualisation, they are not suitable for use in the assessment of flood impacts on buildings.

**COLLADA**

COLLaborative Design Activity (COLLADA) is an XML-based open standard and an exchange format for 3D information between diverse applications and tools. COLLADA supports 3D geometry, topology, texture, effects, animation and also multi-representation of objects (Khronos, 2004). Although a detailed representation of building is possible using COLLADA, however it only accounts for very basic semantics of the objects; therefore, beside the geometries, it only contains little further information about them. Furthermore, the explicit relationships, as well as the attributes for further description of objects are missing. Therefore, COLLADA would have a very limited use for FDA. In the geospatial world, the use of COLLADA has been increased since Google adopted this standard alongside the KML format for 3D visualisation of the globe and cities in its virtual globe, the Google Earth.

**KML**

Keyhole Markup Language (KML) is an XML-based format and an OGC standard (OGC, 2008). The geometry in KML is similar to GML (Zlatanova et al., 2012). KML is widely used for a variety of web applications to annotate and visualise geographic features in 2D maps (e.g. Google maps or Open Street Maps) or 3D virtual globes like Google Earth platforms and Virtual Earth (He, 2012). Although KML supports 3D geometries (e.g. points, line, polygons as well as B-Rep and extrusion), similar to previously discussed formats, KML objects are presented using their geometries with very basic semantics. KML maybe compressed in KMZ (KML zipped) files that may contain additional media like images and videos as well as 3D models in COLLADA format. Figure 3.4 illustrates the application of COLLADA in KML in Google platform for 3D visualisation of the photorealistic buildings.
Figure 3.4: Photo-realistic and COLLADA models of buildings in KML format and visualised in Google Earth

**ShapeFile**

ShapeFile is a binary format and was previously used for storage and exchange of only 2D spatial information. Since the release of ESRI ArcGIS 10, ShapeFiles can account for 3D geometries (using polyhedron as a collection of polygons connected at their edges) by considering the z values in addition to x and y coordinates. Despite the representation of the 3D geometries in ShapeFile, they still cannot store topology; and the semantics of objects are basic.

**3D PDF**

A quite recent development is the 3D PDF that allows for publishing and 3D visualisation of building design in an interactive PDF format. The 3D geometry in this format can be integrated with the PDF text document and provide an interactive tool to explore a 3D building. In here, similar to ShapeFile, the semantics lie in the name of the layer. 3D PDFs normally are large in size and difficult to transfer over the web (Zlatanova et al., 2012).

**GML 3**

GML as previously discussed in Section 3.2.2, is the most comprehensive and widely supported data model and open standard for geographic information (Wu and Hsieh, 2007). As opposed to its older versions, GML 3 provides support for 3D spatial information. The geospatial phenomena are essentially 4D, considering their spatiotemporal dynamics (Zobl et al., 2011). By following the ISO 19107 standard, GML 3 allows for storage and exchange of 4D entities. In addition, it can store 0 to 3 dimensional composite geometries as well as 0 to 3 dimensional geometry aggregates (where geometries do not share topological boundaries) (OGC, 2007b; Zlatanova et al., 2012). A few
application schemas of the GML 3 have been developed to support community-specific use cases requiring 3D information. These application schemas are summarised by OGC (2015a) and the important ones to the scope in this chapter include the CityGML and IndoorGML which will be discussed next in the context of 3D virtual city models.

Up to this point, although the discussed 3D formats can support a wide range of 3D geometries and properties; yet, no or limited semantics is accounted for (Prechtel, 2014). Next, the developments in the context of 3D virtual city models where such important aspects are extensively supported are presented and discussed.

3.2.5 Three dimensional Virtual City Models

Virtual 3D City Model, as a subset of Urban Information Models (UIM) (Nagel, 2014), is a relatively new but important concept in the Geospatial domain and refers to a "geo-referenced semantic representation of urban data by means of 3D geo-virtual environments" (Dollner et al., 2006a; Stadler and Kolbe, 2007). As an enabler for collaboration, interoperability and consistency, they integrate heterogeneous and complex 3D geo-information within a single framework and can be considered as the foundation for storage, exchange, analysis and presentation of such information (Hijazi et al., 2011; El-Mekawy et al., 2011a; Hildebrandt and Timm, 2014). For these reasons, it is suggested not to consider 3D city models simply as an extension of 2D maps (Hajji, 2013). Different frameworks have been proposed to develop 3D city models from heterogeneous data sources (Zeile et al., 2005; Nagel et al., 2009). He (2012) explains that 3D city models can be created from scratch using (a) surveying-based method by collecting data from the real world; or (b) designed-based modelling where construction designs are used as inputs.

Evidence in the literature suggests the increasing number of 3D city models around the globe (V3DCM, 2013; Hajji, 2013; Zhao et al., 2013; Alam et al., 2013). These models represent the urban environment as observed in the reality in the world coordinate systems (Nagel et al., 2009). The initial focus of these models was the geometric representation of the city in 3D for visualisation that bear no analytical capabilities (Groger and Plumer, 2012; Benner et al., 2005). Groger and Plumer (2011) and El-Mekawy et al. (2012) discuss however that the visualisation is only the tip of the iceberg. By utilising such rich urban data along with the querying and analysis capabilities in 3D GIS, the use of 3D city models can go beyond the pure visualisation of the world and can benefit a variety of urban management processes (Métral et al., 2013). This is considered as a driver for shift towards new

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34 Natural and/or man-made entities or phenomena in the real world
approaches of urban management (Benner et al., 2005) like urban planning, facility management, emergency management, location-based services, real-estate, flood or noise mapping, simulations and visualisation using Virtual Reality (VR), tourism, 3D cadastre, energy analysis, etc (Kwan and Lee, 2005; Kolbe et al., 2011; Groger and Plumer, 2012).

Wang et al. (2007), Duncan and Abdul-Rahman (2013), Gia et al. (2013) and Valencia et al. (2015) summarised and reviewed the existing 3D Virtual City Models as well as those spatial data models that have been used as the foundation of 3D city modelling. Some of the important models include the Simplicial Simplex Model (SSM) (Zlatanova, 2000), Urban Data Model (UDM) (Coors, 2003), 3D TIN (Duncan and Abdul-Rahman, 2013), ESRI 3D City Information Model (Reitz and Shubiger-Banz, 2013), AriBIS (Aydinoglu et al., 2013), City Geographic Markup Language (CityGML) (OGC, 2012b) and the INSPIRE data specification on buildings which is designed based on the overall design of CityGML (INSPIRE, 2013; Groger and Plumer, 2014). The most prominent and comprehensive standard to represent the built environment in 3D within the Geospatial domain is the OGC's CityGML (El-Mekawy et al., 2011b; Isikdag and Zlatanova, 2009b). For the importance and widespread use of CityGML, the others are not further discussed and the focus in the next section will be on this standard.

**City Geographic Markup Language (CityGML)**

CityGML is an application schema of the GML 3 and was originally developed in 2002 by Special Interest Group 3D (SIG3D) and currently its version 2.0 (OGC, 2012b) has been adopted as an international open standard by OGC for the representation and exchange of 3D urban objects (Kolbe, 2009; Herman et al., 2014). CityGML is XML-based and facilitates the storage, management and visualisation of 3D city models' data for a variety of applications (Sharkawi and Abdul-Rahman, 2014; Huang, 2014).

CityGML is modularised and as Figure 3.5 illustrates, the urban features are conceptually organised in the "core" and 11 other thematic modules (OGC, 2012b). The core module contains the base classes and common attributes used by all the objects in the CityGML. Other thematic modules represent the terrain, roads, railways and other transportation-related objects, water bodies, vegetations, land use information, buildings, city furniture and bridges. In addition, the visual aspects (e.g. texture) of the objects and methods for ad hoc extension of the CityGML for further use are provided in the generics and appearance modules.
CityGML extends the GML 3 base classes for coherent semantic and geometric definition of the aforementioned objects (see Figure 3.6), their topology, attributes as well as their appearance aspects (Stadler and Kolbe, 2007). In addition to semantic and geometry, the objects’ relationships are also explicitly defined in CityGML. All the objects in CityGML are defined as the subclass of _CityObject (representing any urban feature) and can be defined in relation to the terrain (and also water) surfaces (Groger and Plumer, 2012). Explicit definition of semantic information (e.g. knowing which object is flood or which represents the building or its doors) is a crucial factor in CityGML. These defined semantics can further improve the interoperability for urban data management (Benner et al., 2005). Despite the richness of CityGML in defining the city objects, their definition only covers spatial aspects without consideration for their temporal dimension.

CityGML supports applications at city or at the larger-scales as well as those at facility or a single building level (Herman et al., 2014). In CityGML, objects can be modelled in five discrete and coexisting resolutions referred to Levels of Details (LoD) (Kolbe et al., 2008). Higher LoDs not only increase the geometric complexity but also the semantic richness of the objects (Emgård and Zlatanova, 2008; Biljecki et al., 2014). Groger and Plumer (2012) provide a comparison between
different CityGML LoDs and examples of different objects in each. They underlined a drawback of current version of CityGML that does not provide any rules to indicate whether a particular object should be modelled in a particular LoD or not. For this reason, Cheng et al. (2013) investigated the common definition of LoDs and provided guidelines for this purpose.

A central part of the 3D city models and CityGML is the 3D building model (Benner et al., 2005; Groger and Plumer, 2012; Li et al., 2013). In comparison with the terrain and other natural objects, the structures of building models are much more complicated and much effort has been put for its modelling in this standard. Buildings in CityGML can be represented simultaneously in different LoDs (see Figure 3.7).

Figure 3.7: Building representation in different LODs of CityGML (Groger and Plumer, 2012)

A building in LoD0 is basically a 2.5D polygon of its footprint. LoD1 is a solid or multi-surface representation of the building which can be an aggregation of different building parts. The roof type (e.g. gable or flat) in here is specified by an attribute. In this LoD, the position of the building in relation to the elevation surface can be set by a Terrain Intersection Curve (TIC). In LoD2, a generalised roof structure is added to the LoD1 representation of the building with differentiation of walls as wall surfaces. LoD3 presents a more detailed representation of the building which includes the openings (e.g. windows and doors). Finally in LoD4, the interior of the building such as furniture, floor surface, and other aspects are also modelled. Figure 3.8 illustrates a simplified UML of the CityGML building model and its elements in the aforementioned discussed LoDs.
In CityGML many building components like foundation, columns, beams, slabs, connections and other structural aspects are not modelled or all are represented by generic objects like "building installations" without the details of each specialised component. In addition, many of the building components are modelled using surfaces instead of actual objects. For example, as illustrated in Figure 3.9, the wall object in this standard is not explicitly defined and instead, is represented by "wall surface" and "interior wall surface" objects. This is the case of many other building elements like floors, ceilings and roofs. Therefore, many limitations in terms of assignment of material or confusion in use of the full geometry of any of these elements exist.

Figure 3.8: CityGML Building Model in UML (adopted from El-Mekawy and Ostman, 2010).

Figure 3.9: Building component representation using surfaces CityGML (adopted from Nagel, 2014)

For a more detailed Building model, see (OGC, 2012b, pp 63)
CityGML is not a universal 3D city model as it was not possible to include the requirements of many applications in its original development (Hajji, 2013). For example, this standard does not provide support for utility networks or geotechnical aspects of the city. However, the extensible structure of the CityGML allows for its extension for inclusion of these entities. It generally uses two different mechanisms for extension; (1) use of generic features and attributes; and (2) Application Domain Extension (ADE) (OGC, 2012a). Many different application-specific CityGML extensions and specialised ADEs have been developed for a variety of use. Some examples include the Indoor Spatial Data Model (Kim et al., 2013), navigation and smart city services (i-SCOPE) (Prandi et al., 2013), Utility Network (UtilityNetworkADE) (Becker et al., 2010), Geotechnical objects and features needed for infrastructure development (Tegtmeier et al., 2013), Dutch-specific elements for their Spatial Data Infrastructure (SDI) in the IMGeo ADE (Van den Brink et al., 2012), Computer Aided Facility Management (CAFM), and subsurface geotechnical aspects (Tegtmeier et al., 2013). Water courses often form prominent parts of a 3D model (Prechtel, 2014). The modelling of water bodies in CityGML is schematically presented in Figure 3.10(top) and an example is provided to illustrate the water and WaterGround surfaces (Figure 3.10[bottom-left and bottom-right]). However, except for the surface representation of the boundaries of water bodies, CityGML does not support the other water/flood characteristics. Therefore, an ADE (the HydroADE) for exchange of dynamism and spatio-temporal distribution of water depth was developed by Schulte and Coors (2009). However, the main purpose of this extension was for 3D visualisation only and again, other important aspects of flood like velocity were overlooked.
IndoorGML

CityGML is a widely used standard for representing indoor data (Cho and Choi, 2014). However, it does not represent the topology between rooms and other spaces in the building. Although an ADE was previously developed for CityGML to cover these shortcomings (see Kim et al., 2013), the IndoorGML was developed by OGC to complement CityGML for storage and exchange of indoor spatial information about the building (OGC, 2014). It can represent, store, and manage primal (volumetric and boundary representation) as well as dual (the hierarchical graph model and its connectivity) representation of the rooms with their semantic details (OGC, 2012b). Although it appears as a new standard for modelling of the building interior, the representation of building elements and rooms in primal view of the IndoorGML is not much different from the CityGML.

The 3D city models have been used for a variety of applications like noise modelling and propagation (Stoter et al., 2008), emergency response (Kolbe et al., 2008), Utility network 3D models and analysis (Becker et al., 2013), etc. In addition, studies like Schulte and Coors (2009), Adda et al. (2010), Mioc et al. (2011), Kemec et al. (2010b) and Kemec et al. (2010a) adopted 3D virtual city models including buildings, elevation and maximum flood depths for flood risk management.
However, the sole purpose of these studies was on visualisation of floods in an urban context (see Figure 3.11) and no interior aspects of the building and/or damage analysis had been included. In some cases, as shown in Figure 3.11 (bottom left), the flood representation was also not appropriate.

Figure 3.11: Visualisation of flood and the building using 3D models (adopted from Adda et al., 2010; Kemec et al., 2010b; Kemec et al., 2010a; Mioc et al., 2011; Bogetti, 2012);

3.2.6 Summary of developments in the Geospatial domain

In this section, an overview of the efforts and standards in the Geospatial domain for representation of the building and flood information was presented. As described in the presented standards and developments in this domain (see Table 3.1), flood depth and extent information can be represented in 2D and 3D, however, other characteristics discussed in Chapter 2 are missing. On the other hand, in many cases, the building representation is still incomplete, the semantics are not well-supported, and the geometries are simplified or misrepresented for use for detailed analyses. Some underlying reasons for these include the deep roots of GIS in (Karimi and Akinci, 2010b):

- Large-scale outdoor applications with relatively recent attention to the indoor space;
- Requirements for lower granularity of information rather than detailed designs;
• Geometry approximation using points, lines, polygons, surfaces and extrusion; and

• Strength in spatial data management and geo-processing rather than detailed design.

On the other hand, no single framework or data structure/model could provide a complete set of building and flood information together in support for a detailed FDA on buildings (see the bottom row of Table 3.1).

Table 3.1: Comparison of 3D standards within Geospatial domain (modified from Zlatanova et al., 2012)

<table>
<thead>
<tr>
<th>Criteria/Standards</th>
<th>VRML</th>
<th>X3D</th>
<th>KML</th>
<th>COLLADA</th>
<th>GML3</th>
<th>CityGML</th>
<th>IndoorGML</th>
<th>SHP</th>
<th>3D PDF</th>
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Not supported (-), basic (0), supported (+), extended support (++)

In contrast to the Geospatial domain, other fields like AEC/FM require more detailed design of the building and infrastructure models (as built or very close to it). Normally in this domain, buildings are modelled at the highest level of detail with detailed representation of their exterior and interior using high granularity and decomposition of objects (Van Berlo and De Laat, 2010; El-Mekawy and Ostman, 2010). Objects for this purpose can be based on complex mathematically-generated geometries that can be possibly used for building performance analysis and decision making (Isikdag and Zlatanova, 2009b; Kensek and Noble, 2014, pp 144). Herman et al. (2014) discuss that industries in the AEC/FM domain have developed their methods to represent and exchange these 3D models. In the next section, developments in AEC/FM and their capabilities will be discussed further.
3.3 Developments in AEC/FM domain

Chapter 3

The two-dimensional Computer Aided Design (CAD) was developed in the 1960s and many developments have happened in this area since (Karimi and Akinci, 2010a). Despite the long tradition of 2D CAD and Computer-Aided Modelling (CAM) for design and engineering purposes in the AEC/FM domain, they were associated with considerable time and costs for assessing the design in terms of structural details, cost and energy usage estimation, etc (Eastman et al., 2011). In addition, as discussed earlier, 2D data is limited to represent complex situations. Therefore, although 2D versions can still be seen in the engineering practice, they have been mainly replaced by 3D CAD from various vendors (e.g. Intergraph, Autodesk, and Bentley). As CAD progressed from 2D to 3D with more complex shapes and their attributes, a variety of non-proprietary and vendor-specific data formats have emerged over the years. Due to the heterogeneity of these software and their data formats, concerns and issues regarding the information exchange and interoperability between these tools has been raised and repeatedly discussed in the AEC/FM-related literature (Pouria and Froese, 2001; NIST, 2004; Isikdag et al., 2007b; Eastman et al., 2011; McGraw Hill, 2014). Interoperability is a source of many issues and large costs within this industry and much effort is made in the AEC/FM domain to address the aforementioned interoperability issues (Eastman et al., 2011). These efforts evolved from simple file and drawing exchange formats to those product- and domain-modelling initiatives that were followed by the object-oriented software development (Isikdag et al., 2007b; Kosovac, 2007, pp 81). Eastman et al. (2011), Karimi and Akinci (2010b), Isikdag et al. (2007b) and many other researchers like Dong et al. (2007), Kosovac (2007) and Laakso and Kiviniemi (2012) provided an overview of developments in AEC/FM and open standards to address the interoperability issues in this domain. Karimi and Akinci (2010b) classify these initiatives into (a) early geometry and topology information/data exchange formats, (b) product model exchange standards, and finally (c) the semantic building information model exchange standards and specifications. These developments vary in storage mechanism (file-based vs. xml-based) and can be proprietary or non-proprietary. In the following subsections, an overview of these developments is presented and important initiatives (and standards) are discussed in more detail. A summary of the prominent standards in the AEC/FM domain is provided in Appendix 5.

36 It results in over 15.8 billion dollars per year in the US alone (Eastman et al., 2011).
3.3.1 Information/data exchange formats for geometry and topology

The initial developments towards interoperable data exchange formats amongst the CAD applications included the Drawing Exchange Format (DXF) and the Initial Graphics Exchange Specification (IGES) by Autodesk and a different joint initiative by Boeing and General Electric. File size in DXF was small and the 2D graphic and geometry data could be efficiently exchanged. However, in this 2D format, semantics are limited and the topology of the objects was not accounted for (Karimi and Akinci, 2010b). IGES, on the other hand was a platform-independent file in ASCII format and its advantages over DXF included its ability to exchange the geometry (2D/3D), topology and the attributes. However, the files were large and required much resources for processing (Slansky, 2005).

DXF, IGES, and the other similar exchange formats (e.g. DWG and DGN) are considered as fixed schemas. However, accounting for the ever-expanding developments in various industries like piping, mechanical, electrical and other building and infrastructure systems in these formats would result in very large-size files and uninterpretable formats (Eastman et al., 2011, pp 110). Therefore, new initiatives emerged to support these complications in the data exchange for products in the above industries which will be discussed in the next section.

3.3.2 Product model exchange standards

With the introduction of the object-oriented approaches, new product-modelling initiatives emerged. Isikdag et al. (2007b) discuss that the effort by the International Standardisation Organisation (ISO) resulted in the release of Standard for the Exchange of Product model data (STEP) as a major development for the exchange of 3D product data. STEP (ISO 10303) allows for the storage and exchange of 3D geometry, topology, assemblies, configuration and properties (e.g. materials) using a neutral ASCII file format. Files in STEP format were however large and the documentation using the STEP was complex and resource-intensive (Slansky, 2005). The "EXPRESS language" (ISO standard 10303-P11, 1994), as the formalised standard data modelling language for product data, has been the main output of the STEP (ISO 10303) and a major mechanism for modelling of products in relevant industries within the AEC/FM domain.

A variety of data formats, standards and data models have been developed and implemented for domain-specific data exchange in the product model category which their overview has been provided

37 Product models include the models of different building assemblies from a variety of vendors. Example includes a particular door product model which has geometry and properties.
by Tolman (1999) and Karimi and Akinci (2010b). Some of these developments were later combined as part of a more comprehensive set of ISO standards. The more recent and important developments in this category include the **CIMsteel Integration Standards (CIS/2)**, **Green Building eXtensible Markup Language** (gbXML, 2014), **Building Construction eXtensible Markup Language** (bcXML) (eConstruct, 2003), **Open Building Information eXchange** (OBIX, 2015), **Automated Equipment Information eXchange** (AEX) (FIATECH, 2009), **standard of the Associated General Contractors of America**, the agcXML (2014), and **BIM for Precast Concrete (BPC)** (FIATECH, 2006). Additional standards like **AP 225** (with limited CAD application support), **AP 241** (only for industrial facilities) and **ISO 15926** (for oil and gas facilities) have been also highlighted amongst the other product model standard formats (Eastman et al., 2011). It is further discussed that despite the success of these developments in their industry (e.g. CIS/2 in steel industry), they are very specific and their cross-disciplinary applications and interoperability were still an issue and to be addressed. In this way, only specific aspects of the building/facility are modelled resulting in its incomplete representation. This led to the development of a more comprehensive semantic Building Information Model exchange standards that will be discussed next.

### 3.3.3 Semantic Building Information Model Exchange Standards and Specifications

Semantic models include those with the ability to account for the semantics of the objects from multiple disciplines within the AEC/FM. There has been only a handful of these models and as summarised by Isikdag et al. (2007b), Tolman (1999) and Eastman (1999), their prominent examples include the **GARM**, **Integration Core Model** (ICM), **Integration Reference Model for Architecture** (IRMA), and the **Building Construction Core Model** (BCCM). A current open standard in this category is the **Industry Foundation Classes (IFC)** (ISO 16739) which was developed in support of the modern Building Information Modelling. In the last decade, BIM has been the focus in the AEC/FM as a more efficient process for managing a building or facility. It further provides better interoperability and communication of all aspects of a building or facility information (including all disciplines and products) amongst the relevant participating organisations (Kensek and Noble, 2014). In the next section, BIM is discussed in more detail.

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38 See (Isikdag et al., 2007b) for the various definition of BIM.
3.3.4 Building Information Model (BIM)

BIM is currently one of the most promising and fast growing developments in the AEC/FM industry (Kensek and Noble, 2014). It is an N-dimensional digital representation of all aspects of a building and its components throughout its lifecycle along with their spatial and thematic properties in a single information repository (Karimi and Akinci, 2010b, pp 11; Succar, 2009). BIM has large benefits over the traditional 2D/3D CAD and paper-based practices (Eastman et al., 2011, pp 1, 20; Azhar et al., 2008a). The global and country/region-specific research by McGraw Hill Construction (2010, 2012a, 2012b, 2014b, 2014a) suggest that despite the early days of BIM, its adoption rate has been increasing with recorded positive return on investments for building and infrastructure projects. In addition, mandates for use of BIM in various countries like Singapore, UK, US, Norway, etc (Zeiss, 2013) are evidence of the importance of BIM to the development process and the future of the AEC/FM. The full adoption of BIM is no longer an "if" but "when"; as the adjustment in the mindset of practitioners and design firms towards adoption of the BIM paradigm is apparent (Brewer et al., 2012).

The term “BIM” can describe the “Building Information Model” as a data model (product) or “Building Information Modelling” as a Process. A commonly referenced definition of BIM describes it as (NBIMS, 2006)

"A computable representation of all the physical and functional characteristics of a building and its related project/lifecycle information, which is intended to be a repository of information for the building owner/operator to use and maintain throughout the lifecycle of the building”.

In a similar way, BIM is defined as (AGC, 2006)

"Data rich, object-oriented, intelligent and parametric digital representation of the building/facility....which its data can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivery of the building/facility”.

The major characteristics of BIM as summarised by CRC Construction Innovation (2007) include the robust and precise 3D geometry (as built), semantic richness, integrated information, and lifecycle support. The true richness of BIM is sourced in the definition of objects and their relationships with

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39 Improved profitability, reduced costs, better time management and improved customer-client relationships (Azhar et al., 2012).
40 For example, United States, Canada, Australia, New Zealand, Brazil, Japan, Korea, UK, France and Germany.
41 Singapore has aimed for 80% adoption of BIM in the construction industry by 2015 and its full implementation by 2016 (BuildingSMART, 2012).
comprehensive and extensible properties that expand the meaning of the object. BIM allows for a completed building model to be created, manipulated and visualised virtually even before its actual construction.

Despite their differences, the confusion between BIM and 3D CAD is not uncommon (Karimi and Akinci, 2010a, p.77; Azhar et al., 2008b; Bazjanac, 2006). In BIM, in contrast to 3D CAD, the modelling of shapes and geometries is replaced with the modelling of parametric objects and the use of object oriented approaches (Eastman et al., 2011, p. 101). Azhar et al (2008b) and Karimi and Akinci (2010a, p.77) further explain the differences between BIM and 3D CAD systems: (a) the support of BIM for behaviour of objects, (b) semantic object-based modelling in BIM, and (c) as opposed to only physical building support in 3D CAD, functional aspects of building components are modelled in BIM (Bazjanac, 2006). BIM also maintains the integrity of independent 3D views (which describe plans, sections, elevation, etc.) and ensures their consistency.

Commercial BIM tools usually adopt proprietary data formats for modelling the building which have resulted the interoperability issues in the industry. The BuildingSmart is the largest regulatory body for BIM and up to now have developed three major standards for BIM which include Industry foundation classes (IFC), BuildingSmart Data Dictionary (bsDD) and Information Delivery Manual (IDM) (Svetel et al., 2014). Amongst these, IFC is the standard for data exchange of BIM data and will be discussed next.

**Industry Foundation Classes (IFC)**

IFC (ISO 16739:2013) is an extensible "framework model" and currently is the most comprehensive publicly available non-proprietary ISO-based open standard exchange format for BIM (Hecht, 2010; Eastman et al., 2011, p. 129). This conceptual data schema has been developed by BuildingSmart, aiming for addressing all building information for all phases of its lifecycle and to overcome the limitations of other industry-specific product models discussed in Section 3.3.2 (Khemlani, 2004). IFC model is text-based and uses local coordinate system for defining the geometry of objects. It relies on the STEP-based Express language to define building elements that represent parts of building, their material and geometry and other aspects in various domains including architecture, building Mechanical, Engineering and Plumbing (MEP) as well as Heating, Ventilation and Air Conditioning (HVAC) systems and services, structural systems, etc.

42 Formerly known as International Alliance of Interoperability (IAI).
IFC4 is the latest release of this standard with modular structure (see Figure 3.12) that consists of four layers, each containing classes that become more specialised as one navigates to the upper layers. At the bottom, the "resource layer" contains the definition of reusable base classes like geometry, topology, materials, actors, roles, costs and properties. These base classes are used further for the definition of hierarchy of classes in the "core layer". The Kernel schema defines the most abstract classes in the IFC specifications. These classes are further used to create the base classes for physical products (product extension) as well as processes and controls (process and control extensions) and those more specialised ones in the "interoperability layer" to include the commonly used objects (called shared objects) in IFC like floors, walls, structural components, service elements, windows and doors, etc. Domain layer at the highest level contains highly focused classes for domain-specific applications like HVAC or MEP.

IFC enables the exchange of product information with their geometry, relations and properties. The geometry in IFC model can be represented by points, vectors, parametric or conic curves, polygons as surfaces, swept solids, boundary representation, bounding boxes, and complex Constructive Solid Geometry (CSG). CSG uses primitive geometries along with different algebraic operators (e.g. union or subtraction) to create composite geometries. Parametric modelling on the other hand uses parameters and complicated calculations to generate geometries which their design behaviour is intelligent with an automatic low-level editing. These methods are discussed in detail by Eastman et al. (2011, pp 33-40, 118).

Relations on the other hand are also explicitly modelled and derived from IfcRelation objects. They establish semantic and additional properties for particular link between two or more building elements or products (e.g. as illustrated in Figure 3.13, IfcRelFillsElement which connects an IfcOpeningElement like IfcWindow or IfcDoor to an IfcWall via RelatedBuildingElement and relatingBuildingElement properties of the relationship). Properties, on the other hand, describe a particular object in the IFC model and are mainly used in terms of property-sets. These include an extensible set of properties for the objects.
A representation of a subset of building elements in IFC as a standard for representing indoor data is provided in Figure 3.13. Although it is the most comprehensive BIM exchange format, IFC may still lack various elements that would be addressed in the future versions. In the meantime however, according to the extensible structure of the IFC and its object-oriented design, its structure can be extended for different applications by defining new classes as sub-types to define new entities or extending the property-sets to include those required properties. An example of this extension is provided in Cemesova (2013) that extended IFC model for building energy analysis.
IfcXML

In addition to the Express-based IFC, an XML version of this standard, the ifcXML, has been derived from the Express model and targeted a larger range of tools, databases and users (Nisbet and Liebich, 2007; BuildingSMART, 2015). IfcXML does not require the costly and complicated tools for implementation and querying of STEP-based IFC model (Ilal and Macit, 2007). It further facilitates the transmission, querying and the visualisation of the BIM model over the internet using BIMServer (2015). Although ifcXML is more human-readable, yet its large size is one of its major downsides (Eastman et al., 2011, p.135; Van Berlo and De Laat, 2010). A comparison of merits and disadvantages of ifcXML in relation to the STEP-based IFC model is provided by Cemesova (2013, pp 59).

BimXML

BimXML (bimxml.org, 2012), as an alternative to IFC (and ifcXML), represents the building information including the site, building, floors, spaces and the building equipment using a simplified model (i.e. points, extruded shapes and spaces) for the BIM collaboration via web services. It is currently used by various organisations (e.g. Onuma System, Data Design System, Tokmo, and BIM Connect) and various plug-ins for BIM and CAD applications (Revit, SketchUp, ArchiCAD) have been developed. BIMXML is not a replacement for IFC and cannot manage the detailed building information the way IFC can.
Building Element Classification Schemes for BIM

A variety of building elements such as doors, windows, walls exist in a complex BIM model. For facilitating the identification and formal classification of the building elements (assemblies or products), universal standard codes across the industry (e.g. UniClass, UniFormat, and OmniClass) were developed. The most comprehensive development for all facets of AEC/FM domain throughout the entire lifecycle of the building and the built environment is the OmniClass (2013) which is designed to provide a shared terminology for classification, storage and retrieval of AEC/FM assembly information. On the other hand, UniFormat II (ASTM, 1993) with narrower focus, is a standard for building element classification. The classification codes can be used for exchange of product information; but are mainly for cost estimates and/or management of the building throughout its lifecycle. They provide a backbone for BIM models.

Other classification and dictionary/vocabulary standards may include MasterFormat, ISO 12006-3, BARBi, LexiCon and SDC which are explained in more detail by Kosovac (2007) and are not discussed in here.

3.3.5 BIM applications

As a knowledge repository and an excellent building data management tool, BIM provides fast access to building information in a single centralised database (Meadati and Irizarry, 2010). It can be beneficial for use in simulations and modelling for a variety of applications (CRC Construction Innovation, 2007; Zhang et al., 2009) that may include planning, design, visualization, code review, forensic analysis, facility management, cost estimation, construction scheduling, and conflict and collision detection applications (Azhar et al., 2008b). Energy and sustainability performance analysis, facility management, emergency response and evacuation, 3D cadastre (registration of property rights), etc constitute some other areas that can benefit from BIM (NIST, 2005; Apostolakis and Lemon, 2006; Isikdag and Zlatanova, 2009a; Guven et al., 2012; Leite and Akinci, 2012; Wong and Fan, 2013; El-Mekawy et al., 2014; Tashakkori et al., 2015).

BIM for damage assessment

BIM can facilitate the vulnerability and risk assessment (Guven et al., 2012) and by containing all the details of the building elements, it has been used for the evaluation of building damage from hazards like earthquake (e.g. Christodoulou et al., 2010; Georgiou and Christodoulou, 2014;
Charalambos et al., (2014) and fire (e.g. Ruppel and Schatz, 2011). For example, Christodoulou et al (2010) proposed a damage assessment framework in order to create a cost estimation of damages and the visualization for Earthquake events (see Figure 3.14). For this purpose, they used the benefits of BIM, fragility curves and Assembly-based Vulnerability (ABV) technique to compute the damage magnitude to the individual structural components in the building.

Despite the use of BIM for assessment of damage to a building from a number of other hazards, no use of this technology for FDA is yet considered and generally, it is suggested that BIM has been underutilised for risk and emergency management (Leite and Akinci, 2012). This may be due to the inability of BIM to store or integrate the flood or similar large-scale information.

Figure 3.14: BIM/ABV integration for damage assessment against earthquake (left) the BIM model (right) the colour coded damage status of assemblies (adopted from Christodoulou et al., 2010; Georgiou and Christodoulou, 2014);

43 Similar to damage curves discussed in Chapter 2, however, for individual building components.
3.3.6 Summary of developments in AEC/FM domain

In this section, an overview of the 2D and 3D developments in AEC/FM was provided. Although 2D CAD data (e.g. DXF) supports larger extent applications (e.g. terrain or roads), it was recognised that the two-dimensional information cannot represent the complexity of the urban information effectively. On the other hand, the majority of the explored formats focus on the representation of industry-specific data and products and therefore, building could only be partially represented by these standards. BIM, on the other hand, as the most comprehensive development in AEC/FM, allows for managing building information throughout its lifecycle. However, the focus of BIM is mainly on buildings and it is still immature on representation of geographically extended concepts (like flood). Although efforts has been made to include geographically extended entities in IFC4, the geometry types in BIM cannot support for storage and exchange of spatiotemporal information for flood (those discussed in WaterML in Section 3.2.2). In addition, BIM tools lack spatial analysis capability. These highlight the shortcoming of this standard/technology to perform/manage those tasks that are considered as the major strength in GIS.

Due to the aforementioned reasons and in support of a variety of applications that require both detailed building data as well as the geo-analysis on large-scale and/or outdoor information, sometimes BIM and GIS are combined (Khan et al., 2013). In the next section, an overview of the previous works and techniques for this integration, its applications and benefits are provided.

3.4 BIM and GIS integration

GIS and BIM originate from different domains and were developed for their specific needs. However, with consideration for strength of each, integration of BIM and GIS can create a seamless and scale-independent view of the world across both domains that can benefit a variety of applications that meeting their requirements would not be possible by independent use of BIM or GIS (Amirebrahimi et al., 2015). This integration however is not simple. This is mainly due to the BIM and GIS disparities which are usually discussed in terms of their coordinate system\(^\text{44}\), spatial scale, level of granularity and details in modelling of physical world, geometry representation method (see Figure 3.15), Time scale\(^\text{45}\), storage and access methods as well as the semantic mismatches between them (Van Oosterom and Stoter, 2006; Isikdag and Zlatanova, 2009b; Karimi and Akinci, 2010b; El-Mekawy and Ostman, 2010; Hijazi et al., 2010; El Meouche et al., 2013).

\(^{44}\) Local coordinate system in BIM vs. Geographic coordinate system in GIS.

\(^{45}\) BIM is applied to smaller time scale than GIS that models phenomena that possibly occur for longer period of time.
The abovementioned differences result in challenging integration of BIM and GIS into a singular perspective (El Meouche et al., 2013). However, Van Berlo and De Laat (2010), Isikdag and Zlatanova (2009a) and OGC (2007c) highlighted the benefits of the BIM-GIS integration and opportunities that makes it worthwhile. These include the management of building construction process or other construction types (e.g. bridge, metro, etc), real-estate, emergency preparedness and response, facility management, insurance, security management, urban and landscape planning, tourist and leisure, environmental simulations, seamless indoor/outdoor navigation, training simulation, etc.

Isikdag and Zlatanova (2009a) and Dakhil and Alshawi (2014) discussed the potential use of BIM-GIS integration for damage assessment for different hazards like flood. For example, the semantic information of BIM and geospatial information like flood can be combined and used in geo-analysis in a GIS environment for answering questions such as if the electrical wiring have suffered damage or if wall linings should be replaced.

The previous research (e.g. Isikdag et al., 2008) as well as the review of various attempts for integration between the BIM and GIS in this research show that they generally can be classified into three levels: i.e. application, process, and data levels.

3.4.1 Application level

At the application level, the integration methods use reconfiguring or rebuilding (Karimi and Akinci, 2010b) where an existing GIS (e.g. ArcGIS, MapInfo) or BIM tool (e.g. Autocad Revit) is either modified by software patches or is rebuilt from scratch to support the functions (or data formats) of the other. Examples here include CAD in GIS (e.g. ArcGIS can to read and import CAD formats like DGN and DWG and DXF) or GIS in CAD/BIM software (e.g. AutoCad to read
shapeFiles from ESRI). On the other hand, linking methods such as ArcSDE (ESRI, 2015b) facilitates data transfer between BIM and GIS software by an Application Programming Interface (API) developed on the GIS side.

### 3.4.2 Process level

Process level integration between the BIM and GIS allows for participation of these platforms in tasks that require the capabilities of both, while they remain simultaneously distinct and live in the operation level. OWS-4 project by OGC (2007c) and Lapierre and Cote (2007) adopted the Service Oriented Architecture (SOA) model and created a workflow to utilise BIM and GIS software. Other frameworks were developed for BIM-GIS integration for construction project cost estimation (Park et al., 2014b), selection of the optimise crane locations in the construction site (Irizarry and Karan, 2012) and monitoring of the supply chain (Irizarry et al., 2013). A similar method using semantic web technologies was proposed by Karan and Irizarry (2015) for integrating BIM and GIS for construction management processes. Wu et al. (2014) proposed a BIM-GIS integration for Facility management at a process level via utilising BIM Server and GIS servers and the power of cloud to visualise and report the facility-related analyses outputs. On the other hand, Peachavanish et al. (2006) and Akinci et al. (2010) utilised intelligent automatic interpreters combined with ontologies to break down a particular task into a number of smaller jobs and have these matched with web services from BIM or GIS sides that are later combined in a chain to generate the required result (see Figure 3.16).

Process level integration provides more flexibility than the first group. However, at the process level, the challenges of integration are still to be resolved at the underlying data level to provide interoperability between these systems.
3.4.3 Data level

At the data level, the BIM-GIS integration happens for unifying/combining BIM and GIS data or conversion of one type to another for use in the other or both domains. A variety of methods were developed for this purpose. Similar to the classification in Mignard and Nicolle (2014), the review of literature in this research categorises these methods into

- One-way conversion between BIM and GIS (referred to translation/conversion method);
- Extending standards on either BIM or GIS side to allow for storage of data from the other domain (called Extension method); and
- Two-way communication between the two models using an intermediate tool or model (called Mediation).

Next, the methods in each of these categories are explained and their details are discussed.

**Translation/Conversion**

These models tend to translate/convert one format to another from GIS to BIM or vice versa. Simple methods for translation from CAD/BIM to GIS in the early days included the *ESRI’s Intelligent CAD/GIS Translator* (Maguire, 2003), *DWG (form Autocad Map 3D)* to ArcGIS (El
Meouche et al., 2013), *ArcToolbox Conversion Tools* (ESRI, 2006), and *CAD2Shape 7.0* (Guthrie, 2015). Pure geometry translation between 3D CAD and 3D GIS was performed by Li et al. (2006) with no consideration for transferring the semantics. Wu and Hsieh (2007) also proposed a method for conversion of geometry from IFC to GML data model with consideration for coordinate system transformation. The algorithm only allows for transformation from swept solid geometry to B-Rep from IFC to CityGML and those with CSG geometry cannot be translated. Herrlich et al. (2010) described a mapping between IFC and COLLADA for geographic data visualisation in gaming environment. COLLADA only provides simple semantics (see Section 3.2.4) and although it is useful for visualisation of BIM information (for an example see Shojaei et al., 2014), significant amount of semantics from the IFC model is lost during this transformation.

In addition to the above research, *FME* (Safe, 2013), *BIMServer* (2015) and *IFCExplorer* (FZK, 2012) are tools that allow for conversion from IFC to CityGML. Although in most cases they provide good geometry conversion, Donkers (2013) underlined that none of them can provide a complete semantic conversion of BIM to CityGML.

Lee et al. (2009) provided an integration method between the 3D CAD/BIM information and 3D GIS for facility management. In the proposed method, a plug-in was developed to extract geometry of 3D CAD/BIM objects and store them in an XML file. A manual attribute data entry was designed to store the properties of objects in the XML file. This XML file was then used to feed the information to the 3D GIS software.

Without accounting for semantics, the topological and semantic meanings will be lost in the conversion between the BIM and GIS and there will be a need for data re-entry (Van Oosterom and Stoter, 2006; Lee et al., 2009). Cheng et al. (2015) suggests that for conversion between the BIM and GIS, the mapping between the objects/concepts is necessary. CityGML and IFC were recognised as the most comprehensive standards for exchange of urban (and building) data in Geospatial and AEC/FM domains (refer to Section 3.2 and 3.3). Therefore, they are used as information exchange points between the two domains and the integration of BIM and GIS commonly adopt these standards for conversion (or mapping) purposes. CityGML can also be used as an intermediate model for exchange of unstructured spatial information to BIM models (Cheng et al., 2013). As an example, Nagel et al. (2009) proposed a conceptual framework for this purpose that in the first step, all the unstructured information are converted to CityGML and then by mapping between the CityGML and IFC, the data are transformed for applications in BIM or AEC/FM. No further semantic or geometry mapping details were provided.
Rafiee et al. (2014) provided an automatic BIM-GIS integration method in support of spatial planning in Netherlands. In this method, the geometry and semantic of the building components in IFC are converted to vector GIS format separately using Extract, Transform, and Load (ETL) method and matched using their global identifiers. The model is further georeferenced via employing the latitude and longitude of the IfcSite object in the IFC model. This work provides the conversion of limited types of building components and overlooks their relationships. In addition, the reliability of geometry conversion in this method was questionable.

Isikdag and Zlatanova (2009b) on the other hand proposed a three-phase framework for a unidirectional conversion between the geometry and semantics of IFC (2x3) and CityGML (version 1.0). While the first step defines the rules of conversion for semantic mapping between the IFC and different LoDs of CityGML, in the second step, Model View (MV)\textsuperscript{46} is used for transfer of the required subset of IFC. Finally, the attributes of the IFC are transferred to the CityGML model.

A method for IFC to CityGML geometric and semantic conversion was proposed by Donkers (2013). However, it only focuses on the LoD3 of CityGML which does not consider the interior objects. Cheng et al. (2015) provided a framework for semantic matching between the IFC and CityGML using linguistics and similarity checking between the name to name and/or description of concepts in each model. This method is complex and allows for, as opposed to 1-to-1 mapping in traditional mapping methods, a 1-to-m mapping between the IFC and CityGML concepts. The validation for the framework was performed and illustrated the benefits of the model; however, no geometry mapping or conversion was supported between IFC and CityGML.

On the other hand, Shi and Liu (2014) provided a framework (see Figure 3.17) for fire evacuation and visualisation via integration of BIM and 3D GIS. BIM is used for both fire simulation and visualisation of the indoor environment. The 3D GIS was used for navigation and route finding in the building for evacuation.

\textsuperscript{46} As defined by BuildingSmart, “An IFC View Definition, or Model View Definition, MVD, defines a subset of the IFC schema, that is needed to satisfy one or many Exchange Requirements of the AEC industry.”
Isikdag and his colleagues (Isikdag et al., 2007a; Isikdag et al., 2007c, 2008) provided multiple attempts for the integration between BIM and Geospatial domain at a data layer to facilitate the fire emergency response management. The approach they used was to extract information (geometry and semantic) from IFC using BIM Server API and convert the geometry (CSG and Sweeping, not B-rep) to geospatial info (B-rep) and storing them to a geodatabase using the ArcObjects API. The evaluation of this method by the authors and the community found it inadequate. Isikdag and his colleagues further used Model Views of the BIM according to the required information for the fire emergency response and mapped the MV to the IFC. In this way, the non-geometrical information was extracted on one hand, and then the geometry of the elements (both Swept solid and CSG) was converted to B-rep and the information were then stored in an ESRI Geodatabase in the form of Multipatches.

A semi-automatic ontology-based approach for CAD/BIM-GIS integration was developed by Eldabiry and Osman (2010) on the basis of semantic data wrapping. The model uses ontology to resolve semantic and syntactic discrepancies between different CAD/BIM and geospatial infrastructure information models. The concepts from both domains are wrapped using a developed ontology and based on the semantic hierarchy in the ontology and a matching algorithm, suggestions are made to the user and the best match is then selected. This method was tested for an “infrastructure routing case study” at micro-level to find the best solution for routing the pipes.

**Extension**

Extension methods intend to augment one model via the information requirements from the other for data integration purposes. Van Berlo and De Laat (2010, 2011) highlighted that there is no possibility to integrate the complete IFC semantics into CityGML by default and for this reason,
developed a CityGML ADE called “GeoBIM”\(^{47}\) to transfer semantic IFC data into a GIS context. This work did not contribute to the geometry conversion between IFC and CityGML. On the other hand, the designed model (UML model is illustrated in Figure 3.18) is for LoD3 (Herman et al., 2014) and does not include the semantics for all the building elements (e.g. utilities) and does not allow for representation of the inverse relationships in the IFC.

![Image](http://www.citygmlwiki.org/index.php/CityGML_GeoBIM_ADE)

Figure 3.18: GeoBIM ADE for CityGML (adopted from Van Berlo and De Laat, 2010)

Considering the shortcomings of Van Berlo and De Laat (2011)'s work in accounting for interior aspects, Bleifuss (2008) developed the CAFM ADE for CityGML to extend its LoD4 building model to include more details about rooms and other information that benefit the facility management.

Cheng et al. (2013) developed the Semantic City Model (SCM) ADE for CityGML that for all _CityObject elements, it considers relationships, inverse relationships as well as the property sets. Their method provides a smaller file size and a more complete geometry than Van Berlo and De Laat (2011) and allows for transfer of the inverse relationships. They further extended the method for

\(^{47}\) http://www.citygmlwiki.org/index.php/CityGML_GeoBIM_ADE
conversion of the output LoD4 building information to other LoDs as well. Despite the power of this method, some semantic aspects are still distorted throughout the conversion.

On the BIM side, Zobl and Marschallinger (2008) and Zobl et al. (2011) proposed an extension to BIM (GeoBIM) that in addition to the above-surface objects, includes the spatiotemporal sub-surface geotechnical objects (e.g. soil and rock and man-made ones like tunnels) and their details. The link between the geometry in the 3D geometry-builder software (e.g. AutoCAD or Voxel builder) and the properties associated with the geometries were established at the database level. They highlighted a need for standards for covering natural and technical objects above and below the ground.

Industry Foundation Classes for GIS (IFG) Project (IAI, 2005) was an effort by Norwegian state planning authority that aimed to make it possible to communicate relevant intelligent information from various GIS standards to CAD systems using IFC. IFG is a data model developed for enabling the exchange of GML-based information in the IFC schema (IFG 2008). IFC to GML and GML to IFC conversion was accomplished during the project using IfcXML and GML physical files and Extensible Style Sheet Language Transformation (XSLT). Mignard et al. (2011) provided a similar development to extend BIM to include urban information. They called their semantic model framework, the Urban Information Model (UIM) which allows for modelling of the city information, including urban proxy elements, networks, buildings, etc using ontology. This framework integrates semantic and geometric entities from IFC 2x3 and CityGML 1.0 at the data layer which is the base of the system to work. Semantic graphs in the ontology are used here to define relationships and the context. In this model, definition of topological relations is also possible.

**Mediation**

The mediation approaches of BIM-GIS integration commonly use an intermediate meta-model between the IFC and CityGML. These methods usually intend to provide a two-way transformation method for the exchange of information from GIS to BIM or vice versa. On the other hand, they may adopt a Database Management System (DBMS) for a shared access between BIM and GIS software/tools.

Hijazi and his colleagues (Hijazi et al., 2009; Hijazi et al., 2010; Hijazi et al., 2011) designed and implemented a meta standard, the Network for Interior Building Utilities (NIBU). This model can

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bring together the utility information from IFC and CityGML’s UtilityNetworkADE (Becker et al., 2010) for seamless indoor/outdoor utility management. On the basis of this meta-model, the indoor and outdoor utility network were populated from BIM and GIS and the network analysis was performed (see Figure 3.19) for a variety of use cases (Hijazi et al., 2010).

The Unified Building Model (UBM) (El-Mekawy et al., 2011b) is another effort, which was developed as an intermediate data model for formal mapping and bi-directional semantic conversion between IFC and CityGML using a combination of logical and reference ontologies. This metastandard includes four LoDs (see Figure 3.20) and was designed to address the complex heterogeneity between IFC and CityGML and for applications that neither of IFC or CityGML can support. This model does not contain all the information from IFC and consequently much semantics and building elements (e.g. utilities) are lost during the IFC to UBM translation. In addition, it only integrates the building from GIS and BIM and other geographic information and building elements are not considered.
QUASY (Benner et al., 2005) as a new information model was developed on the GIS side using GML features that focused on the building and the majorly on its geometry aspects. In terms of the semantic complexity, the QUASY model lies between IFC and CityGML. However, it focuses on the building and not its other systems and many concepts of the IFC (e.g. HVAC systems) were considered irrelevant. Similar to UBM, the geographic information like elevation, roads, water bodies, etc were also overlooked.

Van Oosterom and Stoter (2006) discuss that for realisation of the BIM-GIS integration, Database Management Systems (DBMS) can be considered as an "implementation platform". Pu and Zlatanova (2006) attempted to realise this integration at the DBMS level. However, this effort was purely at the geometrical stage. One of the early integration methods was the ProjectWise initiative (Bentley, 1998). This project allowed CAD software alongside with ESRI ArcSDE and geodatabase for storage of CAD data and spatial data together. Another example is the Building LifeCycle Interoperable Software (BLIS) project. In BLIS, ArchiCAD and ArcGIS were used in this database approach to accommodate information such as terrain and roof forms and other structural features simultaneously (Karimi and Akinci, 2010a, p.61).

Li and He (2008) developed a framework for indoor Navigation within a 3D GIS (VEGGIS) (see Figure 3.21) where the required indoor data were imported from BIM and stored along with GIS data in a shared repository for use in the application. As part of this framework, an indoor navigation
ontology was developed that facilitated the automatic extraction of semantic and topological data from the BIM. No further details of integration of BIM with GIS were further discussed.

![BIM-3D GIS integration for Indoor evacuation](image)

**Figure 3.21: BIM-3D GIS integration for Indoor evacuation (adopted from Li and He, 2008)**

Van Oosterom and Stoter (2006) proposed a conceptual framework that uses DBMS as a single point of storage for both CAD/BIM and GIS information. They developed an integrated data model and used a RDBMS approach for its implementation and data management by extending the database spatial types. This work suggested the DBMS, instead of a file-based method, allows for a more efficient integrated management of GIS and CAD/BIM data.

### 3.4.4 Summary of BIM-GIS integration

The combination of BIM and GIS capabilities was highlighted as a solution for different applications that required the capabilities of both. This section summarised a variety of methods at application, process and data level for realising the challenging BIM-GIS integration that each of which can be utilised for particular purpose. While costly restructuring of the applications in the first method and underlying data integration in the second was highlighted as the main challenges in this section, Mignard and Nicolle (2014) discussed that nearly all the discussed proposals for integrating IFC and CityGML at data level led to similar problems which include little/partial semantic information about the building, data loss (semantics and/or geometry) in the transformation process, and lack of management of building and geographical elements in a single model. In addition, the simultaneous semantic mapping and geometry conversion is rarely tackled completely (Cheng et al., 2015). Amirebrahimi et al. (2015) underlined further shortcomings of integrating BIM and GIS at the data level which include the specific focus of methods on

- Particular use cases (e.g. fire evacuation or seamless indoor/outdoor utility analysis) that the included concepts and relationships in them may not suit other applications (with different functional requirements); and
• Overcoming the technical challenges of the integration (e.g. geometry conversion or semantic mapping) and no attention to the actual required functions or data for particular or multiple applications.

Due to these shortcomings, none of the discussed methods in this section can provide an effective integration between BIM and GIS for use in FDA and some issues are associated with the outputs that are highlighted in each work and require further investigation.

3.5 Chapter Summary

This chapter provided a critical review of different technological developments in the Geospatial and AEC/FM domains from data structure point of view to evaluate their potential application for supporting a micro-level FDA on a building that was discussed in Chapter 2. While the formats in the Geospatial domain (GML and particularly CityGML) have limited support for semantics of buildings and its complete geometric and semantic representation and seem more suitable for outdoor and large-scale applications, in contrast, BIM supports for a full representation of the building. However, it has limitations in representation of geographically extended entities (flood for instance).

It was further discussed in this chapter that due to the requirements of certain applications for capabilities of both BIM and GIS capabilities, sometimes these technologies are integrated. However, for a variety of reasons, this integration has not been completely realised and the majority of the attempts are application-specific and not suitable for other applications with dissimilar requirements. In addition, there has been no consideration for flood information in any of the discussed integration methods in this chapter. While the BIM-GIS integration seems to be the most suitable source of data for bringing together a complete representation of the building and flood information (and other data like elevation) to support the FDA on building at a micro level, based on the evaluation in this chapter, none of the highlighted integration methods can be adopted to support this application. Therefore, there is a need for further research for this purpose.

As part of this research, the combined benefits of a suitable BIM-GIS integration method and engineering theories is used to realise a new method for FDA. The method allows the distinct behaviour of a building to be included in the damage evaluation to address the research problem highlighted in Chapter 1. The next chapter will provide the methodology used in this research and explain different steps for achieving its discussed aim.
Part 3: Research
Chapter 4

Research Design & Methodology
4 Research Design and Methodology

4.1 Introduction

While in the previous chapters the foundation of the research, the background to the problem and potential technologies to address the problem were discussed, this chapter provides the details of the adopted research methodology and design to achieve the research objectives put forward in Chapter 1. Research design is an essential instrument to guide one for making decisions through the journey from an initial problem or a [set of] research question[s] to reach a suitable answer or solution for them (Bordens and Abbot, 2008). It is further considered as an indication of the validity of the research process (Klein and Myers, 1999).

This chapter is organised into four parts (see Figure 4.1). The first part presents a conceptual design framework for achieving the aim of the research to address the problem. In the second part, "Design Science Research" as the selected methodology for this research is introduced and its historical development and philosophical basis are explained. This part also highlights the link between the aforementioned framework and this research strategy. The third part elaborates the details of the adoption of the design science method here and justifies the appropriateness of this methodology for this research. Lastly, the overall design of the research and details of different methods adopted for data collection and analysis are presented in this chapter and a discussion is provided regarding how the presented work satisfies the requirements of a good "Design Science" research.

Figure 4.1: The overall chapter structure

4.2 Conceptual design framework

In Chapter 2, the principles of FDA were explained and different methods for assessment of flood damage to a building at micro level were reviewed. According to this thorough review, a number of gaps in the research were identified.
On the other hand, various technical developments in different domains of knowledge and practice were investigated to seek solutions for bridging the discussed research gaps and particularly the final item in the list. An important development that is discussed as a potential technology to facilitate the FDA at a building level is a combined use of BIM and 3D GIS. To recap from Chapter 1, for achieving the aim of the research, the following key questions were put forward:

1. What is the current state of FDA on building at micro-level in the world? And what are the limitations of the existing methods?

2. Can an approach for FDA be designed to support the evaluation of damage to a building by accounting for its unique characteristics and behaviour against flood? How can this framework be designed?
   i. What analytical processes and components are required for this purpose?
   ii. What technical developments can be used to support these identified processes and how? How a suitable method for integration of BIM and GIS can be used within this approach?

3. Can this FDA method overcome the limitations of the existing methods for FDA and provide an effective assessment and communication of flood damage to a building?

According to these questions and the aim of the research, a conceptual design framework was designed to bring together the required concepts and suitable methodologies to develop a new method for FDA according to the benefits of BIM-GIS integration. This framework is illustrated in Figure 4.2. While the research context, problem, objectives and the questions have already been discussed in the previous chapters, the research methodology towards achieving the outcome of the research (the framework for flood damage assessment) is yet to be explained and is addressed in this chapter.

A methodology is defined as "a system of principles, practices, and procedures applied to a scientific branch of knowledge" (Peffers et al., 2008; Bordens and Abbot, 2008). It can provide a process and a mental model for researchers to conduct their research (Geerts, 2011). Peffers et al. (2008) underlined the widespread use of interpretive methods (see Section 4.3) and the shortcomings of their applications in engineering and similar disciplines. The research method adopted in this research is the "Design Science" (Hevner et al., 2004) which in the next section, its historical development, philosophical basis and its process are elaborated and explained in detail.
4.3 Design Science methodology

In the "natural sciences", emphasis and the focus of research is more towards finding the truth about the world and understanding its phenomena by answering the questions like "how things work?" or "why they work in the way they do?" (Geerts, 2011). These research generally follow interpretive methodologies in which the process starts with the problem definition followed by literature review and the development of hypotheses; and furthermore the analysis of the collected data and presentation and discussion of the results. The output of this type of research is mostly explanatory and arguably not suitable for research with applications in other disciplines like engineering, medicine, information systems. This is due to the necessity of research in the artificial (human-constructed) world in these domains for creating or improving artificial solutions and products (Peffers et al., 2008). Simon (1996) discusses that these disciplines are usually covered by "sciences of artificial". The focal point of these sciences includes the identification and testing of the possibilities and design of effective solutions and successful artefacts. The importance of research for such solutions and designs in various fields (e.g. medicine, law, industrial design, engineering, architecture, planning and other technology-based fields) with an explicit emphasis on effective
solutions for application-specific problems underlined the necessity of methodologies for conducting research in these areas (Davenport and Markus, 1999; Peffers et al., 2008; Simon, 1996).

Design Science, as a response to the abovementioned needs, emerged nearly two decades ago. In contrast to natural and social sciences that attempt to understand the reality using interpretive and other research methods, Design Science has become an important methodology for discipline-oriented design or improvement of solutions for human-related problems (Walls et al., 1992). It emphasises on "creation" and addressing questions like "how things ought to be in order to attain goals, and to function?" (Simon, 1996).

The common notion in this methodology is "artefact" which can be social innovations, informational resources, constructs, models, methods, or instantiations (March and Smith, 1995; Hevner et al., 2004). In general, Peffers et al. (2008) discuss that the artefact can be "any designed object with an embedded solution to an understood research problem". In the Design Science, two characteristics of the artefact are important and must be ensured; i.e. rigour and relevance (Geerts, 2011). While rigour indicates that the artefact should be novel, built on the existing knowledge, and present a verifiable contribution, on the other hand relevance implies the application of the artefact to solve an observed problem (Hevner et al., 2004; Hill, 2009). In engineering and its similar fields, these two concepts are not antagonistic and are often pursued simultaneously.

The application of Design Science in Information Systems (IS), engineering, computer science and accounting has been evidently discussed (Hevner et al., 2004; Geerts, 2011). In these disciplines, Design Science provides more flexibility and two major advantages (namely the scope and the artefact) over the commonly used methodologies such as the system development (Burstein and Gregor, 1999) and prototyping (O'Leary, 1988) as instances of action research (Hill, 2009). In terms of the scope, instead of focusing on information systems in those methods, Design Science benefits a wider range of disciplines. In addition, as opposed to only the instantiations, the definition of artefact in Design Science is much broader and includes models, methods and frameworks allowing for more abstract artefacts rather than just working prototypes and instances.

Referring back to Chapter 1, the artefact here is a framework for flood damage assessment; hence, the Design Science can be a good fit for its design. Therefore, this method is adopted in this research. Many research (Eekels and Roozenburg, 1991; Reich, 1994; March and Smith, 1995; Fulcher and

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49 Instantiation refers to "creation of an instance or realisation of an abstract concept or template." (for more details visit http://whatis.techtarget.com/definition/instantiation)
Hills, 1996; Rossi and Sein, 2003; Hevner et al., 2004; Adams and Courtney, 2004; Cole et al., 2005; Peffers et al., 2008) in various domains attempted to provide principles, guidelines and basis for conducting Design Science research and justifying its application. In a relatively recent and well-referenced publication, Peffers et al. (2008) provided the Design Science Research Methodology (DSRM) which includes six activities: i.e. *problem identification and motivation, objectives of a solution, design and development, demonstration, evaluation, and communication* (see Figure 4.3). It involves a rigorous and iterative process for design and evaluation of an artefact for an identified problem and communicating the research outcomes to a range of relevant audiences. Although the steps in the Design Science are normally in sequential order, however, there is no requirement that the process starts from the first step and other activities may be considered as possible research entry points (Peffers et al., 2008). In here, Design Science research methodology and its steps are briefly explained.

![Figure 4.3: Design Science Research Methodology (DSRM) process model (adopted from Peffers et al., 2008)](image)

In the first step, a specific observed or understood problem is defined, its relevance is clarified, and the value of a solution to it is justified. The main questions in here include "*what is the problem?*" and "*Why the current solutions cannot effectively address the problem?*" The answers to these questions are beneficial in two ways: (1) motivation of the researchers and audience to pursue the solution, and (2) clarifying the reasoning associated with the researchers' understanding of the problem (Peffers et al., 2008). Since the problem is not directly and automatically translated into objectives to design an artefact as a solution, it is necessary to define such objectives and criteria for the effectiveness of the solution. The main question in the second step is that "*how should the problem be solved?*" Hill (2009) discusses this step as "suggestion phase" which provides an insight into the solution for the identified problem from other disciplines' point of views. Literature review and obtaining the
knowledge of emerging technologies constitute common instruments used in this step (Geerts, 2011). Once the objectives and the possible solution are identified and formalised, according to the desired functionalities and the knowledge of applicable theories, the artefact is designed and created to solve the problem. Design and development is the core of the Design Science methodology and constitutes its main contribution - the artefact.

Following the design and creation of the artefact, the use of the artefact for solving one or more instances of the problem must be demonstrated. This would be an evidence that the idea of the solution actually works (Rossi and Sein, 2003; Hevner et al., 2004). Simulations, case studies or experimentations are often used as instruments for this purpose (Peffers et al., 2008; Geerts, 2011). Following the demonstration, a formal evaluation of the artefact must be performed to determine "how well does the artefact work?" At the end of this phase, according to the nature of the research, it is decided that whether to iterate back to the design and development phase and try to improve the artefact; or go to the next phase and leave further improvements to the future projects (Peffers et al., 2008). In here, the knowledge of objectives (defined in step 2) and relevant criteria and method for evaluation are crucial requirements (Geerts, 2011). Lastly, the problem and its importance, the artefact, its novelty and application as well as its effectiveness in comparison with the existing method for addressing the problem is communicated to the relevant audience.

Having the process of conducting a Design Science research clarified, the next section intends to explain the specific application of this research methodology for this research.

4.4 Employing Design Science methodology for this research

In this research, the aim is to design a framework for assessment and visualisation of the potential flood damage to a building at micro-level. This research, in contrast to attempting to understand the truth, intends to investigate the design and feasibility of an artefact for a defined problem and therefore it is considered as an "applied research"; therefore, it is suitable target for the use of the Design Science. The selected Design Science model in here is the Design Science Research Methodology (DSRM) which was originally proposed by Hevner et al. (2004). The overall procedure of this model is presented in Figure 4.4. DSRM implements the requirements of the Design Science research - the relevance and rigour - and is built on the basis of two "modes": i.e. design/build and justify/evaluation. The reasons behind the selection of this particular model of Design Science include its maturity and well-acceptance in the research community. Additionally, this model provides
guidelines for an effective Design Science research which can be used for assessing the research (Hill, 2009).

Figure 4.4: The selected Design Research model (modified from Hevner et al., 2004)

As Figure 4.4 depicts, DSRM designs and evaluates an artefact by building on an existing body of knowledge (knowledge base) to address a problem (business needs) raised in an organisation or process (Environment). Prior to explanation and detailing the use of DSRM for this research, it is important here to differentiate possible Levels of Abstraction (LoA) and link them to what this research is attempting to achieve. These LoAs include:

- **Level 0**: to design or adopt a model for conducting the design science research;
- **Level 1**: to design a framework (or tool) that allows for assessment of flood impacts to a building;
- **Level 2**: to design a framework (or tool) for assessment of damage in support of the collective needs of a group of organisations/individuals (e.g. the involved stakeholders in the FRM); and
- **Level 3**: to design an organisation-specific framework (or tool) (e.g. engineers, councils, etc involved in the FRM process).

Having the abovementioned LoAs in mind, the intention in this research is not to address the requirements of a particular organisation (LoA 3) or attempting to consider all the needs of the
stakeholders for assessment of flood damage in the FRM process (LoA2). According to the defined problem in this research, there still exists an absence of a micro-level method for assessment of flood damage to a building according to its unique characteristics and behaviour against the flood actions. Therefore as the first step for achieving LoA2 and LoA3, the purpose in here is to design and evaluate a framework that assesses the impacts of the relevant flood actions to a building and estimate and communicate its physical and financial\textsuperscript{50} damages. The framework defines the process of a micro-level appraisal of damage to a building (LoA1) and mainly provides guidelines as a basis of a decision support tool for the general needs raised previously in Section 2.5. These mainly address the performance requirements of a building against the flood in its design and planning stages. It is noted here that this research is a first step towards the creation of a decision support tool for specific individuals or organisations according to their specific requirements. According to the defined problem and requirements discussed in Chapter 2, the research in this dissertation sets the environment to the design and planning stages in the ”[land] development process” and addresses the first iteration of the overall design science towards the development of an organisation-specific tool for FDA in this process (see Figure 4.5). In this way, future research would be necessary to test the applicability and [minor] modifications to the framework to tailor the framework to the processes within each organisation.

Having discussed the above levels of abstractions and re-establishing the intention and scope of this work in this context, the elements of the Hevner et al. (2004)’s model (LoA 0) is further mapped to this research (LoA 1). Figure 4.5 illustrates this mapping process.

\textsuperscript{50} In this case, financial and economic damage are similar.
4.4.1 Business needs

The business need is a crucial concept in DSRM model indicating the goal of the research and further ensures its relevance. This need is assessed or interpreted in the context of strategies, business processes, culture, etc. According to the drivers of a micro-level FDA framework for building in the "problem domain", the need was highlighted in Chapter 2 that ensures the relevance of the developed framework to the existing gaps in the context of FRM within the [land] development process. However, as Figure 4.5 illustrates, this research only serves the design and evaluation of the framework as the first step; and further investigation for development of the organisation-specific instances and determining how it should be developed and integrated within each organisation's process is beyond the scope of this research. Such investigation requires extensive time and resources to understand the users, their requirements, organisation's processes, technical capabilities (Technologies and Infrastructure) and operating environments.

4.4.2 Knowledge Base

In order to achieve rigour in Design Science research, the knowledge base provides the applicable theories and methodologies; and is sourced from different domains to supply the raw materials for conducting the research towards designing an effective artefact (Hevner et al., 2004; Hill, 2009). The
applicability of various knowledge bases is highly topic-dependant. These knowledge bases may lie in emerging journal articles, conference papers or those well-established books in the "reference domains", and/or even discussions with practitioners.

The adopted knowledge from the reference domains in here include the technical developments in Geospatial and AEC/FM domains and knowledge of various BIM-GIS integration methods, Australian Standards documents, geospatial information analysis methods and civil engineering theories like Assembly-based Vulnerability (ABV), materials science, FDA-based literature, etc. These in addition to the methodologies for data collection (e.g. interview), data analysis, and validation and verification approaches form the knowledge base and the fundamental ideas and methods for the design and evaluation of the framework in this work.

4.4.3 Develop/Build

As discussed earlier in this chapter, for a research to be considered as Design Science, its output should include a designed and evaluated novel artefact that is cumulative in its nature, meaning that it should be built using an existing knowledge base and contributes back to it (Hevner et al., 2004). In this research, a variety of previously developed technologies and their application extension to the FDA domain is used. In this way, the aforementioned criteria - to be both cumulative and novel - are met to satisfy a Design Science research (see Section 4.6).

As explained in Section 4.4.1, the intention in this research is not to design an instantiated product for an individual or group of practitioners or organisations, but a generic FDA framework that can potentially be adopted in the [land] development process in flood prone areas. Accordingly, the design/build component in this research involves

- Synthesising a large body of knowledge from various disciplines to understand and calculate the effects of flood on the building
- To design an effective information basis for integration of various data from different sources for the analysis purpose
- Putting together all the required components in the body of a framework

It is important in here to emphasise on the advantage of the selection of the Design Science over the prototyping and system development methodologies (as instances of action research). Since in this research, the framework is not an instantiation and is not directly linked to the requirements or
processes of any organisations, therefore the "intervention" of stakeholders during the design course and the reciprocal effects are not required to be investigated. These steps constitute the inevitable phases of the action research methodologies and would be the limiting factors for this research, if they were adopted here. Therefore, the suitability of the Design Science method for this research is further justified.

4.4.4 Justify/Evaluate

Once an artefact is designed/built, to ensure that it would be effective in practice (relevance) and contributes back to the knowledge base (rigour), a formal evaluation process must be undertaken. The evaluation not only should check that if the artefact generates either qualitative or numerical outputs, but also must generate confidence in its users regarding the reliability of its outputs (Hill, 2009). Recalling from the highlighted intention of this research to design a framework at LoA 1, the evaluation does not include all the individuals and organisations in the design and planning process, but focuses on (a) testing the feasibility of implementation of the designed framework and its demonstration and (b) its verification and validation. These two tests are simultaneously required for the framework to address the research problem and to contribute to the FDA and FRM body of knowledge. The details of this phase will be discussed further in Section 4.5.4.

Having the adoption of DSRM for this research explained and justified, in the next section the details of the research design are presented.

4.5 Research design

According to the specific adopted model of the Design Science methodology (see Section 4.4), as Figure 4.6 illustrates, the research design in here consists of five phases: i.e. Conceptual, design, Development, Evaluation, and synthesis and communication. These phases are discussed in more detail in the next subsections. Figure 4.6 also provides the linkages between the research phases, objectives and the chapters of this thesis.
4.5.1 Conceptual Phase

In the conceptual phase a number of activities are undertaken to form the knowledge base as a basis for the design of the artefact in this research (see Section 4.4). These activities include:
• review of various concepts and methods in the "problem domain" (in Chapter 2 to address the research objective 1[a]) to identify the gaps and also to investigate those criteria required for evaluating the artefact in this work;

• investigation of the potential "reference domains" and technical developments in them (in Chapter 3 to address the objective 1[b]) that contribute to partial development of the overall knowledge base in this work;

• identification of damage mechanisms to a particular building type\textsuperscript{51} and the susceptible building components to different flood actions (to address the objective 2[a]). This activity is followed by the investigation of potential analytical methods for assessing the physical damage to various key building components and identification of the most suitable ones for this purpose (Objective 2[b]);

These activities in the conceptual phase are undertaken mainly based on a qualitative review and the assessment of existing body of knowledge using literature review.

**Literature Review**

Literature review is a major contributor to the majority of conducted research in the world and can be either "narrative [or traditional]" or "systematic" (Cronin et al., 2008). Where narrative literature review intends to summarise a body of knowledge and drawing one or more conclusions from it, the systematic type targets a specific subject area for a more rigorous and well-defined review of the field. Cronin et al. (2008) discuss that the systematic method should cover all the most relevant literature and resources to a specific area and for a particular purpose. It usually defines inclusion criteria for the reviewed literature and exclusion factors for those that were overlooked.

In Chapter 2, a narrative literature review was utilised in the problem domain (FDA) and the other important overlapping body of knowledge in the field of flood risk management. As presented in Chapter 2, the conclusions included a number of research gaps that formed the overall basis of this research. Similarly in Chapter 3, the narrative literature review was adopted for a qualitative assessment of a wide range of technical developments in two major reference domains, the Geospatial and AEC/FM domains. The sources for the literature review in these chapters covered primary, secondary, conceptual/theoretical and anecdotal discussed by Colling (2003). They included relevant

\textsuperscript{51} The building type and justification for its selection is provided later in this section.
books, journal articles, conference papers, organisation reports, the standards as well as the other published information on the Internet.

In contrast to above review of literature, a further systematic review of existing knowledge was undertaken (see Chapter 5) to understand the possible damages (what damages and how) to a specific building type and its components.

Similarly to the abovementioned third activity, a systematic literature review was used to assess and identify suitable analytical methods for assessment of damage to each important susceptible component of the building (see Chapter 6). The resources used in the literature search included all those relevant resources providing information about possible impacts of a flood to one or more assemblies or evaluation of damage to them. The scope of literature search spanned across various domains; i.e. FDA, civil engineering, material science, guidelines for construction in flood prone areas, Australian standards, etc. Due to the limited resources and time provided for this research, an in-depth investigation for all literature around the world was not possible; therefore the balance in the review was maintained only by focusing on relevant and important resources according to the researcher judgement. Such judgement was developed over time and based on the experience and knowledge acquired prior to and throughout the fundamental phases in this research. As for exclusion criteria, the irrelevant sources and those published in other languages than English were excluded in the literature search.

**Justification of the building type**

According to the previous investigation by Geoscience Australia (Maqsood et al., 2014), there are 19 different building types in Australia which are generally divided according to a number of factors including the construction type, number of stories, etc. As discussed in Chapter 2, each building type may have different mechanisms to resist against flood parameters and can be damaged differently. The time and resources allocated for this PhD research however were not adequately sufficient for covering all building types and their details. Therefore, the decision was made to limit the scope of the research to the most common type. HNFMSC (2006) - as the basis for many planning schemes in New South Wales and also one of the important documents referred in Building Code Australia (BCA) - discusses a detached single-storey brick veneer house with slab-on-ground foundation as the

52 A one storey brick veneer house with slab on ground and integral garage (justification of this building type is provided later in this section.)
most common Australian building type. This claim is also supported by early research (e.g. Gad, 1997) and discussed by Sargent (2013) and Australian Bureau of Statistics (ABS).  

For evidence-based adoption of this building type, a methodology was designed which involved the investigation of building types in the flood prone Local Government Areas (LGA) in the most populated regions of Australia, including Victoria, New South Wales and Queensland (that together contain over 70% of Australian population). Contacting each LGA in these states to confirm their most common building type was extremely difficult and time consuming. Also, as the data collection in different councils may vary markedly, the acquisition of a consistent range of building/house information across these areas and LGAs would be cumbersome (Mason 2012, Personal Communication). For this purpose, the information about the flood hazard (both historical floods as well as the planning overlay maps for "Land Subjected to Inundation") could be accessed and were utilized and overlaid with the local councils in GIS software to narrow down the search to find those suburbs and LGAs in risk of flood to investigate the most common types of buildings (see Figure 4.7). As this research focuses on the urban context, the major metropolitan areas in these states (namely Melbourne, Brisbane and Sydney metropolitan areas) were considered.

![Figure 4.7: Offsetting design flood overlay with the LGA information for Melbourne metropolitan area](http://www.abs.gov.au/AUSSTATS/abs@.nsf/0/CD4A162A384B48B8CA25750E00108550?opendocument)

![Figure 4.7: Offsetting design flood overlay with the LGA information for Melbourne metropolitan area](http://www.abs.gov.au/ausstats/abs@.nsf/mf/3101.0)
To identify the most common building types, the National Exposure Information System (NEXIS) by Geoscience Australia was used. NEXIS (Geoscience Australia, 2014) is a publicly available resource and provides a comprehensive information about the building types at LGA and Statistical Local Area (SLA) levels. NEXIS data are collected by GA from local governments and is updated every year (Wehner, 2012, Personal Communication). Therefore, it seems to be a useful and reliable source for this investigation.

According to the analysis of NEXIS data for Victoria, NSW and Queensland, it was concluded that brick veneer, double brick, and timber houses constitute the most common construction types. Further investigation, as Figure 4.8 illustrates, shows that the one-storey detached unreinforced masonry\textsuperscript{55}-veneer house with slab-on-ground foundation type is generally the most common current Australian building type. For this reason, this type was selected and mainly focused in this research.

Although, the construction type, number of stories and the attached/detached factors are illustrated separately in Figure 4.8, the investigation included simultaneous statistical analysis of all these factors and the above conclusion was drawn by combining them.

\textsuperscript{55} Brick masonry
4.5.2 Design Phase

In this phase, according to the synthesis of the knowledge acquired during the conceptualisation phase, different theories and methods (artefacts) were adopted (or developed if no previous method existed) and by logical integration and linkage of these components, the framework was designed.

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56 The horizontal axis in these charts represents the LGAs in Victoria and Queensland.
The designed framework mainly illustrates the damage assessment process (see Chapter 7) to address the objective 2[d] of the research.

In addition to the framework, a new BIM-GIS integration method was designed for addressing the highlighted challenges of the data inputs for the FDA in Section 2.8. This new integration method is realised at a data level and for this purpose, the "Data Modelling Cycle", a common methodology for design of data structures/models, was adopted (Teorey et al., 2011). This methodology as Figure 4.9 illustrates consists of five main steps. It commonly starts with the mapping of the real world concepts and their relationships to a conceptual model. Via undertaking the required steps in the "Business Analysis" process, the concepts and their relationships in the model are identified using a variety of data requirement gathering methods like survey, interview, review of relevant previous publications, etc. The conceptual data model is further translated to the logical data model defining the structure of the database. The last step in the process involves the development of a physical data model and its implementation (Elmasri and Navathe, 2011).

![Figure 4.9: Data modelling process for this research (modified from Teorey et al., 2011)](image)

4.5.3 Development Phase

Subsequently to the design phase, the design of the framework is used to build a prototype system for detailed micro-level FDA on a building. This implementation addresses the third objective of the research.
Since a prototype in this research is an information system, other research methodologies like system development and prototyping can be used as part of the overarching Design Science. In the prototype development, as Olfat (2013, pp 102) explains and it is illustrated in Figure 4.10, first the system is designed according to the developed framework in the previous phase. Subsequently the system architecture is presented and refined via simultaneous consideration for alternative designs. Finally, the prototype system is built using appropriate technologies. Although, testing the usability of the prototype should be included as a part of prototyping and/or system development process, it is not included in this research since the prototype (in a case study) in here is only for demonstration of the feasibility of implementing the framework and not testing it. The formal evaluation of the designed framework, as the main artefact of this research, will be performed later in the evaluation phase. The details of the implementation of the prototype will be explained in Chapter 8.

Figure 4.10: Schematic flow of the adopted tasks in prototyping methodology (modified from Nunamaker et al., 1990-91)

4.5.4 Evaluation Phase

As previously discussed, the Design Science methodology requires a demonstration of the designed artefact to answer questions like whether the solution actually works or not. Although in the Design Science the demonstration of the framework is formalised prior to the evaluation of the framework (see Figure 4.3), these phases are conceptually merged together in this research to evaluate the
framework. Therefore, the evaluation phase of the Design Science in here is redefined (see Figure 4.6) as a twofold process:

- demonstration of the framework to answer the question of feasibility of its realisation; and also to assess if the solution actually works for real life situations; and
- Formal validation and verification of the framework.

To address the first point, a case study method was used and the prototype system was employed to assess the damage to a building from a real design flood. In a complementary way, to formally validate and verify the framework, expert opinion was used along with a structured face-to-face interview. These two processes are explained in more detail in the next sub-sections.

**Case Study**

The case study demonstrated the power of the framework to assess the potential damages to a building in a real case situation. This study is an "instrumental case study" and in contrast to explanatory and exploratory types, it intends to provide a supportive role to refine the theories proposed in this research and demonstrate the proposed framework (Baxter and Jack, 2008).

➢ **Case study Selection**

The selected study area in here is the Maribyrnong council in Melbourne, Australia (see Figure 4.11[left]). This council was chosen due to its accessibility and also a number of other factors which are explained here. According to the literature, this council has been seriously affected by floods in 1906, 1974, 1983, 1987, 1993 and 2011. The 1974 flood with approximate severity of a 1-in-100-year event inundated over 370 buildings and caused over $16.5 million in 1974 dollars in economic damage (SES, 2012a). This council is still at the risk of flood (Pykoulas57, 2013, personal communication) and this is illustrated in the output of study by Melbourne Water in the area (see the highlighted flood risk area in red in the Figure 4.11[right]). On the other hand, the survey of 282 buildings in the case study area also showed a similar trend in the investigated NEXIS database and over 40% of the buildings included brick-veneer houses/buildings. Therefore, the area was considered as a good fit for this research and was selected.

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57 The emergency manager of the Maribyrnong council at the time of this study.
The study was undertaken in collaboration with the council and the Melbourne Water, the floodplain management authority in Melbourne metropolitan area. The interests of Maribyrnong council and Melbourne Water in the study and also their willingness to provide the required data for the study constitute further reasons for this area to be chosen.

**Case study data collection**

Once the area was selected, the required information for the case study was collected. In addition to the GIS information (including the contour elevation, roads, building footprints, building values, council open areas, rivers, etc.) provided by the council, a building of the selected type (see Section 4.5.1) was chosen for assessment of its potential flood damage. For this purpose, after an investigation in the area and the selection of a flood prone site, the relevant documents for issuance of building and planning permit were provided by the council for a proposed building and according to the specifications requested. Referring to the request of the council and privacy concerns, the location of this building is not presented in this research.

In addition to the building data, as discussed in Chapter 2, flood information was also required to complete the case study. The raw information for conducting a flood simulation (including boundary conditions and also a reference flood study) was requested and received from the Melbourne Water based on their previous investigations in this area.

To adopt a flood simulation tool, according to the review of literature, a number of candidate software packages were identified. Amongst them, 2D simulation packages were specifically focused due to their consideration for the effects of obstacles on the flood path (to provide more realistic velocities around houses). Amongst a variety of 2D methods discussed by Neels and Pender (2010), according to a number of selection criteria such as accessibility to the software, popularity and acceptance, and also costs involved in its acquisition, the MIKE 21 simulation tool (DHI, 2015) was chosen and used in this research.

Although the implementation of the framework can to some extent indicate a level of its logical validity, yet further formal evaluation of the framework was considered to detail its validity and reliability and will be discussed next.
Model Validation and Verification

Model verification and validation are two essential phases in the development of any simulation model. They confirm the usefulness of the model to be accepted for decision making (Macal, 2005). While verification ensures the completeness and correctness of the model, validation establishes its credibility for determining the degree that it can reasonably represent the real world (MITRE, 2014). In here, different methods for validation and verification are discussed.

Methods for Validation and Verification

Macal (2005), Law (2008), Merz et al. (2010b), Eddy et al. (2012) and Meyer et al. (2013) discuss a number of methods for validation of a designed model. These methods include external validity (using historical data), predictive validation, comparison of alternative models (or cross validation), face validity, and the parameter validation (or internal validation). These methods are presented and explained in Table 4.1.
Table 4.1: Model validation methods

<table>
<thead>
<tr>
<th>Validation Method</th>
<th>Description</th>
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<tbody>
<tr>
<td>Validation using empirical data</td>
<td>In case of existence of empirical data (historical), some of this data can be used for developing and testing the model and the rest can be used to determine if the model can predict this data. This method also discussed in Meyer et al. (2013) as &quot;cross sampling&quot;.</td>
</tr>
<tr>
<td>Predictive Validation</td>
<td>In this validation technique, the predictions of the model and the behaviour of the real world system are compared to validate the model. The behaviour of the system can be obtained from lab experiments or field tests.</td>
</tr>
<tr>
<td>Comparison to alternative models</td>
<td>In this method, the result/output of the model is compared with the results of one or multiple validated models. Eddy et al. (2012) refers to this method as cross validation.</td>
</tr>
<tr>
<td>Face validity</td>
<td>The validity of the model is checked via asking experts or other knowledgeable individuals if the model can reasonably describe the behaviour of a real world system. Expert intuition used in here to validate the model. It is discussed that whilst the components of the model are theoretically sound and can produce reasonable results, therefore the overall output will also be reasonably correct to be used as decision support.</td>
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</tbody>
</table>
| Parameter Variability (Sensitivity Analysis) | In this validation method, the value of the inputs and internal parameters of the model are changed to investigate the change in behaviour of the model. In this way, those parameters that cause significant change in the model's output are identified. Therefore, their use in the model for simulation can be used with caution or more accurate data for them to be considered.  
Sterna (2012) discusses that the analysis of the potential uncertainty sources can be adopted as an alternative validation method instead of the absolute technique which is the most common one. |

On the other hand, model verification is a process for ensuring that the calculations are properly implemented according to the model/framework's specifications and if the model does what it is indented to do (Macal, 2005). There are generally two steps for verification: i.e. checking and verifying the process and equations in the model, and checking their implementations (Eddy et al., 2012). Different model verification strategies have been proposed in the literature which are highlighted by Macal (2005) and Eddy et al. (2012). They may include

- developing an up-to-date documentation of the computer code;
- conducting structured walk-through (or one-step analysis)\(^{59}\);
- comparing the model results with hand calculations;

\(^{58}\) Also known as "Absolute model validation" method (Merz et al., 2010b)  
\(^{59}\) Explaining the model and its processes to other individuals or groups. Model verification using one-step analysis is similar to the validation method using expert intuition (Macal, 2005).
• sensitivity analysis (parameter analysis);
• trace analysis, model simplification;
• making the models deterministic;
• tracing;
• animation; and
• explaining the process and code by the programmer to others;

Verification is a safety check for making sure that there are no unintentional errors in the model development and implementation. The choice of method is directly related to the complexity of the model/framework under investigation (Eddy et al., 2012).

Selection of the validation and verification methods

According to the assessment of possible alternative methods for validation (see Section 4.5.4), "Face Validity" technique was selected for this research. The main reasons behind the selection of this validation method include

- The inaccessibility of comparable and reliable empirical damage data that could match the assumptions in the framework;
- Insufficient resources and time for undertaking a full-scale laboratory experiment discussed in predictive validation method; and
- Inability of previously validated FDA models to provide a comparable level of details of damage with the proposed framework.

In this way, the face validity using expert opinion seems to be a reasonable choice to validate the process of development of the framework. This can also help the model verification according to the aforementioned "one-step analysis" technique that uses expert judgment for this purpose.

The face validity method is subjective, and to perform a validation using this technique, four aspects of this method must be addressed (Eddy et al., 2012):
Problem formulation\textsuperscript{60}: to check if the context, outcomes, and time horizon of the model correspond to those of interest;

Model structure: to check if the model covers all the aspects of the reality that are important in the view of the expert and if the model processes are consistent with the theories in the FDA or engineering fields;

Data sources: to check if the best available data sources were used in the model; and

Results: to check if the predictions of the model match the expectations of the expert and if not, whether they can plausibly explain them.

These factors allow for a multifaceted validation of the framework. As illustrated in Table 4.2, it is assumed that if the components of the framework are theoretically sound and tested to produce reasonable results, the overall output would also be reasonably acceptable to be used as decision support.

On the other hand, two complementary methods were selected to verify the framework. In the implementation of the framework, the developed modules and calculations were compared with hand calculations and modifications were made to the code [wherever required]. On the other hand, a one-step analysis (structure walkthrough) was undertaken as part of the validation process to verify the correctness of the structure, logic and processes of the framework from the expert point of view.

\textbf{Validation process}

The adopted validation technique, the face validity, requires collecting and the synthesis of the expert opinion about the framework and regarding different abovementioned aspects of the artefact; i.e. the formulated problem, model structure, data sources, and results. Therefore, a suitable data collection method is required for this purpose. The selection of this method is explained next.

\textbf{Selecting the data collection method}

For obtaining the opinion of the experts regarding the framework, amongst the alternative methods (e.g. including case study, observation, paper- or web-based surveys, focus groups, etc.), a structured face-to-face interview was chosen. Interview is a suitable method for "exploring the views, experiences, beliefs and/or motivations of individuals on specific

\textsuperscript{60} This has been previously addressed in this research in Chapter 1 and also chapter 2.
"matters" (Gill et al., 2008). It is also beneficial for the purpose of evaluation in this research because

- It allows for direct presentation of the structure of the framework and the underlying processes;

- It includes an interactive conversation and engagement with the interviewees that allow for capturing their responses in a greater way than other methods (and in particular survey method);

- It ensures that the selected experts actually respond to questions;

- It is less susceptible to low-response risk associated with questionnaire method;

- It allows for tailoring the questions to individual interviewees in order to capture their unique experiences.

In addition, due to the complexity of the framework, additional information (e.g. examples for the question) can be provided to the interviewees on the spot. Due to these reasons, a structured face-to-face interview was adopted as the main data collection method in here.

### Selecting the participants

For validation of the framework, the best group amongst the potential experts include the engineers and are selected here. The major drivers behind this selection include

- Expertise/experience in design/approval of building (in particular for flood-prone areas);

- Knowledge of structural and non-structural elements of the building and potential response of elements under loading; and

- Understanding of the technical language for calculations of [flood] actions on various building components.

In here, various types of engineers were selected for validating the model. They include:

- **Engineers in engineering/design firms** with experience in design of the particular building under investigation in this research;
• **Building Surveyors** with experience in approval of buildings and specifically in flood prone areas;

• **Researchers** with relevant experience in flood/structural-design engineering; and

• **Geoscience Australia's personnel** for their knowledge of potential damages to various building types. Geoscience Australia's vulnerability section has a long tradition in developing building-related damage curves in Australia according to empirical or synthetic methods.

To be considered as relevant, in the selection of the potential interviewees, it was assured they have relevant qualifications and sufficient years of experience. This criterion was incorporated in the selection of the interviewees/experts for validation of the framework. The experience and also the diversity of the interviewees' background provide an unbiased and rich feedback for validation purpose.

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**Sampling**

In this study, since the purpose is to collect experts' opinion, amongst various sampling methods discussed in the literature, a combination of non-probabilistic "expert sampling" and "purposive (judgmental) sampling" was adopted (Kumar, 2010). This combined method advises targeting (1) those who are likely to possess the information required and are willing to share it and (2) known experts in the field or those who can demonstrate the knowledge to be considered as experts. Once the participants were identified, their consent for participation is obtained and subsequently the data collection is performed on an individual-basis.

The choice of the number of participants was made with consideration to the concept of "point of saturation" where the heterogeneity of the responses becomes insignificant amongst the participants and although provide new data but diminishing returns (Mason, 2010). This is discussed to be related to the following (Ritchie et al., 2003):

• heterogeneity of the population;

• the number of selection criteria;

• extent to which 'nesting' of criteria is needed;

• groups of special interest that require intensive study;
Research Design and Methodology

- multiple samples within one study;
- types of data collection methods use; and
- budget and resources available.

○ Design of questions

For the purpose of the structured interviews, a questionnaire containing a mix of close- and open-ended questions was designed. In the questionnaire, the total of 8 qualitative and quantitative questions (sub-questions were added if necessary) were included and designed to cover all the discussed aspects of the face validity technique in Section 4.5.4 (e.g. problem formulation, structure, data inputs and results). A reference copy of the questionnaire to support the interview process is provided in Appendix 6.

In addition to the questionnaire, a presentation was prepared to detail the framework and its various aspects that the experts' comments were required for their validation. The questions were asked whenever required during and/or following the presentation.

○ Refinement of the questions

Before conducting the interview, the questions were internally evaluated against the objectives of the research and the requirements of the face validity technique. The interview content and the questions were discussed with the members of the Centre for Disaster Management and Public Safety (CDMPS) and also the Centre for Spatial Data Infrastructures and Land Administration (CSDILA) in the Department of Infrastructure Engineering at the University of Melbourne. The evaluation took place in a number of rounds and at each step, the feedbacks were collected and refinements of the interview questions were made accordingly.

4.5.5 Synthesis and communication phase

In the final phase, the synthesis and communication simply covers the outputs including the findings, prototype system, dissertation, publications and presentations from this research.
4.6 Assessment of the research design

A crucial question in each research is related to the quality of the work (Hill, 2009). The nature of the answer to this question is subjective, hence Hevner et al. (2004) developed a number of general guidelines (see Table 4.2) for assessment of research that uses the Design Science methodology.

For each guideline given in Table 4.2 a discussion about how this research met the criteria put forward for the Design Science is presented in the third column. According to the responses to them, one can conclude that all these criteria were met in this research and therefore, it can be considered as an effective and successful Design Science research.
Table 4.2: General assessment guidelines for Design Science Research (the left two columns) and the discussion on how this research meet these criteria (right column) (Hevner et al., 2004)

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Description</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design as an Artefact</strong></td>
<td>Design Science research must produce a viable artefact in the form of a construct, a model, a method, or an instantiation.</td>
<td>The micro-level FDA framework developed during the design and development phases in this research meets the defined criteria in this guideline. It is an abstract artefact that allows for the assessment of flood damage to a building.</td>
</tr>
<tr>
<td><strong>Problem relevance</strong></td>
<td>The objective of Design Science research is to develop technology-based solutions to important and relevant business problems.</td>
<td>As highlighted in the Chapter 1, the designed framework bridges a research gap that despite the current need for FDA on building and micro level (from literature and the industry-based meetings during this research), none of the current methods can support such analysis.</td>
</tr>
<tr>
<td><strong>Design evaluation</strong></td>
<td>The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.</td>
<td>In addition to its formal verification and validation using expert opinion, the framework was also evaluated using a case study and real data and in a real scenario.</td>
</tr>
<tr>
<td><strong>Research contribution</strong></td>
<td>Effective Design Science research must provide clear and verifiable contributions in the areas of design artefact, design foundations, and/or design methodologies.</td>
<td>This research responds to a clear identified gap (see Chapter 2) and attempts for filling it via adoption and integration of a range of suitable technologies and research methodology.</td>
</tr>
<tr>
<td><strong>Research rigour</strong></td>
<td>Design Science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.</td>
<td>This research was well founded by the literature from various domains (including flood damage assessment, civil engineering, geomatics, and hydrology as well as the information systems) for understanding the needs and the existing body of knowledge (knowledge base). This research integrated a variety of technologies into a single framework and extended new horizons for their applications that were never considered before.</td>
</tr>
<tr>
<td><strong>Design as a search process</strong></td>
<td>The search for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment.</td>
<td>In this research, the artefact was designed and implemented via integration of existing and justified technologies to meet the defined criteria in the aim of the research to facilitate, although adoptability is left to future research, the discussed applications in Section 2.5 according to the set scope and explanations in Section 4.4.</td>
</tr>
<tr>
<td><strong>Communication of research</strong></td>
<td>Design Science research must be presented effectively both to technology-oriented as well as management-oriented audiences.</td>
<td>The progress as well as the outcomes of the research was communicated to industry and academic bodies via publications in a book and a number of journal and conference papers. In addition, in multiple occasions the applications of this research was informally discussed with the potential users. As discussed previously in Section 4.4, a formal investigation of the applications should be addressed in future research.</td>
</tr>
</tbody>
</table>
4.7 Chapter summary

This chapter detailed the overall research strategy and design employed in this research. It described the designed conceptual framework to address the research questions and the identified problem during the conceptualisation phase. Furthermore, the selected research methodology, Design Science, was discussed in detail and its suitability for this research was justified. On the basis of the DSRM method, the mapping of different aspects of this model to the objectives discussed in Chapter 1 was explained and according to this foundation, the research design was prepared and described. The research design here consists of five main phases; i.e. conceptual, design, development, evaluation, and synthesis and communication. The details of these phases and methods employed for completing each were presented. As part of the design phase, an additional methodology, the Data Modelling technique, was adopted and explained. Moreover, two evaluation methods - case study and face validity - were considered and justified amongst the alternatives. The face validity used face-to-face interviews to obtain expert opinion regarding different aspects of the designed framework.

Having the research path clarified in this chapter, the next chapter presents the remaining activities in the conceptual phase of this research and investigates the possible adverse impacts of flood actions on the selected building type.
Chapter 5

Building Vulnerability
5 Building Vulnerability

5.1 Introduction

This chapter intends to present the acquired understanding of the flood vulnerability of the building and its components. As discussed in Chapter 4, for designing the framework for damage assessment on a building this understanding is crucial. Deriving from the existing knowledge in the literature review and further investigation with experts, the vulnerability of buildings and their component to riverine floods are explored and discussed. Furthermore, following the provision of a summary of these vulnerabilities, this chapter scopes the investigation of damage to some typical buildings in this research (which will be discussed in Chapter 6) and justifies the selection of the relevant flood actions and building components.

5.2 Brick Veneer slab-on-ground building

The unreinforced single storey masonry (brick) veneer building, also known as "light framed construction", is the most common building type for residential and some light commercial construction in Australia (see Section 4.5.1). The popularity of this construction type is due to its advantages over the other construction types in terms of cost-effectiveness, quick construction process, thermal efficiency, strength and durability, appearance, acoustic performance, fire resistance, maintenance costs, and flexibility of wall design (Irving, 1985; Beall, 2003, pp 326; HNFMSC, 2006; Paton-Cole, 2014). The major components of this building type include the structural and non-structural elements in the veneer wall system, roof, flooring, internal linings and finishes, and its foundation.

As illustrated in Figure 5.1, based on the Australian and New Zealand design standards and also according to the International Building Code (IBC, 2006), the external walls in this construction type are composed of a system of flexible structural load-bearing backup frame and a cladding masonry leaf which are connected using wall ties across the cavity with minimum prescribed width of 25mm-40mm or more (AS3700, 2011; AS4773.2, 2010). This cavity is usually ventilated using the weepholes, air bricks and other devices to allow air circulation between the inside and outside of the cavity. The cladding is considered as a non-structural component supporting only its own weight. In Australia, the cladding is commonly constructed from a single leaf unreinforced masonry (URM) with clay materials (Thurston and Beattie, 2008). The brick cladding is slender and has little tensile strength which makes it vulnerable to lateral loads. Therefore, the frame, normally made of either
Building Vulnerability

timber or steel elements, is designed to support the external cladding from the lateral loads (e.g. from wind and earthquake). These loads are assumed to be transferred from cladding to the frame via "brick ties" (Yi et al., 2003). The wall is usually completed with an insulation component and a plasterboard lining as its internal finish (HNFMSC, 2006; Sargent, 2013). Although the plasterboard linings constitute non-structural members in this complex wall system, yet it has been reported that they can provide some limited structural support to the frame against the lateral loads (USACE, 1988; Paton-Cole, 2014, pp 23).

Figure 5.1: Typical Brick veneer system with timber frame construction (left); elements in the external veneer wall (middle); cross section of brick veneer wall system adopted from Australian Standard AS3700 (2011) (right)

The frame can be considered as the most important component in a veneer system determining the overall response of the brick veneer house against the external loads. The frame is a load-bearing component in this system and according to the AS1684 (2010) it is designed to transfer permanent and imposed vertical and horizontal loads from floors or roof to the foundation. A typical load-bearing wall frame, as is illustrated in Figure 5.2, consists of wall studs (common or jamb), plates, nogginings, top and bottom plates, lintel, and sheet (or panel) or diagonal (also known as cross or x-) bracing. These elements and also the mechanical connections linking them together in the load-bearing system play a crucial role in assuring a successful load transfer (Becker et al., 2011).

The roof structure in this type of construction is normally built using trusses covered by either steel sheeting or concrete/terracotta roof tiles. The roof timber structure is highly stiff and in case of lateral loads and via accounting for the roof bracing, it is generally assumed to provide diaphragm effect to transfer the imposed loads (Paton-Cole, 2014, pp 24).

On the other hand, the foundation types commonly used for brick veneer construction include either slab on ground (e.g. stiffened or waffle raft foundation) which is normally a reinforced concrete slab directly on the bed soil (or fill), or the "suspended floor system" which comprises of piles/stumps, a floor and sub-floor components. In Australia, these foundations are commonly designed according to the guidelines provided by the Australian Standard AS2870 (1996). In this research the focus is on slab on ground foundation and the suspended floor is considered outside the scope. As Figure 5.3 illustrates, in this foundation type the slab is connected to the frame via bolts and possibly other connection types. Due to the nature of the slab-on-ground construction, buildings of this type generally do not include basements.

The past floods in Australia have exposed the vulnerability of the brick veneer structures. For example, the post flood survey of Brisbane flood in 2010-2011 by Emergency Architects Australia (EAA, 2011) illustrated the significance of the damage to the slab on ground brick veneer houses in comparison with other building types. The typical design of brick veneer dwellings with plasterboard internal wall lining is not resilient to floodwater impacts and as discussed by Sargent (2013) it can be severely affected even at shallow immersion depths. Their popularity in the community as well as the tendency of designers towards this type of construction underline the existing and increasing level of
vulnerability of the community to floods and there is an urgent need for better understanding of these vulnerabilities (and consequently the damages) and finding solutions for them. In the next section, a thorough discussion around the potential flood damages to this type of house and its components are provided. These damages are discussed as an interaction of building components and the previously explained flood actions (see Table 2.6).

5.3 Vulnerability of buildings and resulting damages from floods

According to Chapter 1 and Chapter 2, the presence of particular flood actions is highly related to the type of flood. Irrespective of whether the flooding is as the result of storm surge of a hurricane, riverine overbanking or from failure of an artificial hydraulic system (e.g. dam), the impacts on residential buildings share many common structural concerns (Jordan and Rogers, 2012).

In case of many building components, although they are designed to withstand rain and moisture contact, the effects created in a flooding context are different from those situations and the potential long duration of water contact can significantly damage the materials of these building components (HNFMSC, 2006). These impacts of flood actions may include warping, weakening, breakage, or collapse of the building components (Kelman and Spence, 2003a). Depending on the duration of flooding and if the water sufficiently enters the building, relevant flood actions can significantly affect the building's substructure and superstructure as well as its supporting services (Wordsworth and Bithell, 2004; Proverbs and Soetanto, 2004; Wingfield et al., 2005; HNFMSC, 2006; EAA, 2011, pp 18; Jordan and Rogers, 2012; FEMA, 2012, pp 59). These can be discussed more specifically in terms of foundation, doors, structural elements, external and internal walls, windows, floors, skirting boards, interior finishes and plastering (lining), decoration, and the electrical, gas, water, and drainage systems. On the other hand, a rapid flow of floodwater around the building can cause acceleration in the expansion of the soil and consequently damage to the sub- and super-structure. Figure 5.4 provides a graphical summary of the potential damages to a typical brick veneer building. These damages are briefly mentioned in this figure and each will be discussed in detail in the sub sections 5.3.1 to 5.3.12.

Findings in the literature (see Figure 5.5) suggest that 40-50% of flood damages to a typical brick veneer building occur in the first 0.5m of the above floor inundation (HNFMSC, 2006, pp 40). Although a consensus on particular building damages exists in the literature, yet there is also an observed debate on the exact impact of flood on assemblies. In the following subsections, a synthesis
of the existing literature on the potential impacts of floodwater actions on the building and its components is presented.
Figure 5.4: Vulnerability of building components to flood actions (adopted and modified from HNFMSC, 2006)
5.3.1 Damage to external walls

Referring to Section 5.2, the external walls of the brick veneer building is a complex system including the cladding, frame, insulation, and the internal lining and finishes. It is possible that the entire wall experiences failure or collapse as the result of individual or combination of flood actions (Kelman, 2002, pp 139). The cladding (brickwork) of the wall can experience various degrees of cracking and possibly collapse due to the hydrostatic (from the pressure difference between the outside and inside of the cavity space), hydrodynamic, debris actions as well as the unbalanced movement of the foundation (HNFMSC, 2006). Failure (e.g. bending or snapping the frame) can occur as a result of the excessive deflection of the timber frame from compression or tension in the brick ties from the external lateral pressures. Similar effects can be resulted by the generated bending moment from flood loads that exceed the flexural or bending capacity of the brickwork or the failure of ties (in compression or tension) connecting the brickwork to the backing frame (see Figure 5.6-left). Once these ties are failed, the brickwork behaves independently from the rest of the wall system (Kelman, 2002). The Unreinforced masonry has high compressive strength but is weak in bending. The lower tensile strength of mortar than brick can result in failure and rupture of these bed joints

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62 in case of positive and negative hydrostatic and hydrodynamic pressures
followed by the overall failure of the brickwork (AS3700, 2011; Kelman, 2002, pp 141; Beall, 2003, pp 379; HNFMSC, 2006). This is supported by various tests on the behaviour of masonry veneer against flood loads (e.g. USACE, 1988). HNFMSC (2006) discusses that the failure of studs in bending or their top/bottom sliding can contribute to cracking in the brickwork or the overall collapse of the wall. Once cracks start to appear, the elastic behaviour of the cladding is compromised and any further pressure can result in expansion of the cracks or failure of the wall (Paton-Cole, 2014).

Furthermore, the presence of salt in the floodwater can lead to brick crystallisation, chipping off, and possibly corrosion of the concrete foundation (Roos, 2003; BORAL, 2002). The Australian standards AS/NZS4456.10 (2003), AS3700 (2011) and AS/NZS4455.1 (2008) provide guidelines for adoption of salt-attack resistant brick grades to prevent this issue. On the other hand, in many cases it is observed that if the brickwork is painted and/or coated, the wall required repainting after the flood according to the sensitivity of the material of the finishes against water contact and contamination (HNFMSC, 2006, pp 88).

Figure 5.6: (Left) Failure mechanisms of brick veneer wall against lateral loads; and (right) Failure of internal lining of the wall against the hydrostatic pressure (adopted from HNFMSC, 2006)

An indirect flood damage to the cladding of the veneer wall is the presence of damaged sarking (moisture barrier between cladding and the frame or internal lining). In this situation, although the cladding is not directly damaged by the flood, however, its demolition and expensive reconstruction would be required for replacing the sarking (EAA, 2011).

Another flood impact on the external wall system is the potential damage to its internal lining and finishes (DTLR, 2002; HNFMSC, 2006; CSIRO, 2014a). The damage to this component can be caused by the hydrostatic pressure between the cavity and the interior of the house (see Figure
5.6]. According to ABCB (2012b) and HNFMSC (2006), water level difference of 100mm between the two sides of plasterboard is sufficient for its failure. Although plasterboard breakage can have positive effects by balancing the hydrostatic pressure, yet the sudden drop in the cavity water level can significantly increase the hydrostatic pressure on the cladding and possibly its collapse. If not damaged by hydrostatic pressure, it is possible that the prolonged water contact or contaminants can cause damage to the material of the wall lining. This damage is highly dependent on the material susceptibility of the wall lining and if exists any skirting boards to protect the lining from water (HNFMSC, 2006). Furthermore, it is argued in the literature that the lining may become damaged due to the removal of the wet/saturated insulation or for drying process of the timber frame. In this process, with the exception of those that are screwed (not nailed) to the frame and can be safely removed and reinstalled, the plasterboard requires replacement (Breamley and Bowker, 2002; Timber-Queensland, 2011).

The use of insulation in the external walls for improving the thermal efficiency of the building is a common practice in Australia. The insulation, depending on its materials and water resistance, may lose its effectiveness due to water immersion and requires to be replaced (HNFMSC, 2006; EAA, 2011).

5.3.2 Damage to internal walls

As illustrated in multiple literature (e.g. AS1684.2 or HNFMSC), internal walls of the brick veneer houses commonly use finished plasterboard/gypsum lining on timber framing and the insulation is installed, whenever required. The timber in the wall frames is generally assumed to be resilient to water contact (Breamley and Bowker, 2002), and accordingly this action would not result in any compromise to the structural stability of the building in specific case of load-bearing internal walls. Floods can damage the internal and external wall insulation and lining in a similar way. According to the type of lining and finish materials of internal walls (e.g. paint or wallpaper) and their susceptibility to water contact, they can be damaged (FEMA, 2012; CSIRO, 2014a). Yet, not always the whole internal wall lining is replaced. It has been suggested in the abovementioned references that the first horizontal piece of lining above the water mark can be removed and replaced (see Figure 5.7[left]).
Figure 5.7: According to low depth of water, only the bottom half of the lining is removed due to damage (left) (adopted from HNFMSC, 2006); extreme damage to internal wall frame (right).

In addition to the water contact, hydrostatic pressure and debris can act upon and damage the internal walls severely affecting them and in extreme cases result in their total damage (see Figure 5.7[right]). For these walls, since no cavity is used, the application of hydrostatic load is highly depended on the water depth differential ($f_{diff}$) between the wall's sides. It is highly probable that before the timber-framing of the internal wall becomes affected; the linings of the wall fail and allow for water transfer, equalisation of the water levels at both sides, and cancellation of the hydrostatic forces. On the other hand, doors (depending on their opening method) can possibly become open (or fail) and allow for water level equalization on the sides of the wall. The debris inside the house is mostly based on the floating furniture and deposited silt (or mud). HNFMSC (2006) discusses the potential failure of the doors on the upstream side can lead to high velocity flows inside the house. This can potentially increase the damage level to the internal walls from hydrodynamic and possible debris impact.

5.3.3 Foundation damage

The foundation system serves the building in two ways; it transfers the permanent and imposed loads from the superstructure to the ground, and on the other hand, is used as an anchor to resist against the uplift force of flood as well as the seismic, wind and other possible loads (FEMA, 2012, pp 126). The foundation is an important component of the building and any instability or destruction of the foundation can severely impact the overall stability of the structure (Kelman, 2002). Foundation is considered as a flood susceptible component which suffers mainly due to scouring or undermining
effects of floods (HNFMSC, 2006; Jordan and Rogers, 2012; ABCB, 2012b). This is significant to shallow foundations where the susceptible supporting soil underneath the foundation is washed away by the moving water resulting damage to the unsupported foundation (Roos, 2003; Nadal et al., 2010). The sloping sites can also be subjected to slumping when they are affected by floodwater. This results in destabilisation or movement of the building foundation that often causes major structural damage (CIRIA, 2005). In addition to erosion and scour, collapse of the poorly compacted soil, soil piping, batter slumping and shrink and swell of reactive soils can also cause damage to the foundation (HNFMSC, 2006 pp 42).

Failure or cracks in the foundation may occur as the result of its differential movement from the shrink and swell effect of reactive soil types (HNFMSC, 2006; Jordan and Rogers, 2012). This can lead to secondary damages causing cracks or collapse in the walls attached to the foundations. Normally, two Australian standards (i.e. AS3789-1996 and AS2870-1996) discuss the foundation design and also the earthwork of commercial and residential buildings to avoid such adverse impacts. Furthermore and as discussed earlier in this section, the salt attack can cause corrosion and long-term damage to the concrete foundations. In the aftermath of a flood, the concrete foundation needs to dry in order to avoid other adverse impacts of high moisture level on other components such as the floor covering.

5.3.4 Frame damage

The timber framing is considered susceptible to failure from high horizontal forces due to water pressure; especially when components are weakened by long immersion. Breamley and Bowker (2002) and Wingfield et al. (2005) discuss that as long as the walls or floor materials (e.g. wet insulation or floor) allow the frame to dry, the timber frame elements can return to their original state. Otherwise, the frame members may become weakened, deformed (warp or swell), and loosened (HNFMSC, 2006). The literature and empirical evidence show that the damage to timber frame from flood actions include cracked or broken members, loose joints and connections, racking failures and damage to trusses and plates (Robertson et al., 2007; Timber-Queensland, 2011). On the other hand, wet conditions of the timber frame can corrode metal connections and loosen joints which would possibly cause further structural failure in the framing system.

The literature further suggests that the imposed loads on the roof in a flooding situation (including the weight of water or even the buoyancy action) - which are not normally considered in the design of buildings - can result in stress in the roof framing members and the connection between them. This
can cause further compromise of the stability of the structure and its collapse (Timber-Queensland, 2011).

5.3.5 **Floor and floor covering damage**

Floors constitute another flood vulnerable building component (Breamley and Bowker, 2002). Different floor types (e.g. suspended timber floor, concrete slabs, etc) have been highlighted in the literature. However, the floor of the house under investigation in this research is commonly either the foundation slab itself or can be placed directly on the concrete slab (see Section 5.2). The best available evidence shows this type of floor is the most flood resilient type and is unlikely to be damaged from the horizontal flood actions (Kelman, 2002, pp 112; HNFMSC, 2006; FEMA, 2008; Bowker et al., 2007). However, similar to the concrete foundation, this floor type is susceptible to uplifting buoyancy action of the supporting soil and if not appropriately reinforced, it can possibly result in cracks and breakage of the floor slab. As the concrete floors require proper drying to regain their strength, any issues in this process may result in cracking of the floor and damage to it in the aftermath of the flood (DLTR, 2002). Although floor damage can be more significant in terms of suspended floors (e.g. damage from loads imposed from saturated flooring or the uplift pressures from buoyancy) that according to the scope of this research will not be discussed here any further.

In contrast to the concrete floors, the coverings installed on them can be susceptible to floodwater actions. The floor cover can be sheeting (i.e. plywood or particleboard), carpet or tile which may constitute different layers that are connected to the floor structure. Any above-floor inundation of house, even though shallow, can damage the flooring and affect their materials and dimensional stability (HNFMSC, 2006, pp 119). In here, the type of flooring, its water sensitivity and durability of the covering materials play an important role in their performance and level of damage (Bowker et al., 2007, pp 71; CSIRO, 2014b). Particleboards and carpet floorings are highly susceptible to floodwater and require replacement after flood (DTLR, 2002; EAA, 2011). Following a long immersion, the timber floors on slab are unlikely to be able to be returned to their original state and require to be replaced (Timber-Queensland, 2011, pp 6). They, depending on their timber species, may cup and according to the severity of cupping, they may require removal and replacement (Timber-Queensland, 2011). In addition, the cupping may generate pressure to the adjacent walls and pushes them outwards and causing damage to their lining and structure (HNFMSC, 2006).
5.3.6 Ceiling damage

Ceiling is a non-structural component of the building (see Figure 5.8[left]) and although it is unlikely to be affected from horizontal flood actions, it can be affected from floodwater in a number of ways (FEMA, 2012, pp 304). The main mechanisms damaging this component may include (HNFMSC, 2006)

- Water contact damage to the internal lining of the ceiling which may result in its collapse or permanent sagging;

- Increase in the weight of the saturated ceiling lining and/or insulation can possibly result in its collapse. Similar outcome can result due to the weight of trapped water above the ceiling (see Figure 5.8[right]); and

- Mould growth in the space above the ceiling;

In addition, if the ceiling is sealed (with no ventilation or ceiling fan considered), the trapped air above the rising water can generate pressure and result in damage to the ceiling lining and timber structure. It has been discussed in the literature that any damage to the ceiling would require the replacement of lining and the ceiling insulation (HNFMSC, 2006). Yet, it is dependent on the installation method of the insulation and if it can safely be removed and reinstated in case it is not damaged. The wet insulation should be removed since it can increase the drying time of the above ceiling space, causing decay in timber and corrosion of the metal connections in its structure. CSIRO
(2014a) discusses that although damage to ceiling is important, once the water level reaches the ceiling level, there are more serious damages at lower levels that the attention should be paid to.

5.3.7 Window damage

Windows are generally composed of glazing panels, their framing (also known as lining) and locks, catches and hinges. In addition to these, the window-to-wall attachment mechanisms and the window surrounds are also included in the window system. On the other hand, windows may have mullions and transoms. All these components can be affected from the actions of riverine floods and become damaged. While the window surrounds, framing and their finishes are more susceptible to water contact damage according to the sensitivity of their materials, the other components like glazing, mullions and transoms (and also the frame) can be affected via hydrostatic, hydrodynamic, and debris (if present) and can result in the following (Kelman, 2002; HNFMSC, 2006; Nadal, 2007):

- Failure of glass panels as the result of either the direct failure of glazing or the failure of glass attachment to the frame (e.g. using gasket);
- Failure of attachment mechanism of the window to the wall (mastic seal, nails or screws);
- Damage to framing and lining from the effects of water contact and contaminants;
- Dislodgment of mullions, transoms, the frame or the total failure of the window (ejection) from destructive impacts of debris (depending on its size and velocity and also where it hits);
- Failure of locks, catches and the hinges (depending on its opening mechanism) that can potentially open the window; and
- Failure of the window as the result of collapse of the host wall.

The existing literature on failure of windows argues against the likelihood of simultaneous failure of the above components against lateral loads. The weakest element in the window is suggested to fail first and reduces the loads on other components before they start to become damaged (Kelman, 2002; Kelman and Spence, 2003a).

Kelman (2002) provided a thorough discussion on the failure of the windows and concluded that the failure of non-glass components of the window from hydrostatic and hydrodynamic actions, particularly for window sizes designed for the residential buildings, is unlikely. He justified this based
on the typical strength of these components against the glass resistance capacity which also applies to the Australian context (AS2047, 2014). Kelman (2002) discussed that the screws and bolts can potentially withstand an approximate load of 10kN. It is highly possible that before the ultimate resistance of nails and screws is reached and the window fails, wall failure occurs causing more severe damage to the building. In this way, Kelman and Spence (2003a) concluded that as the most vulnerable sub-components, the glass should be considered as the main failure mechanism of the window against lateral loads, and therefore requires attention in the analysis of flood damage to a building. Connections (locks and hinges) were also discussed in the same way alongside the glass panels (Nadal et al., 2010). In addition to these sub-components, the lining and framing of the window can be damaged from water contact and according to their material resistance.

On the other hand, more complex interactions between the components of the window can result in possible secondary impacts and failures in them. A warping frame can impose loads on the wall-window attachment mechanisms and result in further damage. Furthermore, the damage to mullions and transoms can scratch the glazing and by reducing its stress capacity, causes glazing damage significantly below its actual failure capacity. It is also possible that due to the failure of locks and impacts of buoyancy and lateral pressures, the windows become open. This is similar to the situation where the windows are left open.

5.3.8 Door damage

The Doors include the pathways for entry and navigating between the interior spaces inside the house. The interior and exterior doors can be impacted via multiple flood actions including the hydrostatic, hydrodynamic, debris, and the water contact. Flood in this way can cause severe and unrepairable damage to doors that may include the following (Kelman, 2002; DTLR, 2002; Kelman and Spence, 2003a; HNFMSC, 2006; Nadal et al., 2010; EAA, 2011; Timber-Queensland, 2011)

- damage to the door panel material/construction from the water or contaminants in the floodwater;
- failure of locks, hinges and latches;
- door frame (and architraves) damage from the water contact;
- door frame and jamb damage as a secondary impact of the pressure from the swollen door panels; and
- failure of the glass components of the door against the lateral loads;
The type of the door, its material, and opening method constitute the determining factors for the level of damage to them. HNFMSC (2006) highlighted the high sensitivity of hollow core doors whereas the solid (if dried properly) and metal doors are suggested to provide a more flood resistant door construction against the water contact. Research by CSIRO (2014a) and the empirical evidence in the aftermath of the Queensland flood in 2011 (EAA, 2011) suggest that while solid core doors provided better resistant to floodwater impacts, all the hollow core doors were severely damaged and had to be thrown away.

Doors can have glass components which are susceptible to lateral pressures applied to the door. With less failure capacity than the non-glass components of the door, glass components can fail against these loads and allow the water entry to inside the house (Kelman, 2002).

Sliding doors are commonly used in Australian residential structures. Australian standards (e.g. AS2047, 2014) suggest that these doors can be treated in two ways; one include the external sliding doors which are mostly constructed from glass panels. These doors are suggested to be treated similar to windows with sliding panels. On the other hand, internal sliding doors can be constructed using either glass or timber panels which depending on their construction material, they can be damaged similarly to previously discussed door damage mechanisms.

Garage [roller] doors, according to their materials and construction, can become damaged from the hydrostatic loads and pressures induced from the moving water and debris. Yet there has been not much attention and research in the literature targeting this component.

5.3.9 Roof damage

The roof is the main building component designed to protect the residents from rain water and it is structurally connected to the walls to transfer the wind-related loads to the foundation of the structure. Roof structure in the house under investigation (see more details in Section 5.2) can be affected from flood actions in different ways which are as follows (HNFMSC, 2006; FEMA, 2012, pp 217):

- Dislodgement of the roof tiles from the moving water or buoyancy action;
- Failure of the roof structure from overloading the rafters (from above roof water weight or the roof covering becomes heavier as the result of the water absorption) and the weakening of the structural members. However, the deflection capacity of the roof structural members is more than those in the wall. According to HNFMSC (2006), they are designed to
accommodate significant loads (e.g. velocity of 2m/s) which make it rare that the roof collapses from heavy loads in the case of floods;

- Breakage or dislodgement of the roof structural elements and coverings from debris impact;

- Disconnection of the roof from wall due to failure of their connection from uplift forces of buoyancy (similar to wind effects in hurricane situation);

- Rotting and mould growth from the trapped moisture following the flood;

- Potential roof insulation damage according to their materials;

- Damage to sarking of the roof; and

- Corrosion of connectors and fasteners due to the trapped moisture from lack of ventilation or delay in the drying process.

In case of serious damage to the roof, it has been discussed that the building would experience significant level of flood actions that can cause further failure in its other components (Kelman and Spence, 2003a). In most cases, Kelman (2002, pp 222) suggests the building damage would be beyond repair and full damage should be considered.

5.3.10 Moulding damage

Mouldings (including the skirting boards and cornices) constitute the commonly used decorative and non-structural components of the building. Although one may argue that these components are unimportant and cheap to repair or replace, yet due to their large quantities in buildings, their contribution to the overall cost of damage can possibly become significant. Therefore, their vulnerability is important for improving the resilience of the building in flood prone areas.

The major damage to mouldings includes the contact with water in which according to the susceptibility of the materials and finishes, presence of contaminants in the water, and the duration of immersion, different degrees of damage may be caused to them (HNFMSC, 2006).

In addition, during the wall cavity cleanup process in the aftermath of flood, the mouldings should be removed. Although these components may not have been damaged during the flood due to their
water resistance, as they are commonly nailed to the lining, the removal process can possibly result in their damage and replacement may be required.

5.3.11 Utilities damage

Utilities and the other non-structural elements of the house servicing the residents can also be seriously affected in a flooding event. These damages are diverse and may include the electrical sockets, meters and the telephone, mechanical and plumbing services, gas and water and heating utilities, collapse of septic tanks, broken pipes, damage to pumps, etc (FEMA, 1999; DTLR, 2002, pp 34; FEMA, 2012). The major threat to the abovementioned systems is the water contact damage according to their location and material. Damage to the electrical components and wirings can result in secondary impacts like malfunctioning or corrosion of building elements or electrical shocks to humans (HNFMSC, 2006; Breamley and Bowker, 2002). While the external utility elements like meters on the upstream side of the house can be affected by potential debris, it is also possible that scouring of the soil exposes the buried pipes and utilities to other flood actions (e.g. hydrodynamic loads and debris) resulting their dislodgment and breakage (FEMA, 2012). Furthermore, the buoyancy can act on the external water (or fuel) tanks and depending on their contents and anchorage, it can lift them off their support and either damage them or result in damage to other building components from the generated debris (ABCB, 2012a, pp 17).

Additional problems can be caused by the penetrating water and silt into gas systems affecting their safe operations (Breamley and Bowker, 2002). In addition, contaminated floodwater may find its way to the on-site water wells, open faucets and unsealed tanks, or broken pipes and contaminate the water or cause damage to the water systems (FEMA, 2012 pp 315). This, if is left unchecked and not treated, can cause further health issues and risks. These impacts can be magnified by the mixture of floodwater and contaminants (e.g. sewage, oil, petrol, etc) as the result of the back flow of sewerage.

5.3.12 Other damages

In addition to the specific flood impacts discussed for each building component or system, further damages can be caused by the flood actions. As a major damaging mechanism to the building, the buoyancy and hydrodynamic forces can work together and according to the foundation-frame anchors and bolts’ capacity, can lift the building and pushes it off its foundation (Black, 1975; Becker, 2008; Nadal et al., 2010). This is however is unlikely for brick veneer houses due to their heavier nature and the complexity of connections between elements in its construction (HNFMSC, 2006).
Some residential houses may include timber decking which depending on their timber species and also the duration of immersion, may get damaged. In addition, timber deformation may happen during the drying process which can further damage to the components. On the other hand, in case of presence of external stairs for raised foundations, they can be affected from floodwater actions according to their materials and may require replacement (HNFMSC, 2006).

Gutters and downpipes are building components designed and used to transfer the rain water from roof to the ground and the main drainage system. These components are constructed using water resistant materials, however are susceptible to the loads imposed from debris and can be damaged (broken and/or dislodged).

**5.4 Summary of potential damages**

The previous section provided an overview of the potential flood damages to various components of the building and discussed their vulnerability to flood actions. Table 5.1 summarises these components and underlines those actions that can result in their damage.
Table 5.1: The summary of impacts of flood actions on the components of the building under investigation

<table>
<thead>
<tr>
<th>Water contact</th>
<th>Contamination (Chemical, Nuclear, and Biological)</th>
<th>Hydrostatic</th>
<th>Hydro-Dynamic</th>
<th>Debris</th>
<th>Geotechnical</th>
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<td>4 Structural Frame</td>
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<td>5 Floor and Covering</td>
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<td>6 Ceiling</td>
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</tr>
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166
It is important to note that although for some components the damage assessment is feasible, yet in case of many others the flood damaging mechanisms are still not well-understood by the research community and therefore damage assessment would be very complex and uncertain. Therefore, in many damage models discussed in Chapter 2 only the major building components and the most relevant flood actions are included and investigated (Messner et al., 2007). In addition, some of the discussed damages in Section 5.3 are beyond the scope in this research since they do not constitute first-order damage (see Section 1.4).

Next, additional discussion is provided to further clarify the scope of the investigation in this research and to justify the exclusion of some of the flood actions and their impacts on building components.

### 5.5 Scoping the building vulnerability investigation

Due to the limited time and resources for this research, the focus here is mainly on the major components of the building and their damage from water contact and lateral loads from the hydrostatic and hydrodynamic actions. It is discussed in the literature that the majority of damages from riverine flooding are fundamentally resulted by these actions (HNFMSC, 2006). While other actions like buoyancy, debris, geotechnical and contamination are also important, yet they are of less relevance in this research due to the defined scope and other reasons that will be discussed here. The literature discusses the insignificance of the buoyancy action threatening the brick veneer construction with slab-on-ground foundation (HNFMSC, 2006). This is mainly due to the construction weight of the brick veneer system and its complex connections between the walls, frames and foundation that would sufficiently resist against the uplift forces generated by the floodwater (HNFMSC, 2006):

"Full brick and brick veneer houses are unlikely to float – especially those with slab-on-ground construction – even if water is prevented from entering the house. In these houses, hydrostatic forces are likely to damage the walls or doors and allow water entry before sufficient buoyancy forces can develop to lift the slab."

On the other hand, debris and contamination are highly variable and their presence is extremely uncertain (see Table 2.6). Various uncertain factors including the size, speed, height of impact and material of the debris, as well as the degree and type of contamination in the water make the estimation of their impacts very difficult. These factors have resulted in either (a) use of crude calculations for building damage from these actions and according to a number of weak assumptions
(e.g. see Roos, 2003; Nadal et al., 2010); or (b) exclusion of these actions from the analysis (e.g. Kelman, 2002; Becker et al., 2011; Barbato et al., 2013; Mazzorana et al., 2014). According to this discussion, although the presence of debris and contaminants can significantly increase the damage to the building, assessing the impacts of these actions on a building requires separate and detailed investigation with dedicated time and resources that is beyond the defined scope of this research. Consequently such assessment is not further investigated in here.

The riverine floods are generally slow rise and include slow-moving water. Although narrow pathways between the buildings in urban areas can to some extent increase the floodwater velocities (Mason et al., 2012), yet these velocities would not be significant to wash away the supporting soil and damage the foundation by generating a large scour hole around it. In general, this action is more of an issue in the coastal and flash flooding situations where high velocities are expected to be present. The scouring action is rarely considered where slow moving water (Velocity < 1.5m/s) exists. Accordingly, it is also omitted in this work and will not be pursued further.

Furthermore, the shrink and swell impact may cause damage to the foundation and walls and can further affect the stability of the structure. However, uncertainties about the profile of the soil, the degree of water seepage in the soil and the knowledge of "to which extent it penetrates underneath the building" constitute some barriers to implement this potential flood impact on a building. To the knowledge of the author (referring to Chapter 2), no previous direct tangible damage assessment model have incorporated this action. Due to these factors as well as considering this action to cause secondary damages to the building, shrink and swell will not be the focus in this dissertation.

According to the above discussion, only the impacts of water contact, hydrostatic and hydrodynamic actions on a number of selected building components are considered in this research. The selected building components against the considered actions are highlighted and the exclusions will be justified here. These components include the external walls (including their cladding, frame components, lining and insulation), the lining and insulation of the internal walls, floor covering, insulation and lining of the ceiling, mouldings (including skirting boards and cornices), doors, windows, structural connections, utilities (only electrical components) as well as the single-leaf load bearing garage walls.

For the interest of the reader, the following references are suggested for better understanding and estimating the scour: FEMA (2012), Nadal (2007) based on the work of Jones (1983), Oliveto and Hager (2002), Bundaberg Regional Council (2013), Barbhuiya and Dey (2004), Cardoso and Bettess (1999), and Kohli and hager (2001). For slab-on-ground single storey houses, the suggested method includes the scour of abutments discussed in Kohli and hager (2001) which also considers the temporal aspects of the scour.

63 For the interest of the reader, the following references are suggested for better understanding and estimating the scour: FEMA (2012), Nadal (2007) based on the work of Jones (1983), Oliveto and Hager (2002), Bundaberg Regional Council (2013), Barbhuiya and Dey (2004), Cardoso and Bettess (1999), and Kohli and hager (2001). For slab-on-ground single storey houses, the suggested method includes the scour of abutments discussed in Kohli and hager (2001) which also considers the temporal aspects of the scour.
Walls in the house have significant importance and their failure can potentially result in the partial or total collapse of the building. While all the selected actions apply to the external veneer wall system and its components, yet for the internal walls, only the insulation and lining damages from water contact are considered. Excluding the evaluation of internal wall frames against lateral loads is due to the assumption here that the velocity of water inside the house would be insignificant. In addition, all the internal doors are assumed to be open. Although the latter assumption is uncertain and may vary in different flooding situations, it can be considered reasonable as generally in contrast to the external doors that are shut and locked for security reasons, the internal doors can be open (without security concerns) to facilitate the navigation inside the house. In rare situations, upstream doors can fail (or become opened) and create a wave of high velocity water inside the house that can cause severe damage to building components; yet, in this research the assumption is that no water velocity (still water) exists inside the house.

As discussed previously in Section 5.3.3, the concrete floor slabs are generally not affected by water contact and lateral loads; accordingly they are excluded in the analysis in this research. However, the floor coverings, according to the flood resistance of its materials, can be damaged from even shallow above-floor water depths. This will also be the case of skirting boards and therefore these components are included for further investigation against water contact.

If the water level inside the house reaches to the ceiling level, it can damage its lining and insulation and also the cornices (mouldings) according to the susceptibility of their material to water. Therefore, these components, except the ceiling structural damage from the saturated insulation that is considered as a secondary impact, are included for further investigation in this research. The water level may continue to rise and in rare cases can reach to the roof (HNFMSC, 2006, pp 118). The roof is considered as the major vulnerable element to wind impacts during hurricane and storm surge events where pressure on the lower parts of the building is significantly less in comparison with flooding scenarios (Barbato et al., 2013; Park et al., 2014a). The literature suggests that at high flood levels up to the roof, the bottom (or lower) elements of the building are under significant loads and it is likely that a severe damage to the building has already occurred (Kelman and Spence, 2003a; HNFMSC, 2006). This is also highlighted in Figure 5.5, illustrating that over 60% of the damage has possibly occurred to the building where the water reaches to the roof level. In this situation, as indicated by the literature (Scawthorn et al., 2006; Nadal et al., 2010), the building is better to be replaced than repaired. Therefore, regardless of evaluation of damage to the roof or its exclusion, in most cases, full damage can be assumed. Accordingly, in this research the analysis of roof damage is excluded and will no longer be investigated. In addition, although gutters and downpipes, as discussed
earlier in Section 5.3.12, are considered resistant to floodwater contact, yet debris and possibly high velocities can damage them. Since the study of these actions has been ruled out from the investigation scope, therefore the gutters and downpipes are also not discussed further here.

Windows and doors are also considered within the scope of the investigation. They not only constitute valuable building components but also can significantly alter the flood damaging mechanisms on the other building components. By failing and allowing water entering inside the building, they reduce the flood loads. However, damage assessment in this research is limited to the following components:

- Glazing, framing of the window and its surrounds;
- Glazing, panel and frame for external doors, and
- Panels and frames for internal doors.

Beyond these components, the other parts of the windows and doors (e.g. locks, catches, hinges) will not be investigated. Nadal (2007) argues the failure of connecting mechanisms of windows/doors to wall or the locks and hinges as the main failure mechanisms of these components. Yet in a more detailed work by Kelman (2002), it is discussed that the glazing is the weakest and most vulnerable component in the doors and windows. The required lateral pressures to cause failure for non-glass components in doors and windows for residential buildings are very high. Based on synthesising the expert opinion, Kelman (2002) concluded that

"For doors without glass, walls fail at a low enough depth differential to suggest that wall failure is far more of a concern than door connection failure."

Furthermore, the location of the locks, hinges and catches should be specifically considered in the analysis as discussed by Nadal (2007). These parameters are highly uncertain, may vary from one door to another, and are rarely provided in product guide sheets. Although Australian Standard AS4145.1 (2008 pp 29) for door security provides minimum requirements and coding for the locks (i.e. 3kN to 6kN for the dead bolts and 3kN to 5kN for the latch bolts depending on their security class), the maximum tolerable loads as the damage threshold is not usually provided. Further investigation (Personal communication with Assa Abloy lock manufacturer, 2014) indicated that for privacy and security reasons, such information is rarely issued from the manufacturing companies. Damage analysis using the minimum requirements in the standards is not feasible and the personal
communication with manufacturing and testing department of Assa Abloy lock manufacturer led to the conclusion that during the flood doors (depending on its type and materials) may bend and the gap between the door panel increases beyond the value discussed in the standards. In this situation, while the lock’s bolts and dead latches are still in-act, the door may become open and while no damage to the lock is occurred, the infiltration of water begins lowering the pressure on the components. This discussion illustrates a knowledge gap as a barrier for investigation of flood damage to locks and hinges of doors and in a similar way for windows. Failure of these components can alter the flood damaging mechanisms on the building and constitute an important aspect of damage analysis for windows and doors. Yet, they are excluded from the scope of this research.

Further investigation in the literature and the Australian standards related to the strength of the windows and their components (i.e. AS2047-1999, AS4420.6-1996: ultimate strength test for windows, AS4420.2-1996: deflection test for windows, AS4420.3-1996 - windows operating force test) also shows little evidence to be used for analysis of damage to the other non-glass components of the window from lateral loads. These standards such as AS1288 (glazing) suggest minimum values for the strength of the whole window without providing any details regarding the individual components’ strengths. In addition, according to Kelman (2002 pp 222), the non-glass components of the windows are unlikely to experience pressure difference (ΔP) sufficient to break them before walls collapse. Therefore, by assuming that all the external doors and windows are shut and locked [also considered in Kelman (2002) and Nadal (2007)] the damage analysis in this research focuses on the failure of the glazing from lateral loads as well as the material damage of the window/door frame, panels and surrounds from the water contact. The assumption is justified according to the discussion provided by Kelman (2002, pp 107):

"Estimating the numbers of open or unlocked windows for flood scenarios cannot be done with sufficient accuracy because important criteria include season, time of day, burglary rate in the community, burglary experience of the occupant, and local security culture. The assumption made for this study is that all window units would be shut and locked when the flood strikes."

In regards to the utilities of the building, although a few guidelines have suggested methods for evaluation of damage to water tanks and external utilities from the effects of buoyancy (FEMA, 1999, 2012), in general, the analysis of damage to utilities (spanning across water, sanitary, drainage and sewer, electrical, mechanical, heating and ventilation, etc) using load-resistance analysis is difficult for most cases (Nadal, 2007, pp 179). Although Nadal et al. (2010) discuss the point-base method
(similar to damage curves) as a suitable method for this purpose, it can suffer from the deficiencies of damage curves discussed in Section 2.6.2.2 and 2.7. Although the inclusion of all these utility systems and their components is crucial for a comprehensive damage assessment, due to the availability of limited resources in this research, only the water contact damage to the electrical components is considered. It must be noted that the water immersion in case of the electrical components can result in complete damage or disruption of their operation.

In addition to the highlighted scope of the investigation of potential damages to the vulnerable components of the building, further important assumptions are made in this research and are discussed here.

In this work, a high quality workmanship for construction and installing the building components was assumed. In the absence of this assumption, a significant variation of potential damages to the same component with different workmanship qualities may exist which would make damage assessment extremely difficult and uncertain. Furthermore, to assess the potential damages to the building, precautionary measures (e.g. temporary sand bags and barriers, etc) are not considered in the analysis of damage. It has also been assumed here that the building is empty from furniture; and in the same way, possible live loads in the calculations are not accounted for. This assumption is backed up by the fact that in the slow-rise riverine floods with sufficient warning time, it is common that the residents leave the house for shelters and safer locations. However, in rare cases they may stay back in their house. Such decision can be related to a variety of factors that their discussion is beyond the scope in this research. Lastly, the impacts of previous damage to the components and also their unpredictable and uncertain weakening due to water immersion and fatigue from continuous loads can play an important role in increase in damage to building components. However, due to the complexity of these phenomena and little knowledge about how they can be incorporated in the flood damage assessment, they are not accounted for in the calculations in this research for analysis of damage.

5.6 Chapter Summary

This chapter, in order to address the objective 2(a) in this research (see Chapter 1), provided a thorough discussion on the flood vulnerability of a typical single storey brick veneer type of construction with slab on ground foundation. It first explained the commonly used components in this type of residential construction in the Australian context. Furthermore, amongst different aspects of the building, it underlined the vulnerable components against the relevant actions of a riverine flood. These components were mainly identified as the lining and insulation of the internal and external
walls, the cladding, timber frame, floor covering, ceiling, windows, doors, mouldings and those utilities servicing the building. This chapter further highlighted the scope of the further investigation in the remaining steps of this research and justified the inclusion of the relevant building components and those actions that can result in their damage.

The next chapter, according to the provided foundation in here, will detail the required methods for assessment of the potential damages to the selected building components from the lateral hydrostatic, hydrodynamic and also the water contact actions.
Chapter 6

Building Vulnerability Assessment
6 Building Vulnerability Assessment

6.1 Introduction

Continuing from the background information provided in Chapter 5, this chapter presents the outcome of the investigation in this research for selection of the suitable methods for assessment of a justified subset of the potential flood damages to a building. This chapter first explains the relevant flood actions in this research, i.e. the water contact, hydrostatic, and hydrodynamic. While the hydrodynamic action is the function of velocity of water, the first two actions, in addition to the water level outside, highly depend on the knowledge of the water depth inside the house. Accordingly, various water infiltration pathways and calculations for the infiltrated volume of water to inside of the building are presented and discussed. Furthermore, analytical methods for assessment of damage to the external and internal walls, doors, windows, floor covering, mouldings, utilities, eave lining, and ceilings are investigated and the calculations for each are presented. This chapter and the Chapter 5 lay important foundation for the design and implementation of the FDA framework as the core of the research.

6.2 Flood actions and their calculations

Prior to the assessment of flood damage to the selected building components (see Chapter 5), the relevant flood actions are briefly explained and for each, the required calculations are provided in the following sub sections.

6.2.1 Water contact action

The water contact action\(^\text{64}\) is the damage from floodwater (fresh or contaminated) coming into contact with water-sensitive building elements. This action can be described as a function of water sensitivity of the component material for a particular water contact duration \(R(\omega, t_c)\), its exposed area to floodwater \(A\) and the contact duration \(T_c\) and is formalised using the Equation 6.1.

\[
Water contact action for component (\omega) = f_\omega (A, T_c, R(\omega, T_c)) \quad \text{Equation 6.1}
\]

\(^{64}\) Also discussed in terms of "non-physical" action in the literature.
While the second and third parameters in Equation 6.1 can be obtained using the component location and the dynamic simulation of flood and its rate of rise, the resistance functions for building components according to their material has been provided for different duration of floodwater contact (e.g. for 72 and 96 hours) in various literature; e.g. Proverbs and Soetanto (2004), CIRIA (2005), HNFMSC (2006), Bowker et al. (2007), FEMA (2008), Snow and Prasad (2011), Growth Management Queensland (2011), CDCP (2012), and Insurance Council of Australia (2013).

6.2.2 Hydrostatic action

The imposed load from the hydrostatic action on a building component is mainly related to the depth differential on its sides (Kelman, 2002; HNFMSC, 2006; FEMA, 2012). In addition to the lateral hydrostatic pressures (from water pressure difference), they can also be vertical and are generated by buoyancy or the weight of water (FEMA, 2012; HNFMSC, 2006). Although Kelman and Spence (2004) classified the buoyancy as a separate action, it is sometimes considered as a vertical hydrostatic action due to the nature of the load (HNFMSC, 2006; FEMA, 2012). As explained previously in Chapter 5, only the lateral hydrostatic loads are discussed in here.

The magnitude of the hydrostatic pressure is correlated to the depth of water and accordingly, as illustrated in Figure 6.1(left), it forms a triangular distributed load. The Equation 6.2 provides the basic calculation of the lateral hydrostatic pressure for outside water depth (h) and at a point (y) on the y-axis (Kelman, 2002; Nadal, 2007; FEMA, 2012).

\[
P_z = \text{hydrostatic pressure (kg/m}^2) = \rho_w g (h - y) \tag{Equation 6.2}
\]

Where

- \( g = \text{gravity acceleration (m/s)} \)
- \( \rho_w = \text{mass density of water (kg/m}^3) \)
- \( h = \text{depth of outside water (m)} \)
- \( y = \text{elevation in the y-axis that the pressure is calculated for (m)} \)

As given in Equation 6.2, lateral hydrostatic action also depends on the mass density of water. The water quality, or the presence of contaminants or debris can sometime increase the water density to twice the density of fresh water, resulting in significant increase in the hydrostatic loads (Costa, 1988; Kelman and Spence, 2004). In this research however, for the simplicity of calculations, clear water with bulk density of 1000 kg/m\(^3\) is assumed.
The Equation 6.2 can only calculate the pressure from water on one side of the component. If water depth difference ($f_{\text{diff}}$) exists on both sides (e.g. for window in Figure 6.1[right]), it generates pressure difference ($\Delta P$) between the inside and outside of the building that can cause significant damage to building components. This pressure difference can be calculated using Equation 6.3 as follow:

$$
\Delta P = \rho_w g (f_{\text{diff}} - y) = \Delta P_{y=0} - \rho_w g y \quad \text{for} \quad b \leq y \leq f_{\text{diff}} 
$$

$$
\Delta P = 0 \quad \text{for} \quad y > f_{\text{diff}}
$$

The distributed hydrostatic forces ($\text{Force} = \text{Pressure} \times \text{area of applied pressure}$) can be represented using an equivalent point force in the two-dimensional plain on the relevant building components. This point would be at the height of $h/3$ from the ground where ($h$) represents the depth of water.

### 6.2.3 Hydrodynamic action

Hydrodynamic action is predominantly generated from the moving water; and is basically a function of water velocity (FEMA, 2012; Kelman, 2002). In the current practice, the calculation of
Hydrodynamic forces on buildings is dependent on a specific velocity threshold (i.e. smaller or larger than 3 m/s).

If the velocities exceed 3 m/s, according to Becker et al. (2011), FEMA (2012) and many other sources in the literature, the hydrodynamic pressure can be calculated directly from Equation 6.4. Unlike the triangular distribution for hydrostatic pressure, the hydrodynamic pressure as illustrated in Figure 6.2 is distributed uniformly (FEMA, 2012).

\[
P_d = \text{hydrodynamic pressure (kg/m}^2) = C_{\text{drag}} \rho_w \frac{V^2}{2}
\]

*Equation 6.4*

Where

\[C_{\text{drag}} = \text{drag coefficient (values provided in Table 6.1)}\]

\[V = \text{average velocity of floodwater in vertical axis (m/s)}\]

<table>
<thead>
<tr>
<th>Component width to water height ratio (w/h)</th>
<th>Drag Coefficient (C_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-12</td>
<td>1.25</td>
</tr>
<tr>
<td>13-20</td>
<td>1.3</td>
</tr>
<tr>
<td>21-32</td>
<td>1.4</td>
</tr>
<tr>
<td>33-40</td>
<td>1.5</td>
</tr>
<tr>
<td>41-80</td>
<td>1.75</td>
</tr>
<tr>
<td>81-120</td>
<td>1.8</td>
</tr>
<tr>
<td>&gt; 120</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The Equation 6.4 calculates the magnitude of the velocity vector (e.g. force F in Figure 6.2[left]). However, depending on the flow direction the magnitude of the load on a building element is mainly from the perpendicular component of the velocity vector which as Figure 6.2 (right) illustrates, can be calculated as \( F = F \times \sin \theta_i \).
Figure 6.2: Combined pressure from hydrodynamic and hydrostatic (left); Magnitude of hydrodynamic load/force on the building component (right)

Where the velocities are less than 3 m/s however, they are suggested to be converted to their equivalent hydrostatic pressure (HNFMSC, 2006). The increased water depth from the moving water is calculated using Equation 6.5. In contrast to the point force equivalent of the hydrostatic loads, for hydrodynamic load it acts on a point h/2 from the ground (FEMA, 2012 pp 82).

\[ dh = \text{equivalent water head due to low velocity (in meters)} = \frac{C_d v^2}{2g} \quad \text{Equation 6.5} \]

This additional water depth is then used for calculation of the equivalent hydrostatic pressure and force:

\[ f_{dh} = \rho_w g (dh)h = P_{dh} h \quad \text{Equation 6.6} \]

Where

\[ f_{dh} = \text{equivalent hydrostatic force (kg/m)} \]
\[ h = \text{flood depth (meter)} \]
\[ P_{dh} = \text{equivalent hydrostatic pressure due to low velocity flood flows (kg/m}^2\) \]

Depending on the direction of the local velocity vector around the building, the moving water can also generate drag as well as the negative pressures (outward or suction) especially in the downstream
side of the building (see Figure 3.2 for an example). These negative pressures, by generating suction, can break the elements away from the building.

As discussed earlier in Section 6.2.2, the hydrostatic loads on the building and its components are highly dependent on the water depth difference between the sides of components. Therefore, consideration for Flood Rate of Rise (FRR) on the inside and outside of the house is crucial for determining the level of $\Delta P$. For estimating FRR, the total infiltration rate between the inside and outside of the house would be required and will be discussed next.

### 6.3 Floodwater infiltration

The water levels inside the house and the other confinements (e.g. cavity space in walls) depend mainly on the presence of pathways to allow the seepage of water between the inside and outside of the house (Kelman, 2002). Numerous literature such as USACE (1988), Kelman (2002), Breamley and Bowker (2002), Wordsworth and Bithell (2004), Wingerfield et al (2005), HNFMSC (2006), FEMA (2012) and CIRIA (2005) discuss different water entry pathways into the building influencing the rate of rise of its inside water level. The major examples of these pathways include brickwork of the external walls, vents, airbricks and flaws in the wall construction; through or around windows and doors at vulnerable points such as gaps and cracks in the connection of the frames and walls; the doors' thresholds; concrete slabs; gaps around wall outlets and services such as water and gas pipes as well as the other services; damp proof course (DPC) where the lap between the wall damp proof course and floor membrane is inadequate; the floor slab and wall connection; and sanitary appliances. In addition, failure of a number of building components such as windows, doors and wall lining can increase the infiltration rate to inside the house.

In the brick veneer houses, the cavity walls can create a complex infiltration situation between the outside, cavity space, and the interior of the building (see Figure 6.3). Although many of the abovementioned pathways infiltrate the water directly to the interior of the house from outside (e.g. windows, doors, the cracks in their frame and through concrete slab), some allow water transfer directly to and from the cavity. For example, weep holes and air bricks allow water entry and exit into/from the wall cavity. On the other hand, wall-floor interface, the plasterboard lining and interior vents include the major water infiltration pathways between the house interior and the cavity space.

In the following sections the principles of flood infiltration and also the calculation of the volume of infiltrated water from these pathways into the house are explained and discussed.
6.3.1 Water infiltration principles

In this research, the principles of floodwater infiltration to the inside of the building are adopted from Kelman (2002). As pioneer work, Kelman used the close dynamical similarity between air and water fluids and adjusted the air infiltration theories from Orme et al. (1998) in conjunction with power law principles to develop and verify equations for calculation of Flood Infiltration Rate (FIR). The power law indicates that $Q = C \Delta P^n$ where $(n)$ and $(C)$, as the power law coefficients for air can be obtained for different crack geometries and according to the empirical evidence in Orme et al. (1998).

Although $n$ is considered similar for both water and air (Kelman, 2002), yet in Kelman’s calculations this is not the case for $C$ and hence he proposed a method for its adjustment for water. For applying the infiltration equations in this chapter, the provided $C$ values should be adjusted for water using Equation 6.7.

$$C_{water} = C_{air} \left(\frac{\rho_{air}}{\rho_w}\right)^n \quad \text{Equation 6.7}$$

The values of $C$ and $n$ may vary from one building component to another. These values will be discussed for the case of each component's infiltration calculations in Section 6.3.2.

Kelman considered the maximum FIR for individual components assuming that no infiltration occurs before the $t = 0$. In addition, he assumed that the cracks/opening geometries are invariant with time and the floodwater reaches the $f_{diff}$ and $v$ instantaneously. Furthermore, he assumed the
floodwater is clear and without any debris or contaminants. Finally, the velocity is assumed constant over the face of the structure (or component) which it impacts. Kelman (2002) classified the infiltration calculation methods through previously discussed pathways in three major classes; i.e. length infiltration, area infiltration, and infiltration through orifices which will be discussed next.

**Length infiltration**

The relevant building components to the length infiltration include the cracks of the windows and doors (i.e. bottom, top and side cracks) and their frames, as well as the joints between other openings and the wall (Kelman, 2002, pp 136). In addition, the horizontal length of wall-wall and wall-floor are considered as length infiltration.

The equations provided by Kelman (2002 pp 136) for FIR calculations of the cracks are as follows:

\[
Q_{\text{infiltration for bottom crack}} = C \left( \Delta P_{y=b} \right)^n = CW\left(\Delta P_{y=0} - \rho_w gb\right)^n \quad \text{Equation 6.8}
\]

\[
Q_{\text{infiltration for side crack}} = CW \int_b^{f_{\text{diff}}} \left(\Delta P_{y=0} - \rho_w gy\right)^n dy \quad \text{Equation 6.9}
\]

The infiltration for side crack in Equation 6.9 can be solved and simplified as follow:

\[
\begin{align*}
(b \leq f_{\text{diff}} < s): \\
Q &= \frac{CW}{\rho_w g(n + 1)} \left[ \left(\Delta P_{y=0} - \rho_w gb\right)^{n+1} - \left(\Delta P_{y=0} - \rho_w g f_{\text{diff}}\right)^{n+1} \right]
\end{align*}
\]

\[
\begin{align*}
(f_{\text{diff}} \geq s): \\
Q &= \frac{CW}{\rho_w g(n + 1)} \left[ \left(\Delta P_{y=0} - \rho_w gb\right)^{n+1} - \left(\Delta P_{y=0} - \rho_w g s\right)^{n+1} \right]
\end{align*}
\]

\[
Q_{\text{infiltration for top crack}} = C \left( \Delta P_{y=0} \right)^n = CW\left(\Delta P_{y=0} - \rho_w gs\right)^n \quad \text{Equation 6.10}
\]

Where

\(\Delta P = \text{water pressure difference}\)

\(C = \text{coefficient for the power law in crack flow}\)

\(n = \text{exponent for the power law in crack flow [no units]}\)

\(b = \text{height above ground of the bottom of a the component [m]}\)
An assumption in the use of the length infiltration formulas is that the crack geometry does not vary around a component’s perimeter. Although for various components (e.g. bottom and side cracks of the door and its frame) this is not the case, the assumption and the above equations for the first-order calculation of FIR seem to be appropriate (Kelman, 2002). Further empirical work however is suggested to improve the calculations.

Area infiltration

The area infiltration is generally employed for calculating the water infiltration through the brickwork in walls. The infiltration is integrated over the area of the wall that is inundated. Yet, it does not include the openings in the wall and the portion that is below the floor level. In here two cases are considered which the \( f_{diff} \) is either between the bottom and top of the cladding; or the \( f_{diff} \) is above the top of the cladding. Subsequent to solving the integration over the wall’s surface, Kelman (2002) presents formulas for calculation of infiltration (\( Q \)) of the brickwork using Equation 6.11 and Equation 6.12:

\[
Q \left( b \leq f_{diff} < s \right): \\
= \frac{CW}{\left[ \rho_w g(n+1) \right]} \left[ \left( \Delta P_{y=0} - \rho_w g b \right)^{n+1} - \left( \Delta P_{y=0} - \rho_w g f_{diff} \right)^{n+1} \right] \quad \text{Equation 6.11}
\]

\[
Q \left( f_{diff} \geq s \right): \\
= \frac{CW}{\left[ \rho_w g(n+1) \right]} \left[ \left( \Delta P_{y=0} - \rho_w g b \right)^{n+1} - \left( \Delta P_{y=0} - \rho_w g s \right)^{n+1} \right] \quad \text{Equation 6.12}
\]

Note that all the variables in the above equations have been defined earlier. In the specific case of the brickwork infiltration, Orme et al. (1998) suggests the use of median values of \( C \) and \( n \) for brickwork: \( C = 0.018 \) and \( n = 0.85 \). The median values are used for good quality construction of building components which is also assumed in this research.
Infiltration through Orifices

An orifice is an opening; e.g. air brick, duct, pipe or vent. However, it does not include the joints of these components and the wall as they are considered in the length infiltration. The Equation 6.13 is used for calculating the infiltration through orifices:

$$Q_{\text{orifice}} = 2^{3/2} C_{\text{drag}} W \int_b^s \left[ \frac{\Delta P_{y=0} - \rho_w g y}{\rho_w} \right]^{1/2} dy$$  \hspace{1cm} \text{Equation 6.13}

For $f_{\text{diff}} \geq s$ however, the Equation 6.13 can be simplified as follows:

$$Q_{\text{orifice}} = \frac{2^{3/2} C_{\text{drag}} W}{3g \left[ \rho_w g (n + 1) \right]} \left[ \left( \frac{\Delta P_{y=0}}{\rho_w} - gb \right)^{3/2} - (\Delta P_{y=0}/\rho_w - gs)^{3/2} \right]$$  \hspace{1cm} \text{Equation 6.14}

By assuming that variation in the velocity and turbulence of water is insignificant, the $C_{\text{drag}}$ may range from approximately 0.61 for a thin orifice with a sharp or square edge to 1.00 for an orifice with a more rounded edge or longer path (Kelman, 2002). The value of $C_{\text{drag}}$ for those orifices with sharp, almost square edges is estimated as 0.7. In contrast, other openings with rounded edges have the $C_{\text{drag}}$ of 0.9.

Other infiltrations

In the previously discussed static flood damage assessment of buildings (refer to Chapter 2), instantaneous equalisation of water depth inside and outside has been assumed when any breach in the building envelop occurs (e.g. from the failure of doors or windows). Although the failure of large components such as walls can result in large infiltrations and accordingly the rapid equalisation of water levels, yet it may not be the case for smaller components like windows and doors. In such situations in a dynamic FDA, while the inside water level is still rising as the result of the failure of smaller components, further failure in other components as the result of unbalanced hydrostatic pressures may occur. Therefore, in this research, further investigation for calculation of the infiltration through failed elements was undertaken. For this purpose, with a number of assumptions, the theories from hydraulics engineering (e.g. the design of culverts and weirs) in Chanson (2004) and Bos (1978) were adopted. The assumptions here include
• The geometry of the glass panels of the windows and doors are rectangular. Further, the failure of doors and window glazing panels result in a complete opening (the whole panel) and not its partial collapse;

• The cross-section area of the orifices is invariant; and

• Steady flow is assumed, indicating a small variation of depth and velocity over time (see Equation 6.15).

The final assumption is specifically suitable for riverine floods that include slow-rise and slow-moving waters with small or invariant velocities over time (especially due to its small changes against the $\Delta t$). This assumption intends to provide a way for a quick and first-order estimation of the approximate infiltration rate to inside the house. Although steady state infiltration may be less accurate in comparison with unsteady flow calculations, yet by setting an appropriate length of the time-steps, the assumption of steady state flow across each time-step leads to a minimal loss of overall accuracy for use of the method.

$$\text{Steady state: } \frac{\Delta h}{\Delta t} \cong \text{insignificant (or constant)} \quad \text{Equation 6.15}$$

The calculation of water infiltration through broken windows and doors will be further elaborated in Section 6.3.2.

6.3.2 Floodwater infiltration calculations

Earlier in this section, the important sources of water infiltration were underlined which are illustrated in Figure 6.4. In the following sub-sections, the equations for calculation of the FIR through these pathways (derived from those discussed in Section 6.3.1) are presented and discussed. It is crucial to note that due to the insignificance of the velocity of water in riverine flooding, in here, the velocities are converted to their equivalent depth increase to be incorporated in the calculations of FIR.
Wall infiltration

The common brick veneer wall leaks excessively (USACE, 1988, pp 88; Bowker et al., 2007). The wall area infiltration can happen through tiny cracks in the mortar and also through the bricks according to their permeability. The presence of rendering is an additional parameter that as Figure 6.5 illustrates, can significantly reduce the FIR from the brickwork (Breamley and Bowker, 2002; Kelman, 2002).

For brick veneer wall systems, the water is infiltrated through the brickwork between the outside and the cavity space. In contrast, for single-leaf brick walls (e.g. garages), the water will be directly
infiltrated to the interior of the house. This factor is important for calculating the \( \Delta P \) on the side of the wall, and also the water rate of rise inside the house and cavities. An assumption here is that for the brick veneer construction, the maximum cavity space’s water depth is the height of the wall where the eave lining starts (see construction of brick veneer in Section 5.2).

Where the infiltration for the rendered cladding is assumed zero (see Figure 6.5), the first step for analysing the FIR through non-rendered claddings is to determine the average depth and velocities across the wall panel as well as if the wall panel contains any openings (i.e. windows and doors). If the wall does not include any openings, via use of the derived equations from the area infiltration formulae in Section 6.3.1 the water infiltration is calculated for three major situations (case 1, 2 and 3 below). In these calculations, the variables \( h \) and \( h' \) represent the depth of water outside and the inside of the cavity space. On the other hand, \( W \) is the width of the wall panel. The power law coefficient \( C \) which is provided by Orme et al. (1998) is summarised in Table 6.2.

**case 1:** \( h \leq 0 \) and \( h' \leq 0 \):

\[
Q = 0
\]

Where \( h \leq s \), depending on the \( h' \), the discharge calculations are as follows:

**case 2a:** \( h' \leq h \):

\[
Q = C \ W \left[ \rho \ g \ (\Delta P)^n + C \ W \int_{h'}^{h} \left[ \rho \ g \ (h - y)^n \right] \ dy \right]
\]

**Equation 6.16**

**case 2b:** \( h' > h \):

\[
Q = -C \ W \left[ \rho \ g \ (\Delta P)^n - C \ W \int_{h}^{h'} \left[ \rho \ g \ (h' - y)^n \right] \ dy \right]
\]

**Equation 6.17**

Where \( h > s_{\text{cladding}} \), the infiltration can generally be calculated by using Equation 6.18. While the first component describes the infiltration from the uniform pressure difference between water depth inside and outside up to the inside water level (\( h' \)), the second component estimates the infiltration volume for the height difference between the water depth inside and the top of the wall.

**case 3:**

\[
Q = C \ W \ h' \left[ \rho \ g \ (h - h')^n \right] + C \ W \int_{h'}^{h'} \left[ \rho \ g \ (y - h')^n \right] \ dy
\]

**Equation 6.18**

It is trivial that for \( h' \geq s_{\text{cladding}} \), the second component becomes zero and can be ignored.
Table 6.2: Leakage characteristics for walls (adopted from Orme et al., 1998)

<table>
<thead>
<tr>
<th>Leakage characteristics for each m² of surface</th>
<th>Median C and n values (dm³·s⁻¹·m⁻²·Pa⁻ⁿ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick (bare) - laboratory and field tests</td>
<td>C (n)</td>
</tr>
<tr>
<td></td>
<td>0.043 (0.80)</td>
</tr>
</tbody>
</table>

On the other hand, if openings exist in the wall panel, following obtaining the base height, width and height of each of the wall sections 1, 2, 3, and 4 for each opening⁶⁵ (see Figure 6.6), the FIR is estimated for each section separately using the average relative velocities and depth differentials and combined later. The calculations for section 1 and 4 are similar to the water infiltration analysis for a wall panel with no openings; however, for sections 2 and 3 due to the possibility of different h and h' configurations other than the ones discussed above, additional equations are required which are provided in Appendix 10.

In addition to the cladding, other sources of water infiltration into the cavity space including weep holes and air bricks can be considered and will be discussed next.

![Figure 6.6: The division of wall area in case of presence of openings⁶⁶](image)

⁶⁵ Note that for doors, wall panel section 2 does not exist. On the other hand, for all openings except the extreme right side opening, the calculation of the section 4 is not required as the section 4 for others is basically section 3 for the next right hand side opening.

⁶⁶ An assumption here is that openings are rectangular shaped which is the case for most windows and doors.
Weep hole infiltration

Weep holes are commonly included in the brick veneer cladding to allow the moisture to escape from the cavity. Australian Standard AS3700 (2011) suggests 900mm (maximum 1200mm) distance between centres of the weepholes (approximately every 3-4 common bricks). Although proprietary products in different shapes have been introduced, weep holes are usually the missing vertical layer of mortar between two bricks (see Figure 6.4). They are commonly 10mm wide and in case of use of common brick, 76mm high and 110mm deep. It is possible that due to mud, silt and debris accumulation on the external side of the wall, weep holes become blocked and consequently result in reduction of water infiltration during the flood. Due to high uncertainty however, such situation is not considered in here and weep holes are assumed to remain fully open.

The Equation 6.13 for orifice flow is adopted for weep hole FIR calculation. As Kelman (2002) suggested, the (n) for the case of weepholes should be 0.5. On the other hand, \( C_{\text{drag}} \) for geometry of weepholes with sharp edges is assumed as 0.7 (see Section 6.3.1 for orifice infiltration). It has been observed that weep holes are commonly placed in the first row of the base of the wall (or above the windows) which as suggested by Australian standards to be immediately above the flashing (AS3700, 2011, Section 4.7.2). In addition, although the standards suggest 20mm allowance above the ground (on top of the concrete foundation) to start the brickwork, yet for ease of calculations in this research, this negligible 20mm offset is ignored and \( b \approx 0 \) and \( s \approx b+76 \text{mm}=0.076 \text{m} \) are assumed for weep holes.

Air brick infiltration

Water infiltration through airbricks (or other vent types) is a major pathway for water exchange between the outside and the wall cavity space. Air bricks are used similarly to weep holes for moisture transfer between the inside and outside of the cavity and come in different materials and sizes. An important attribute characterising the volume of infiltrated air or water through air bricks is the "net opening area" which is generally provided by manufacturers in product specifications. The calculation of air brick water infiltration in flooding situation is similar to weep holes using the orifice equations in Section 6.3.1. Appendix 11 provides the situations that can result in infiltration of water inside (or from) the cavity from these pathways and explains the formulae for calculating the FIR. The (n) and C values in these calculations, as Kelman (2002) suggested, are 0.5 and 0.9.

\[ \text{(n)} = 0.5 \quad \text{and} \quad C_{\text{drag}} = 0.7 \]

The major difference between air bricks (and vents) and orifices is that for the former, instead of full opening the 'net opening' should be used for FIR calculations which would result in a fraction of the total FIR. The Equation 6.19 illustrates the calculation of the FIR (or discharge $Q$) from air brick and vents with rectangular outline and the total opening area $= \text{Width}_{\text{airbrick}} \times \text{Height}_{\text{airbrick}}$

$$Q = \text{Calculated discharge for full opening} \times \frac{\text{Net Opening Area}}{\text{Total opening area}} \quad \text{Equation 6.19}$$

**Door and window infiltration**

The infiltration through doors and windows can occur mainly through the cracks between the panel(s), bottom threshold, the top and side cracks between panels and frame, as well as the door-wall frame connection cracks (see Figure 6.4). As discussed previously in Chapter 5, external sliding doors are treated as windows with sliding panels.

The length infiltration equations (Equation 6.8 to Equation 6.10) can be used for the calculation of the FIR through above pathways. Appendix 7 illustrates the equations for calculation of FIR through [bottom, top and side] non-fixed panel cracks, and the [top and side] frame-to-wall cracks in different situations of water depth differential between inside and outside of the building. These calculations are influenced by the water pressure difference between the sides of the door/window, bottom height and the dimensions of the door/window (width and height), number of panels and their dimensions, if the door is weather-stripped, and also the opening method and location of the panels (i.e. fixed, hinged, sliding, or rolling up).

While in Equation 6.8 to Equation 6.10 the $(n)$ is fixed as 0.6, the opening method of the panels is the main determinant of the values of $C$ (see Orme et al., 1998). These values are characterised in lower, median, and upper quartiles which as Orme et al. (1998) and Kelman (2002) suggest for good condition components, median values of $C$ and $(n)$ should be used which are summarised in Table 6.3.

---

68 And similarly for bottom frame cracks of windows.
Table 6.3: Leakage characteristics for doors (adopted from Orme et al., 1998)

<table>
<thead>
<tr>
<th>Leakage characteristics for each meter length of joint</th>
<th>Median C and n values (dm$^3$.s$^{-1}$.m$^{-1}$.Pa$^{-n}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>External doors (weather-stripped)</td>
<td></td>
</tr>
<tr>
<td>Hinged</td>
<td>0.27</td>
</tr>
<tr>
<td>Sliding</td>
<td>No data</td>
</tr>
<tr>
<td>Revolving</td>
<td>1.5</td>
</tr>
<tr>
<td>External doors (non-weather-stripped)</td>
<td></td>
</tr>
<tr>
<td>Hinged</td>
<td>1.2</td>
</tr>
<tr>
<td>Sliding</td>
<td>0.2</td>
</tr>
<tr>
<td>Roller Door</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Note that no infiltration occurs for fixed panels and therefore no C and (n) values are provided for them in Table 6.3. On the other hand, the values of C and (n) for door frames highly depend on if they are caulked or not. The Australian construction code (BCA Volume 2, 2014, Section 3.1.2.3) requires all doors and windows in building construction to be caulked. Table 6.4 summarises the values of C and (n) for caulked and uncaulked doorframes$^{69}$.

Table 6.4: Leakage characteristics for wall/window and door/window frame (adopted from Orme et al., 1998)

<table>
<thead>
<tr>
<th>Leakage characteristics for each meter length of joint</th>
<th>Median C and n values (dm$^3$.s$^{-1}$.m$^{-1}$.Pa$^{-n}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Caulked joint</td>
<td>$2.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Uncaulked joint</td>
<td>0.061</td>
</tr>
</tbody>
</table>

On the other hand as discussed in Section 6.3.1, the failure of glazing panels of the windows (and sliding doors) or the door panels can result in an additional water infiltration which should be considered in dynamic analysis of vulnerability of buildings and their components. Appendix 8 and Appendix 9 present the required equations for FIR calculation from broken windows and failed doors for different configurations of water on the components' sides. As discussed in Section 6.3.1, the failure of a glazing panel may result in different geometry opening in the panel. For simplicity of calculation, the assumption in here is that the failure results in full rectangular opening of the panel.

$^{69}$ Same values are used for window frames.
Wall-to-Floor interface infiltration

In the flooding situation where water has penetrated to inside the cavity, according to the water pressure between inside the cavity and inside the house, the water may be infiltrated through the wall perimeter interface with the floor (see Figure 6.7). Kelman (2002) suggests the use of length infiltration for calculating the infiltration through this pathway. The Appendix 12 details the derived equations from bottom crack length infiltration for calculation of the FIR through this pathway. While the $h'$ represents the depth of water inside the house, the $h''$ is the cavity space water level.

![Figure 6.7: Infiltration through wall-flood interface according to the water depth inside house ($h''$), inside cavity ($h'$)](image)

The values of ($n$) and $C$ for the wall perimeter to concrete floor interface (in case of slab-on-ground foundations) are provided by Orme et al. (1998, pp 26) only for the caulked interface as $n = 0.6$ and $C = 0.083$. Accordingly, in this research it is assumed that the interface between the wall and the floor is caulked. This limitation should be further investigated and addressed for uncaulked wall-to-floor interface.

Total infiltration and the FRR calculations

Once the infiltration for each component is calculated, the total FIR can be estimated for the entire house. As Equation 6.20 illustrates, the total FIR for a designated period of time $I(T)$ is the sum of the FIRs of each component of the building $I(n)$ for $T$. Subsequent to the calculation of $I(T)$, one can determine the Flood Rate of Rise (FRR) inside the house (and also in the cavity space) using Equation
6.21. In here, \( A \) represents the floor area of a particular space (e.g. cavity space or house interior) in which the water is infiltrated into.

\[
I(T) = \left( \sum_{n=1}^{k} I(n) \right) \times T \quad \text{Equation 6.20}
\]

\[
FRR = \frac{I(T)}{A} \quad \text{Equation 6.21}
\]

Having the flood parameters outside and inside the house, the magnitude of loads on the building elements and their water contact duration can be calculated. According to these inputs, damage to each building element can be evaluated separately and according to their resistance.

In the next section, the calculation of the potential damage to those components within the defined scope of this research is presented and discussed.

### 6.4 Component vulnerability assessment

Vulnerability refers to the potential degree of damage to a building component. In this section, suitable methods for assessment of the vulnerability of those selected components discussed in Chapter 5 are presented and the assumptions for each are discussed.

In here for the evaluation of both potential water contact damage and those as the result of applied flood loads, the Limit State Design (LSD) concepts are adopted as the main criteria. Limit states are conditions which the building or part of it can no longer fulfil its intended function (McCormac, 2008). Australian standard for structural design actions (AS/NZS1170, 2002) prescribes two sets of limit states; i.e. Ultimate- and Serviceability- Limit States (ULS and SLS) that are used for the building design process.

As discussed in Section 6.2.1, the water contact damage evaluation can be formalised in Equation 6.1. This damage is assessed by comparing the water contact resistance of the element, the \( R(\omega, T_c) \), against the duration of the exposure to water in a given flooding scenario. Where \( R(\omega, T_c) \) indicates the susceptibility of the component to floodwater contact duration of \( T_c \) or longer, susceptible material in any situation where \( T_d \geq T_c \) become damaged\(^{70} \).

\(^{70} \) \( T_d \) is the design flood duration.
As Figure 6.8 illustrates the general process of water contact damage assessment, the limit state for water contact damage is formalised using Equation 6.22.

\[ f(\omega, A, T_c) \leq R(\omega, T_c) \]  \hspace{1cm} \textit{Equation 6.22}

On the other hand, for load-resistance damage analysis, the limit state condition defined in Equation 6.23 is used for failure analysis by comparing the computed flood loads against the component design upper limits. The values of \( L_A \) and \( L_D \) indicate the applied and maximum allowable load for ULS and SLS. If this condition can no longer be satisfied for a particular load, the limit state is exceeded and damage to the component occurs.

\[ L_A \leq L_D \]  \hspace{1cm} \textit{Equation 6.23}

The response of an assembly can be presented using a gradient of predefined and progressive damage states (Porter et al., 2001). Here, ‘progressive’ means that an assembly passes through the damage state \( D_l \) (e.g. cracked wall) before it reaches the higher damage state \( D_{l+1} \) (e.g. collapse). These damage states qualitatively represent the level of damage to the component and are based on its failure criteria in the defined limit states.
The following sub-sections present the methods for assessment of the vulnerability of building components against flood water contact and loads. While the external and internal doors, walls, and windows are discussed in separate sections according to their vulnerability to both water contact and lateral loads, the other components such as floor covering, mouldings, electrical utilities, eave lining and the ceilings are discussed together in Section 6.4.5 according to the assessment requirements against the water contact. For each component, its damage states will also be defined and presented.

6.4.1 External Walls

The external brick veneer walls, as discussed in Chapter 5 include one of the vulnerable building elements to flood. While the cladding and the frame of the veneer system can be damaged from the hydrostatic and hydrodynamic actions, on the other hand, the lining and insulation of the wall can be damaged by contacting with the water.

The behaviour of veneer wall systems against external (specifically out-of-plane) loading is complex. This is commonly related to the presence of numerous connections between its components (AS3700, 2011). In addition, walls in the residential buildings normally have many openings that influence its behaviour towards axial and out-of-plane lateral loads (Beall, 2003, pp 37; AS3700, 2011, pp 84). USACE (1988) performed empirical tests on brick veneer walls and concluded that they can withstand the water depth difference of slightly over 900mm. Beyond this point, the damage to the wall can occur and its collapse would be likely. The flood forces, spacing and the stiffness of ties, and the displacement of the wall are the determining factors in the behaviour of the wall and its damage (HNFMSC, 2006, pp 122-123; AS1684, 2010). Ties’ spacing determines their tributary area and consequently the magnitude of imposed force on each (AS3700, 2011). The brick ties tend to hold the cladding (external leaf) to the frame and according to their [tensile and compressive] strength, restrict the deflection of the wall. Ties may fail depending on the type of loading applied (USACE, 1988, pp 16; Beall, 2003, pp 156); and as the result, cracks in the wall may appear. These cracks appear as the result of bending (deflection) of the brickwork between the ties and may or may not result in the total failure of the wall (USACE, 1988; HNFMSC, 2006). If ties do not fail however, the transferred loads can possibly cause snapping of the timber frame, resulting in the total collapse of the wall (USACE, 1988, pp 8; HNFMSC, 2006, pp 124).

The most relevant synthetic analyses of damage to unreinforced masonry wall include the research by Kelman and Spence (2003b), Nadal (2007), and Xiao and Li (2013). The first two adopted Yield Line Analysis (YLA) to estimate the failure of the walls. These works, however, are not suitable for
brick veneer systems as they ignored the effects of the wall ties that allow for transferring loads to the backup frame. Additionally, they assumed that the cladding fails independently from the inner backup. While windows and doors in the wall were overlooked in Kelman and Spence (2003b), Nadal (2007) incorporated only a single configuration of openings (one door or window in the centre). Furthermore, where different configuration of yield lines can form (see Figure 6.9), only two of these configurations (D2 and D6) were considered by Kelman and Spence (2003b) and Nadal (2007).

![Figure 6.9: Yield line configuration for unreinforced masonry walls of different sizes and supports (adopted from Lawrence and Page, 1999)](image)

On the other hand, Xiao and Li (2013) utilised finite element modelling and simulated the failure in the mortar joints and bricks in a single-leaf masonry wall by modelling every brick and mortar joint between them. Although they considered the openings in the wall, yet as discussed in Section 2.6.2.3, this method is associated with large computation costs and complexity.

In here, while the Equation 6.22 is used for the analysis of water contact damage to the lining and insulation, by combining the abovementioned LSD with background theories given in Lawrence and Page (1999) and the Australian Standards such as AS1684 (2010) and AS3700 (2011), the damage to the cladding and framing of the wall is evaluated. For analysing the damage to a wall, as illustrated in Figure 6.10, according to the presence of openings in the wall or support of perpendicular internal walls, it is divided into a number of sub-panels with two or more edge restraints (see Figure 6.11). Lawrence and Page (1999) suggest that openings can be treated as if they extend to the full height of the wall and only the load between the edges of the opening is used for damage analysis.
According to the type of edge restraint for each wall sub-panel, relevant one-way vertical bending or two-way bending equations presented in Australian Standard AS3700 (2011, Section 7.4) are utilised to calculate the bending capacity of the sub-panel against lateral out-of-plane loads\textsuperscript{71}. The span for estimating the bending capacity of a wall panel, as suggested by Lawrence and Page (1999), should be assumed as the distance between the intact ties. The bending capacity of the wall ($M_c$) can be compared against the flood loads ($M_d$) to evaluate its potential damage. If the generated moment in the wall is smaller than the capacity ($M_d \leq M_c$), no damage is caused to the wall; otherwise, cracks appear and the SLS of the cladding is reached. Lawrence and Page (1999) suggest a relatively high capacity of veneer walls since the resistance of the wall against bending from lateral loads spans between the ties with maximum 600mm centres (AS3700, 2011). For this reason, damage to cladding occurs if such support of ties is not present. In here, the main assumption is that the failure of the ties for the bottom half of the wall is sufficient to cause cracking and collapse in the cladding. While the bottom half of the wall is deflected against the

\textsuperscript{71} Half-overlap stretcher bonding (typical brick arrangement for masonry wall construction in Australia) is assumed here.
lateral loading and no ties are present to provide support for the cladding, the weight of the top half can no longer be supported by the deflected lower part and the cladding can collapse (see Figure 5.6).

The failure analysis of the ties is highly dependent on their location on the cladding which further defines their tributary area. The calculated lateral forces on each tie in accordance to its tributary area \( F = P \times A \) can be compared with the tension or compression capacity of the tie (depending on the direction of the load) to assess its potential failure. Australian Standards AS2699 (2000), AS4773.2 (2010), and AS3700 (2011) provide the capacity of ties and the requirements for their location. It is noted here that the failure of ties in a particular time step is also considered in the damage analysis for the subsequent time step; hence resulting in larger tributary areas and increase in the possibility of damage.

As long as the ties are still intact, the loads from the cladding can be transferred to the backup frame (i.e. studs). The next step in the wall failure analysis is to check if studs can resist the transferred loads or not. The lateral loads are transferred to studs that are fixed to the top- and bottom-plates using nails, screws or other mechanical fasteners. By drawing a simple bending moment diagram, the moment on the stud as well as the reactions on the top and bottom connections (\( R[\text{top}] \) and \( R[\text{bottom}] \)) can be calculated (see Figure 6.12).
Figure 6.12: The bending moment from the generated point forces at the location of the connection of ties to studs (for the situation that ties are not failed); and the reactions at top- or bottom-plates with stud.

On the other hand, the capacity of the timber stud can be calculated using Australian Standard AS1720.1 (2010, Section 3.2.1) which defines it as a function of dimensions of the stud, load duration parameter, stress grade of the timber and if it is seasoned or not. The material of the studs is also a crucial factor for determining its capacity and consequently its potential damage (USACE, 1988, pp 11; EAA, 2011, pp 17). According to the same standard and Equation 6.24, if the maximum generated moment in the stud \( M_x \) exceeds its design bending capacity \( M_d \), its failure occurs which compromises the structural stability of the building. The strength of timber species against bending is further provided by AS/NZS2878 (2000, pp 9).

\[ M_d \geq M_x \]

Equation 6.24

The failure of top- and bottom-plates' connections with the stud is mainly due to the shear force transfer from stud to floor or top-plate (Becker et al., 2011). If the generated \( R_{\text{bottom}} \) or \( R_{\text{top}} \) is greater than the shear capacity of connections, they fail and affect the structural stability of the structure and possible collapse.

The plasterboard lining of the wall may provide additional support against the lateral loads (Paton-Cole, 2014). However, in the event of flood and a prolonged inundation, these components are weakened and lose their effectiveness as additional support. For this reason, they are not considered in the damage calculation in this research. On the other hand, noggings (see Figure 5.2), may provide
additional support to the wall frame; however for simplicity of calculations they are not considered in the damage analysis process presented in Figure 6.10.

Becker et al. (2011) suggests a further global analysis of load transfer from studs all the way to the foundation. However the analysis of bottom and top plates and global response of the frame to the transferred loads from studs would not be necessary for this study. As discussed by AS1684 (2010), top- and bottom-plates are much stronger than studs; and for flood loads, it is more probable that before any damage to plates, the ties, studs or stud-plate connections fail. Once these elements fail, no further load is transferred and no further analysis would be necessary.

For the insulation and internal lining of the wall, the Equation 6.22 can simply be used to assess their damage against the water contact. These elements may be constructed using water resistant materials. Therefore, they only become wet without any damages and can be recovered after the flood. However, in case of damage from prolonged immersion as discussed earlier in Section 5.3.2, if the water depth does not reach the half height of the wall, only the first horizontal piece of lining (usually the bottom half of the wall) or insulation should be replaced. In some literature the water damage is considered 300mm above the maximum water level that is mainly associated with the effects of "capillary rise" and high moisture level (Timber-Queensland, 2011; WPV, 2011). Therefore, if \( h' + 300mm \leq 0.5 \times \text{wall height} \), only the bottom half of the lining should be replaced. Otherwise, replacement of the full height of the lining for the entire wall is required.

Another factor that can potentially affect the lining damage is the presence of skirting. The skirting can protect the wall lining from water contact. On the other hand, sometimes only water resistant timber skirting is used on the bottom part of the wall that can protect the lining from damage (HNFMSC, 2006). Therefore, for analysing the water contact damage for lining against \( h' \), the base-height of the lining is assumed above the skirting boards.

According to the above discussion, the damage states for different components of the external wall can be defined as illustrated in Table 6.5.
Table 6.5: Damage states for external veneer wall components  
(insulation and internal lining rows can also be applied to internal walls)

<table>
<thead>
<tr>
<th>Wall Component</th>
<th>DS0</th>
<th>DS1</th>
<th>DS2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cladding</strong></td>
<td>No damage (only wet)</td>
<td>Cracked</td>
<td>Collapsed</td>
</tr>
<tr>
<td><strong>Studs</strong></td>
<td>No damage (only wet)</td>
<td>Failed</td>
<td>-</td>
</tr>
<tr>
<td><strong>Connections</strong></td>
<td>Intact</td>
<td>Failed</td>
<td>-</td>
</tr>
<tr>
<td><strong>Insulation</strong></td>
<td>No damage (only wet)</td>
<td>1/2 wall damage</td>
<td>Full damage</td>
</tr>
<tr>
<td><strong>Internal lining</strong></td>
<td>No damage (only wet)</td>
<td>1/2 wall damage</td>
<td>Full damage</td>
</tr>
</tbody>
</table>

6.4.2 Internal Walls

Referring back to Chapter 5, the assessment of damage to the internal walls of the building in this research only focuses on the water contact damage to the internal lining and if present, insulation damage. This analysis is similar to the external wall and will not be repeated here.

6.4.3 Doors

For the analysis of damage to external and internal doors, as discussed in Chapter 5, the focus is mainly on the glazing component (from external lateral loads), the door panel and its frame (from the water contact). A thorough discussion for damage analysis for glazing components in external doors (including sliding doors) will be provided in Section 6.4.4. On the other hand, the damage assessment for the frame and door panels is undertaken according to the presented process in the Section 6.4, the Equation 6.22, and the empirical evidence about the performance of doors against various duration of immersion in HNFMSC (2006), FEMA (2008), Building Services Authority (2010), Insurance Council of Australia (2013) and CSIRO (2014a). While door panel materials such as solid timber, metal, fibre glass and epoxy are considered flood resilient and can be recovered following the flood, yet the hollow core and solid core doors generally cannot survive the floodwater impacts. On the other hand, the reuse of door hardware is suggested for water depth of up to 1.5 meters and beyond this level the door and its hardware should be replaced as a whole (Wehner, 2014 personal communication). On the other hand, CSIRO (2014a) suggests that all fire doors should be replaced according to their design vulnerability to floods.

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72 Only painting is required.
While the above method for damage analysis considers the door as one building component, another method is to analyse the damage to individual sub-components of the door if their information is specifically provided. The damage state of the door and its sub-components determine the required action for its replacement or consideration for repair. These damage states are illustrated separately for internal and external doors in Table 6.6.

Table 6.6: Damage states for internal and non-sliding external doors

<table>
<thead>
<tr>
<th>Component</th>
<th>DS0</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
<th>DS4</th>
<th>DS5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External doors</strong></td>
<td><strong>No damage</strong></td>
<td><strong>Door panel damage with reusable hardware</strong></td>
<td><strong>Frame damage only</strong></td>
<td><strong>Total door panel damage</strong></td>
<td><strong>Glazing damage only</strong></td>
<td><strong>Total damage</strong></td>
</tr>
<tr>
<td><strong>Internal doors</strong></td>
<td><strong>No damage</strong></td>
<td><strong>Door panel damage with reusable hardware</strong></td>
<td><strong>Frame damage only</strong></td>
<td><strong>Total panel damage</strong></td>
<td><strong>-</strong></td>
<td><strong>Total damage</strong></td>
</tr>
</tbody>
</table>

6.4.4 Windows (and sliding doors)

The analysis of the failure of windows (and sliding doors) in this research focuses on the window glazing panels against the lateral loads and also the frame (and lining) damage from water contact. As for the assessment of water contact damage, similar to other previously discussed components, the Equation 6.22 along with the water contact duration and the material susceptibility of the window lining can be used.

A number of previous literature (e.g. West, 1973; Vallabhan, 1983; Beason and Morgan, 1984; So and Chan, 1996) have attempted to provide methodologies for assessment of the failure of the glass. In addition, Australian Standard AS2047 (2014) provides ULS tests for the entire window (and not its sub-components) against uniform wind loads. This standard however does not provide any indication for hydrostatic pressures that is different from wind according to its nature. Other than this, the investigation of the Australian Standards showed that little evidence exists to be used for analysing the damage to the other non-glass components of the window. AS1288 (2006) on the other hand provides the ULS design stresses for annealed, toughened, heat-strengthened, and annealed laminated glass.

73 Glazing damage is not accounted for internal walls since balanced hydrostatic and no hydrodynamic is assumed inside.
glass of 3-25mm thicknesses. This standard is the basis for design of glass-parts of windows and sliding doors in Australia.

The use of ASTM E1300 (2013) guidelines and the Weibull probability function is a common international practice to estimate the strength of glass. However, in determining its failure probability, despite its widespread use, this model lacks formal mathematical proof, nor it is verified by any large-scale systematic experimentation of glazing panels. The parameters used as the basis of the model (i.e. m and k) have no direct physical explanation and there is no generic model that can provide accurate estimates for these parameters’ values. Nurhuda et al. (2010) and Lam et al. (2011) proposed methods on the basis of fracture mechanics to incorporate glass flaws (that is overlooked in ASTM E 1300) in the glass failure calculations against wind loads.

The review of related flood damage/vulnerability assessment literature (see Chapter 2) found Kelman (2002) as the only recent attempt to synthetically evaluate the damage to glazing from the flood lateral forces. Assuming that the material of glass is brittle and the glazing panels are rectangular and supported on their 4 sides, Kelman adopted "thin plate theory" for estimating the probability of failure of window and door glazing under large deflections. In here, thin panels fail due to bending stresses overcoming the tensile strength of the glass. For analysis of the failure of glass, Kelman (2002) adopted empirical data of Aalami and Williams (1975) for maximum stresses ($\sigma_{max}$) applied to the glass from $\Delta P$. However, limited empirical data for panel sizes (i.e. with ratios of $H_{panel}/W_{panel} = 1.0, 1.5, 2.0$ and $3.0$) was available and accordingly used in Kelman (2002). On the other hand, Kelman accounted for only particular flood loading configurations which restrict the use of his model.

In this research, a simple finite element model for estimation of the glass failure in windows and sliding doors is used. This simplified model uses the characteristics of the annealed glass (as the most common glass type used in residential construction) with $\rho_{annealed} = 7850 \text{ kg/m}^3$, the dimensions of the panel, and depth of water inside and outside and also the hydrodynamic pressure outside to calculate the maximum generated stress in the glass from the applied loads. These stresses can be compared with the prescribed ultimate limit state design stresses for glass in AS1288 (2006) to evaluate the damage. As illustrated in Equation 6.25, if the maximum stresses ($\sigma_{max}$) is greater than the ULS stresses ($\sigma_d$), the glazing panel fails.

$$\sigma_{max} \leq \sigma_d \quad \text{Equation 6.25}$$
In here, window glass panels are brittle and assumed to be unprotected. The next section provides the model set up details and the use of the FE model for failure analysis of glazing panels of windows or doors. The advanced finite element program, ANSYS 14.5 was used for this purpose.

**ANSYS Model Setup**

This section illustrates the window damage analysis using ANSYS. Although the software allows for direct definition of the hydrostatic and hydrodynamic loads on the panel, as illustrated schematically in Figure 6.13, the 'relative' depth of water inside and outside were used for the panel for analysis of its damage. This enables the consideration of various configurations of inside and outside water levels in the model \( b \leq h, \ b \leq h' \) and flexibility for damage analysis.

![Diagram of window glass panel with dimensions and pressure notations](image)

Figure 6.13: The variables required for finite element model construction for analysis of failure of window glass

A relatively refined FE mesh was created in ANSYS with the assumption that the panel is supported on its four sides. In this study, it is assumed that mullions and transoms are strong enough to resist the lateral loads and the glazing fails between them. Therefore, in case of their presence, the glazing panels considered only between these elements. This mesh was designed in a way that could be reused for the damage analysis of different panels simply by changing the attributes of the glass, its dimensions, as well as the loading configurations (see Figure 6.14 and Figure 6.15).
By analysing the finite element model in ANSYS, $\sigma_{\text{max}}$ is obtained (in MPa) (see Figure 6.16) and is compared with the $\sigma_d$ for damage evaluation. In the AS1288 (2006, Table B1) two sets of maximum allowable stresses are provided for either "away from panel edge" or "at edge" which according to the location of maximum stress in the result of ANYSIS model, should be selected from.

The window panel may consist of more than one pane (e.g. double-glaze). For double-glazed panels on the other hand, Kelman (2002) suggests that each pane would resist half of the overall applied load. In this way, for the analysis of double-glazed windows, although the abovementioned method is still applicable, yet loads should be modified to take into account only for $\Delta P/2$.

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74 That only takes a few seconds on a regular personal computer.
Building Vulnerability Assessment

Figure 6.16: Results of solving the FEM in ANSYS software

According to the discussion in this section, the damage states of the window (also external sliding doors) can be defined. These damage states illustrate the possible damage progress to the window (or sliding doors) and are presented in Table 6.7.

Table 6.7: Damage states for window or external sliding doors

<table>
<thead>
<tr>
<th>Component</th>
<th>DS0</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window</td>
<td>No damage</td>
<td>Glazing damage only</td>
<td>frame damage only</td>
<td>Total damage</td>
</tr>
</tbody>
</table>

6.4.5 Assessment of water contact damage to other components

In this section, the damage evaluation to floor coverings, moldings, electrical utilities, eave linings and the ceilings are presented. This analysis, according to the scope of this research, focuses only on water contact damage and simply employs the process explained in Section 6.4 (see Figure 6.8).

The floor covering sits directly on top of the floor or foundation slab in the slab-on-ground houses. In here, even the shallow above-floor inundation can cause damage to the floor covering. Floor covering may be constructed from multiple elements. Although not all the covering sub-components may get damaged, yet once the analysis of the inside depth of water above floor (h') shows damage to any of these components, the damage to the entire floor covering is assumed. This is related to the fact that once one portion is damaged, the whole flooring needs replacement.
The assessment of the potential damage to skirting boards, cornices, ceiling (and its insulation), and eave lining (i.e. soffit and fascia) against water contact can be performed in a similar way. However, an important factor for the last three is that the relevant water depth outside (for eave lining) and the inside (for cornices and ceiling) should reach high enough to contact these components. Therefore, in contrast to the skirtings which are immediately above the floor (base height = 0), for those components the water contact and duration should consider the base height of the component first for the damage analysis.

Lastly, for the utilities, only the evaluation of electrical components is considered in this research. For majority of these components, except the cables that can become faulty and are suggested to go through testing after immersion (Mason, 2015 personal communication), water contact is sufficient to damage the other electrical components and disrupt their operations. Accordingly their removal and replacement would be required (Wehner, 2014 personal communication).

According to the provided discussion in this section and the Sections 5.3.5, 5.3.6, 5.3.10, and 5.3.11, the damage states of the floor covering, mouldings, eave linings and ceilings (and their insulation) are presented in Table 6.8.

Table 6.8: Damage states for floor covering

<table>
<thead>
<tr>
<th>Component</th>
<th>DS0</th>
<th>DS1</th>
<th>DS2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Floor covering, ceiling, ceiling insulation, mouldings, eave linings</strong></td>
<td>No damage</td>
<td>Wet only</td>
<td>Material damage or collapse</td>
</tr>
<tr>
<td><strong>Electrical components</strong></td>
<td>No damage</td>
<td>Failure (for cables: they require testing for faults)</td>
<td>-</td>
</tr>
</tbody>
</table>

6.5 Chapter Summary

This chapter provided a thorough discussion about the lateral hydrostatic, hydrodynamic and water contact actions and how each can be formally calculated. The hydrostatic action requires the knowledge of the water depth differential on the building component's sides. With an insufficient water infiltration to inside the house, building components undergo large hydrostatic pressures resulting in severe damage and possibly partial or total collapse of the building. By adopting the water infiltration principles from the existing body of knowledge, this chapter presented the calculation of
floodwater infiltration rate for various building components. The link between these calculations and the FRR inside the house (and the cavity space) was further explained and the FRR calculation was presented.

This chapter further formalised and explained methodologies to evaluate the impacts of the abovementioned actions of the selected building components for estimation of damage. Each of the components may experience various damages; and their formal definition can facilitate the formalisation of damage to each component in the overall damage assessment and communication process. In this chapter, the damage states for each building component were also formalised and presented.

According to the consolidation of body of knowledge in various disciplines (presented in Chapters 2 to 6), the knowledge base for the design of the framework in this research has been developed (see Figure 4.5). According to this foundation and in response to the justified need underlined in Chapter 1 and 4, a framework for a micro-level flood damage assessment on building was designed. The next chapter, as one of the main contribution of this research, will explain the designed micro level FDA framework and further details its processes and different components.
Chapter 7

Framework for Micro-level Flood Damage Assessment of a Building
7 Framework for micro-level Flood Damage Assessment of a building

7.1 Introduction

According to the explored body of knowledge in the previous chapters and their consolidation in the knowledge base of this research (refer to Figure 4.5), a new framework for a micro-level FDA of a building was proposed (rigour) to address those gaps underlined in Chapter 2 (relevance). To achieve the second objective of the research, by incorporating a combined use of GIS and BIM, and building on the foundation of the Assembly Based Vulnerability theories (Porter et al., 2001), the design of the framework was realised.

This chapter presents the design of the proposed framework as the core contribution of this research; and is composed of two main parts. The first part presents the framework and its key components. It details the required processes in each component and highlights the relationships between them. On the other hand, the second part presents an information model designed to realise a new BIM-GIS integration method in support of the proposed framework. This integration is designed using a data model on the GIS side and intends to satisfy the data requirements of the assessment and 3D visualisation of flood damage to a building. These requirements as well as the design and implementation of the data model are further presented.

7.2 Framework for micro-level FDA on building

In this section as the first part of the chapter, the design of the framework for a micro-level FDA of a building is presented and discussed. By building on the ex-ante FDA principles (see Section 2.6.2), the proposed framework integrates the detailed building information from 3D building models with the flood parameters from hydrological modelling and incorporates a number of concepts from ABV paradigm (Porter et al., 2001) and Limit State Design (see Section 6.4) not only for a detailed assessment of building damage, but also a 3D visualization of damage to individual components of the building. The ABV, as discussed in Section 2.6.2.3, is a methodology in engineering domain that estimates the total building loss as the accumulated cost of damage to each building component.

This framework provides the processes to undertake a micro-level FDA on a building and was designed to address a number of use cases. Use cases are informal scenarios describing the expected behaviour of a system as a response to particular organisation (or individual) needs. Defining the use cases is the fundamental step towards extracting the functionalities and the data needs for system/database design. The target uses cases in this research are illustrated in Figure 7.1 and
extracted according to (a) the highlighted needs for assessment of damage to a building at a micro-level in the land development process (see Chapter 2 for more details), and (b) a review of previous publications and liaising with engineering and design firms, councils as well as referral authorities (e.g. Melbourne Water). The illustrated use cases indicate that

- *Engineers* and *designers* should re-evaluate the design of a building in a flood prone area to improve its flood resilience (ABCB, 2012a). This evaluation can be facilitated by (a) better understanding of the safety of the designed building against a design flood, (b) estimating the cost of potential damages to the building for identification of its vulnerabilities and also the cost-benefit analysis of alternative measures, and (c) better understanding of the vulnerabilities and their sources via visualisation of the mode and location of building component damages;

- In the building approval process, the *referral authorities* and *local governments (councils)* should also assess the safety of the proposed building and communicate the potential damages to the owner using easy to understand visualisation language; and

- *Insurance companies*\(^75\) can better set their premiums on a house-by-house basis and according to the buildings' flood risks.

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\(^75\) The insurance companies are not considered as part of the land development process; and therefore according to the focus of the scope of the research, they are not presented in dotted lines.
To support the use cases and development of a micro-scale FDA tool, as depicted in Figure 7.2, the design of the proposed framework consists of four distinct phases: i.e. *data preparation, physical damage assessment, damage quantification, and communication and reporting*. In the first phase, the information requirements for FDA from different sources such as GIS and BIM are extracted and combined in a unified and consistent database. This information is then used to evaluate the physical damage to each building component using engineering methods that were thoroughly discussed in Chapter 6. The obtained damage state of each damaged component at the end of the analysis and their replacement costs are then used to decide on the required actions towards the estimation of the cost of damage. According to the principles of ABV, these costs are accumulated for all components to present the overall damage to the building. Once it is achieved, a tabular report and a 3D visualisation of damage to the building and its components (based on the obtained 3D geometries in the data preparation phase) are provided. The details of the components in each phase of the framework are presented and further discussed in the subsequent sections.
7.2.1 Data preparation

The data preparation phase includes the acquisition and integration of information from various sources that would be required for assessment of flood damage, its quantification and visualisation. The major required information sets here include the elevation model, spatiotemporal distribution of flood parameters, and information about the building, its utilities and materials, as well as their respective repair or replacement costs. An extensive list of data requirements will be presented in Section 7.3.1.

The elevation model can be obtained from Geographic Information Systems (GIS) or the city models (e.g. CityGML). On the other hand, the information about building in this framework is mainly sourced in BIM which includes spatial (geometry and topology) and non-spatial (e.g. type, material, use) information about individual interior and exterior building components that (a) are...
susceptible to flood damage; or (b) play a role in infiltrating the water to inside the house (refer to Section 6.3).

In addition to the building components, their cost information is necessary for damage quantification. This information may either be included in BIM or is obtained from the other external sources such as construction cost databases used by quantity surveyors. In Australia, the Rawlinsons construction handbook (Rawlinsons, 2014) is the most up-to-date and commonly used reference for this purpose. The linkage between the building components and their cost information can be established in the data preparation phase and is facilitated by standard taxonomies such as MasterFormat (CSI, 2013). Such taxonomies provide industry-wide standard classification codes that can be used for assembly typing and cross-referencing for project management and cost estimation.

The other important information used in the framework is the flood parameters. The selected flood parameters in this research, as discussed in Chapter 6, include the extent, depth, velocity, duration and rate of rise that mostly are a function of three-dimensional space and time. These parameters are typically obtained from the hazard assessment process using hydrodynamic simulation tools. Although hazard assessment is not the focus in this research, it is an important prerequisite for the damage estimation. Coherence between hazard modelling and the level of detail and scale of FDA is crucial for ensuring the suitability of the flood parameters for the requirements of the study (Apel et al., 2009). Recent advancements in flood modelling such as 3D Smoothed Particle Hydrodynamics (SPH), commercial tools such as TUFLOW and MIKE, and even more complex and advance 3D Computational Fluid Dynamics (CFD) models can be employed for this purpose. They facilitate the inclusion of buildings and other obstacles in the simulation using different representations for more realistic modelling of the water behaviour in the vicinity of the buildings. Syme (2008) and Smith et al (2012) discussed various building representation methods in 2D hydrodynamic modelling (i.e. blocking out, high roughness, and porous + form loss) that are illustrated in Figure 7.3. Although the inclusion or well-representation of building in flood simulations would not be crucial for large-scale hazard- and damage assessments, it would be a concern in micro FDA as local conditions, geometry and the building orientation are decisive factors in determining the value of flood parameters (e.g. velocity). In addition, a number of functions are included in these tools that allow a multi-resolution elevation model to be created for the study area. Therefore, by focusing on high resolution modelling in the areas of interest, rather than the whole study region, the balance between resource requirements and the essential level of details can be achieved.
Figure 7.3: Different representation of buildings in the flood simulation (adopted from Syme, 2008)

Flood parameters obtained from hazard assessment, the building and cost information and other data requirements should be stored altogether for use in the damage analysis. Highlighting the heterogeneity of the outputs from different flood simulation tools, requirements of information from multiple sources, as well as the spatial integration issues of the resistance (building) and flood parameters, a unified information model is required in the framework to facilitate the integration of data and ensuring a consistent and uniform organization of information in the database. This information model integrates BIM with GIS to satisfy the data requirements of the framework. The design and development of this data model, as a new method for BIM-GIS integration, is discussed in detail in Section 7.3.

Once all the required data for the evaluation of flood damage to the building and its components are prepared, the physical damage assessment is performed.

7.2.2 Physical damage assessment

As discussed previously, the damage to building components is caused by the effects of flood actions. According to the scope of analysis in this research (refer to Section 1.4 and Section 5.5), the damage assessment in this framework only focuses on the riverine flood and its most relevant actions; i.e. the water contact, hydrostatic and hydrodynamic actions.
For assessing the damage to the building components, the process here is facilitated using the dynamic vulnerability concept (refer to Section 2.6.2.3) that evaluates the time-varying actions and their impacts on individual building components over the period of flooding. For this purpose, the flood duration is discretised into a series of equal time steps \( (t_i) \). As illustrated in Figure 7.4 and according to the guidelines provided in Chapter 6, for each time step a number of analytical tasks are performed to

- Calculate the flood actions on individual components; and

- Estimate and profile the potential damages to each component from a particular or combination of actions.

In the first step of the physical damage assessment process, the depth of water outside and inside the house is calculated for the hydrostatic action computation. For cavity walls and their failure assessment, the water depth inside the cavity would also be required. Furthermore, the velocities outside the building should be obtained. For this analysis, the explained water infiltration theories and calculations (refer to Section 6.3) are adopted. The aforementioned water levels for each time-step \( t_i \) can be estimated via the total infiltration from its previous time step, \( I(t_{i-1}) \). Each \( I(t_i) \) as previously illustrated in Equation 6.19, is the product of the duration of the time step \( T \) and the sum of the FIR for each component of the building \( I(n) \).

As also presented in Equation 6.20, the depth of water inside each space (the house interior or the wall cavities) can be calculated by dividing the \( I(t_i) \) by the area of space\(^{76} \) obtained from the 3D building model.

\(^{76}\) For those components that infiltrate water into that particular space.
Figure 7.4: Physical damage assessment process
Having the flood parameters outside and inside the house and the cavities for different time steps, the flood actions on each component can be calculated according to the location and the geometry of the component and the methods presented in Chapter 6. Using the calculated loads on each component and its resistance, the damage is evaluated according to the Limit State Design principles discussed in Chapter 6. As a reminder, the water contact damage is evaluated by comparing a function of water sensitivity of the component material and the contact duration \( T_c \) against the material susceptibility for particular water contact duration, \( R(\omega, T_c) \). While Chapter 6 discussed this evaluation for each component in scope of this research, the \( T_c \) in the context of this work is calculated using the Equation 7.1. In here, \( t_i \) is the current time step being investigated and \( t_{c_0} \) represents a reference to the time step that the water contact was made first.

\[
T_c = (t_i - t_{c_0}) \times T
\]

Equation 7.1

According to the response of each assembly and its defined failure criteria (damage thresholds given) in Chapter 6, its damage state is set or updated to qualitatively represent its damage mode. As discussed in Chapter 1, building assemblies are assumed to be undamaged for the damage analysis. Therefore, the status of all assemblies is set to 'undamaged' at the beginning of the damage assessment process and stored in a 'damage lookup table' containing reference to all assemblies and their damage states. At the end of each time step, this value may change according to the status of the assembly after damage evaluation and would be updated accordingly.

The above steps are repeated for all the simulation time-steps and in each, the structural integrity of the building is checked based on changes in the damage state of the structural and load bearing components as well as the structural connections in the building. For any compromise to the structural integrity, the analysis is stopped and full damage is reported. A 100% damage in here means that the building ULS has been reached and/or it is no longer safe to enter until it is thoroughly inspected from engineering standpoint. However, if no structural instability is indicated, the damage states of the components are updated in the damage lookup database and a check occurs to assess whether any of them affected the FIR and FRR. If infiltration can occur through any damaged component (e.g. windows with failed panels), it is included in the infiltration calculations in the subsequent time steps.

7.2.3 Physical damage and loss quantification

In this phase, the details of the monetary damage to the building are calculated. The damage cost of each building element \( A_n \) is quantified according to its damage state, \( DS_n \), its treatment approach, \( G_n \)
(repair or replace), and its unit cost, $C_n$ (see Equation 7.2). Linking damage states to treatment methods requires careful attention as a variety of factors (e.g. expert judgment, interrelationships between components and whether the building is insured or not) may affect the decision for treating the damaged component. A number of developed guidelines and standards such as Building Services Authority (2010) and CIRIA (2005) can be used to facilitate the implementation of this aspect of the framework. On the other hand, costs should be up-to-date or adjusted to reflect any effect of building or component value depreciation.

As discussed earlier, the total building damage ($D_B$) in this framework is, calculated as the sum of all damages to its individual components (Equation 7.3).

$$D(A_n) = f(DS_n, G_n, C_n), \quad n = 1, 2, 3, \ldots \quad \text{Equation 7.2}$$

$$D_B = \sum D(A_n) \quad \text{Equation 7.3}$$

A threshold, commonly 50-60% of the building value, is considered that beyond this damage level the total building damage cost can be assumed (Scawthorn et al., 2006; Nadal et al., 2010). The main justification for this threshold according to previous experience is that beyond this threshold it becomes more economical to replace the entire building rather than refurbish. Therefore, total damage must be reported and a suggestion to be made to the decision maker for the entire building replacement.

To avoid double counting, ‘flagging’ can be used to mark each assembly in the model once its damage cost is considered. In addition, hierarchies and assembly relationships defined in the 3D model (e.g. damaged window from the failure of wall) can be employed to prevent errors in counting the damage to components and its sub-components.

According to the needs of the decision maker and on the basis of the estimated building losses, the risk to the building can be quantified according to the formal definition of risk in Equation 7.4 (adopted from Jonkman et al., 2008).

$$Risk = \text{Probability of hazard} \times \text{Consequences} \quad \text{Equation 7.4}$$
7.2.4 Communication and Reporting

After the assessment and valuation of the damage, a tabular report regarding the damage state of the building and each of its components is generated. Such reports should contain the number, type and details of damaged components, their damage state and the cost of the required treatment option. In addition, such report can automatically be prepared for each time step that allows for close monitoring of the damage generating mechanisms for the engineer or designer.

Furthermore, the geometry of the individual building elements can be colour-coded in a 3D model by their [intermediate or ultimate] damage states to visualise their damage. Depending on the visualisation requirements of the user, a desktop or web visualisation tool can be developed or adopted. This tool should allow for functionalities such as show/hide component category (e.g. doors or walls), camera movement at an object zoom level as well as selection and inquiry about the details of a particular component. In this way, those damaged assemblies and their locations in the building can be visually inspected and queried to assist the decision making.

As previously discussed in Section 7.2.1, the heterogeneous information about flood, building and other spatial information from GIS and BIM are required to be integrated in a unified information model to support the presented framework for evaluation the flood damage to a building. The next section will present a new approach for integration of BIM and GIS for micro-level FDA on building.

7.3 BIM-GIS integration for micro-level FDA on buildings

The unified information model is one of the key components in the overall design of the proposed framework in Section 7.2. While there is a need for an integrated method for bringing BIM and GIS information together to satisfy the data requirement of the proposed process, the review of the existing BIM-GIS integration methods in Section 3.4 showed that none of the existing BIM-GIS integration methods can effectively satisfy the information requirements of micro-level FDA on a building. Therefore, in this section a new integration approach is proposed at the data layer and on the GIS side. The main tendency towards the development on the GIS side is because of the following:

- BIM is commonly brought into the Geospatial domain because of placing it into the large geographical context (see Chapter 3 for more details);

- Extending BIM to include flood is beyond the definition of BIM (for managing the facility or building) and on the other hand, BIM does not provide any analytical capabilities or
simulation and this data should be transferred into a simulation software. GIS allows for such analyses which becomes a better choice for the integration.

As discussed in Section 3.2.2 and 3.2.3, the GML, as the most comprehensive standard in Geospatial domain, cannot explicitly define the semantics of the geographic features (e.g. buildings or roads). On the other hand, CityGML has limitations for a detailed and complete representation of floods, buildings and their components. For these reasons, a new data model as a profile of GML is proposed to integrate the BIM information alongside the spatiotemporal dynamics of the flood for assessing and visualising flood damage to the building.

The adopted methodology for designing the new data model is the data modelling technique (Teorey et al., 2011) which was explained earlier in Section 4.5.2. The following sub sections discuss the design process of the proposed information model for bringing together BIM and GIS for supporting the micro-level FDA on building.

7.3.1 Business Analysis

The business analysis, as the first and crucial step in data modelling, intends to extract the use cases and their functional and data requirements. According to the highlighted use cases in Section 7.2 and the presented outcome of the research regarding the identification of susceptible building components against floods and their damage calculation methods (see Chapter 5 and 6), the data requirement analysis was performed. Simsion and Witt (2005) discuss this step as extraction and documentation of the data elements and relationships amongst them that describe the data inputs of a particular process (in here the proposed framework for FDA).

The extracted data requirements, according to the abovementioned data requirement analysis, can be categorised into 7 main groups; i.e. hazard data, geographically extended elements, cost data, material data, building information, utilities, and others. Table 7.1 presents the details of these requirements and their spatial representations.
Table 7.1: The result of data requirements analysis

<table>
<thead>
<tr>
<th>Main type</th>
<th>Component</th>
<th>Sub components</th>
<th>Description</th>
<th>Spatial representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard</td>
<td>Flood</td>
<td>Maximum extent</td>
<td>Represents the flooded areas.</td>
<td>2D polygon; 3D surfaces.</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>Indication of spatiotemporal depth of water in the area</td>
<td>points</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Velocity vectors</td>
<td>Indication of spatiotemporal components (U and V) of velocity point</td>
<td>points</td>
<td></td>
</tr>
<tr>
<td>Flood Metadata</td>
<td>Textual information about the exceedance probability of flood, flood simulation software and its version, number of time steps in the simulation, temporal resolution of the simulation, coordinate system, depth and velocity and their temporal resolution and Unit of Measurement (UoM), and flood start and end date/time.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geographically extended information</th>
<th>Property information</th>
<th>Address</th>
<th>Indication of the location of the property containing the building.</th>
<th>Textual description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Footprint</td>
<td>The spatial information related to the parcel/site</td>
<td>2D polygon</td>
</tr>
<tr>
<td></td>
<td>Elevation</td>
<td>Elevation model</td>
<td>Representation of the elevation of the ground surface. The elevation can be an aggregation of multiple elevation models that are in different LoDs.</td>
<td>Using 3D points or Triangulated Irregular Network (TIN).</td>
</tr>
<tr>
<td></td>
<td>Level of details</td>
<td></td>
<td>Determines how detailed the elevation model is modelled at.</td>
<td>Using code types (including the LoD1-4 of CityGML, the detailed elevation model used in BIM, and a mixed mode).</td>
</tr>
<tr>
<td></td>
<td>Extent</td>
<td></td>
<td>Indicates the effective area that is well-represented by the elevation model.</td>
<td>2D polygon</td>
</tr>
<tr>
<td>Spatial structures</td>
<td></td>
<td></td>
<td>Representing virtual containers for the physical elements of the model. It can generally be &quot;city&quot;, &quot;site&quot; or correspond to an existing element like building, storey or space.</td>
<td>Do not require a spatial representation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost information</th>
<th>Building value</th>
<th>Descriptive information about the value of building, the currency type, issuing organisation and date of issue.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building assembly replacement cost</td>
<td></td>
<td>Descriptive information about the unit cost of the building assembly, its UoM, currency type, the organisation and date of issuance, manufacturer, production date, and possible reference to another external database record.</td>
</tr>
</tbody>
</table>

<p>| Materials                         | Representation of building elements' materials and their specifications | Building elements may be comprised of single material or built up of multiple material layers with different thicknesses. The minimum duration of water contact that results in damage to the material is also required. Materials require a label to differentiate them and also their susceptibility to water contact (whether acceptable for floodwater or generally unacceptable for water contact) is required. Specialised material description for timber framing elements such as their &quot;stress grade&quot; if they are seasoned or not. |</p>
<table>
<thead>
<tr>
<th><strong>Building</strong></th>
<th><strong>General building information</strong></th>
<th>The descriptive details of building its containing parcel, address, value, its elevation, height and net total area.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Footprint</strong></td>
<td>Illustrates the building footprint</td>
<td>2D polygon</td>
</tr>
<tr>
<td><strong>Building</strong></td>
<td><strong>Stories and spaces</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Storey</strong></td>
<td>Represent the building stories including height, base height of the storey and its geometry.</td>
<td>3D surfaces or solid (or aggregated geometries of those building elements that are contained in the storey’s corresponding spatial structure)</td>
</tr>
<tr>
<td><strong>Space</strong></td>
<td>Represents the building spaces, their type, their elevation with flooring, net area and height.</td>
<td>3D surfaces or solid</td>
</tr>
<tr>
<td><strong>Building elements</strong></td>
<td>Building elements include physical components that the building is comprised of. These elements all have a number of characteristics in common that include their type, cost, classification, base height, openings in them, if they area covered by any other building element(s), if they can be explicitly broken down to other building elements, and their gross weight. In addition, the formalised damage state of each is required.</td>
<td>3D multi surface and solid geometries (additional representations are possible for specific elements).</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td>The building roof and its required specifically for visualisation of building and the requirements include its geometry, the net area of the roof and its materials.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td><strong>Beams and columns</strong></td>
<td>The columns and beams in the building. Width, height, length, slope and roll, materials, and if they are internal elements or external, or load-bearing or not.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td><strong>Other structural framing members</strong></td>
<td>The other structural (load-bearing and non-load bearing) elements in the [timber] frame of the building other than those that can be represented by columns and beams. Requirements are similar to beams and columns.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td><strong>Floor/slab</strong></td>
<td>The representation of the floors and slabs (horizontal load-bearing elements such as foundation slab) of the building including their material, thickness, area and if they area internal elements or external.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td><strong>Wall</strong></td>
<td>The information of the building walls, their width, height, thickness, materials, comprising components and layers and dimensions, openins, and also if are external or internal. The net area of its components (e.g. cladding, insulation, lining.) and their characteristics, e.g. general details of the cladding like brick type and dimensions and mortar joint thickness are also required.</td>
<td>The 3D multi surface or solid geometries. Also the 2D linear representation would be required.</td>
</tr>
</tbody>
</table>
**Building**  
(cont’d)

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Geometries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stairs</td>
<td>Representing stairs, their flights and railings, materials and if they are internal or external.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Roof soffit</td>
<td>The dimensions and materials of the soffit that represents the component that constitutes the covering underneath the overhanging part of the roof.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Floorings</td>
<td>Representing the building components that are installed on the slabs/floors. The type, materials, and net area of the component are required.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Ceiling</td>
<td>The ceilings in the building, their dimensions and materials. Ceilings may also include the insulation component. The type, materials, and net area of the component are required.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Mouldings (skirting and cornices)</td>
<td>Representing the cornices and skirting boards, their materials and dimensions used in the building. The type, materials, and net area of the component are required.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Connections</td>
<td>Elements like wall ties that work as links and joints between two or more other [structural or non-structural) building elements. Their type and capacity of connections for shear, compression, bending and tension are further requirements for connections.</td>
<td>3D point, curve, surface or volumetric geometries.</td>
</tr>
<tr>
<td>Other elements</td>
<td>Any other building element that is not explicitly defined by the above categories. These elements require the following details: if they are external or internal, if they are load-bearing, their dimensions, their usage, and also their material.</td>
<td>3D point, curve, surface or volumetric geometries.</td>
</tr>
<tr>
<td>Openings</td>
<td>The details (like location, position and dimensions, and net opening areas) of the building opening elements and those that create a void in building elements. In addition, building element that hosts the opening would be required. They can be represented using either 3D surfaces or solid geometries.</td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>The doors, their [sub-component] materials, dimensions, costs, if they are external or internal, if their framing weather-stripped and/or caulked, and their operation type. The door lining and panel information such as materials, position, operation, glazing, and base height are also must be considered.</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Windows (including external sliding doors)</td>
<td>The information about windows, their dimensions, costs, their lining materials, if weather-stripped and their framing caulked, and if they are fixed/openable. Also information about their panels and lining, base heights, and type and frame materials as well as the glazing (the number of layers, glass type, thickness, if necessary).</td>
<td>3D multi surface or solid geometries.</td>
</tr>
<tr>
<td>Building (cont’d)</td>
<td>Vents</td>
<td>Elements that are used for ventilation (e.g. airbricks and weepholes in the cladding component of the wall).</td>
</tr>
<tr>
<td>------------------</td>
<td>------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Utilities</strong></td>
<td></td>
<td>Representing the internal and external utilities (or utility systems) of the building. For example for the electrical system, electrical cables, distribution boards, meters, switches, outlets and light fixtures are considered. For utilities, addition information including their type, location/position, base height, weight, damage state, weights, materials, costs, classification, and if they are internal or external would be required.</td>
</tr>
<tr>
<td><strong>Other information</strong></td>
<td></td>
<td>Physical constants like air density, water density, gravity acceleration, etc. A lookup table is required to store the details of the damage of various elements and reference to the time step that the element was first and last contacted by water. Assembly classification definitions including the label, source and edition. One classification may apply to many similar elements, therefore referencing should be allowed.</td>
</tr>
</tbody>
</table>
7.3.2 Data model design

According to the identified requirements in Table 7.1, the conceptual and logical data models illustrating the required entities and their relationships were designed. Throughout the design process, a continuous investigation was undertaken to identify how these concepts are modelled in BIM (IFC) or GIS formats (GML and CityGML). This mapping was used to refine the design to improve the information translation between the proposed data model and IFC or CityGML. In the remainder of this section the mapping will be presented and discussed whenever necessary. According to the conceptual data model, further design of the logical and physical data models was realised. For the physical data model, the knowledge of the implementation environment is crucial. This environment provides information about the supported data types and other characteristics of attribute data for each concept and dictates other required rules for the design of the physical model.

The designed data model in here inherits its high level feature definitions from the GML classes and as Figure 7.5 illustrates, it consists of eight packages; i.e. the Core, Terrain, Flood, Building, Connections, Utility, Valuation and MaterialDomain.

![Figure 7.5: The data model's high level packages](image-url)
In the subsequent sections, these packages are explained and presented using the Unified Modelling Language (UML) Class Diagram. Furthermore, each package and its respective classes were colour-themed for ease of reading.

**Core package**

The 'CoreUrbanFlood' package (see Figure 7.6) consists of those required high-level concepts for a micro-level FDA on a building. The 'UrbanFloodModel' concept is the highest level entity in the model after the abstract gml:_feature that defines any real world feature. 'UrbanFloodModel' consists of a collection of defined materials (using materialObjectMember relation with _MaterialObject), costs (through the CostDataBase), spatial structures (SpatialStructureObjectMember) and urban features (_UrbanObject) defining an urban flooding scenario. It also contains additional metadata about the model (e.g. model owner, date of creation, flood type, and flood's exceedance probability) and a set of required constants (e.g. air or water density in the Necessities class) for the analysis.

SpatialStructure objects are defined as the generalisation of IfcSpatialStructureElement in the IFC model and can be used in the new model for up to the city level. These spatial containers (e.g. parcel, building, building storey and building spaces that are defined in 'SpatialStructureTypeEnum') may correspond to physical features (e.g. building storey) and can contain any subtypes of _UrbanObjectUrban or building elements (bld:_BuildingElement). Such information is used for damage counting and quantification and can further allow for possible inference in the water infiltration and building damage analysis. For example, if a parcel or storey is flooded, then damage assessment is performed, otherwise, the simulation should stop as there is no flood affecting the contained objects. The _UrbanObjectUrban objects can be contained in one or more SpatialStructures. The _UrbanObjectUrban objects are commonly associated with a unique identifier, a name and the description of the feature. Urban objects may be properties (site), buildings, individual or systems of utilities (_UtilityObject or UtilitySystem), flood (_FloodObject), and a single- or multi-resolution elevation model (_TerrainObject).

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77 It is possible that they do not (e.g. the case of spatial structure 'city')
On the other hand, the UrbanFloodModel contains a reference table (called "DamageLookUpTable") to all the building elements ("Element" class) and their condition. The Element class references the defined building elements in the Building package and holds information like its water contact duration and damage state.

As discussed in Section 3.3.4 the building elements in the construction industry can be referenced using classification codes e.g. UniFormat II (ASTM, 1993) or MasterFormat (CSI, 2013). The 'ClassificationDefinition' and 'Classification' classes are included at high level of the data model for [re-] use of such classifications for building assemblies. They can be directly mapped to 'IfcClassification' object in the IFC model.
Terrain package

For its Terrain package, the proposed data model adopts a subset of the ‘Digital Terrain Model’ of CityGML 2.0 (see Figure 7.7). This adoption was made due to acceptability of CityGML as an urban 3D information model and ease of conversion of majority of elevation models to CityGML ‘relief’ model. A Terrain object in here can be stored by an independent abstract concept ‘_TerrainObject’ with a defined level of detail.

On the other hand, a single Terrain can be represented by an aggregation of a number of _TerrainObjects in different representation forms and levels of details. Each _TerrainObject has a validity extent, represented by a polygon, to define its effective scope. LODs are defined using enumerations (‘TerrainLoDEnum’) as illustrated in Figure 7.7 and can be defined at the Terrain object or its individual sub-components. These sub-components can be either a surface-based object (e.g. Triangular Irregular Network) represented by ‘TinTerrain’; or in a multi-point form using ‘MassPointTerrain’.

Figure 7.7: Terrain package

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78 Equivalent to the Terrain.
Flood package

The Flood package, illustrated in Figure 7.8, consists of the required concepts to define the flood information in an FDA scenario. Any flood in here (_FloodObject) is described by its metadata (FloodMetadata) that provides information about its exceedance probability, flood duration, number and length of time steps, and the value and units of measurement of the depth and velocity. As a subtype of the abstract _FloodObject, the 'FloodBody' represents the flood in either point coverage, GML surface or solid forms.

The point coverage spatial model can represent the flood parameters using a spatio-temporal point distribution (similar to the velocity representation in Figure 3.2). In GML, a coverage class (in here the gml:multiPointCoverage) uses the relationship between GML concepts gml:RangeSet and gml:DomainSet to link the geometry with its attributes (see GML 3.2.1 specification for details). Similar to Schulte and Coors (2009) and WaterML (OGC, 2012a), this GML concept was extended via definition of an array of 'FloodTimeSeriesElement' classes to accommodate the temporal aspects of the flood in addition to its spatial components (see Figure 7.8 for details). Each FloodTimeSeriesElement, according to its order in range- and domain-set, can be related to a point coordinate in the DomainSet and contains the water depth and velocity components (that are missing in the work of Schulte and Coors) of the flood for a particular time step in that location.

Surface representation of the flood was specifically considered for its 3D visualisation. It can either be presented by a single MultiSurface object using 'RepresentedBySurface' relation for the maximum depths; or using the aggregated hierarchy of RepresentedByTemporalSurface → TimeSeriesSurfaces → TimeStep → _floodBoundarySurface classes, for a surface representation for each time step of the flood simulation. While 'floodSurface' and 'FloodGroundSurface' are used for water level surface and the interface between water and ground, the 'FloodClosureSurface' closes the enclosure when the flood geometry is not a closed volume. As illustrated in Figure 7.8, a similar hierarchy is used to represent the flood in 3D via solid geometry representation. However, instead of use of multiple surfaces, a single gml:_solid geometry is used to represent the flood body. GML specification (OGC, 2007b) provides the details and differences between solid and multi-surface representations.
Figure 7.8: Flood package
Valuation package

The valuation package (see Figure 7.9) contains an abstract concept, the '_CostObject', which defines the value of a particular object (building or building assembly). The 'AssemblyCostObject' and 'BuildingValue' realise the _CostObject for the repair/replacement value of building assemblies or the construction cost (or market value) of the building as a whole. These objects can either define the cost/value by specifying the required attributes of the class such as issuing institution, date of issue, currency type, cost value, etc; or refer to an existing cost object via referencing to the unique identifier of another cost object (by 'Ref' attribute). On the other hand, these value objects can reference to external databases using URIs and attribute 'ExternalReference'. These referencing methods prevent redundant definitions of cost object for similar assemblies.

Figure 7.9: Valuation package

The 'AssemblyCostObject', as Figure 7.9 illustrates, should indicate the unit of measurement of the cost of assembly and its unit costs, currency type, and issuing institution and date; and the assembly's manufacturer and production date.
Materials package

The MaterialDomain package contains classes that define the construction materials of the building elements. As illustrated in Figure 7.10, this package consists of three kinds of material definitions i.e. Material, MaterialLayer, and MaterialConstituent that are subtypes of MaterialObject. These definitions correspond to the IFC's 'IfcMaterialDefinition' subclasses i.e. ifcMaterial, ifcMaterialConstituent, and ifcMaterialLayer.

The 'Material' class defines a single material and is either directly assigned to a building component or is used as a layer in other material classes. The flood susceptibility of the material as an important attribute for water contact damage assessment is determined via the 'MaterialClass' attribute which its value can be derived from the 'MaterialWaterResistanceClass' enumeration. This value is determined from a combination of the 'MinimumContactDuration' - indicating the minimum required water contact duration with the material that results in its damage - and the resistance of the material for this duration according to the previously discussed resources in Section 6.2.1. Another attribute of the Material class determines if this material defines a material or a component (or system) in the building. For example, in a layered wall, rather than different building assemblies, can be defined in terms of a layered material. In here, the material type should be selected as a component using the 'MaterialTypeEnum' code types.

A special type of material is the 'TimberFramingElementMaterial' which defines additional attributes for timber framing members (e.g. studs) including the stress grade of the timber and an indication of whether it is seasoned. These in addition to the other attributes of this class can determine the resistance capacity of framing elements against external loads.

'MaterialLayerSet' on the other hand, defines multiple layers of materials (MaterialLayer) used to construct a building element. An example here is a wall panel which includes the paint, lining and brick material layers. The order of definition of these layers defines the position of the material in the object. On the other hand, thickness of the layers is defined using 'thickness' attribute of each material. Each layer may also have a replacement cost according to their dimensions and cost unit of measurement. Some layers (e.g. the cavity space) may be defined as empty space via indicating its attribute 'IsVentilated' as true.

'MaterialConstituentSet' is another material definition method which consists of one or more 'MaterialConstituents' each of which defining the material of an identified part of a component (e.g. 'frame' or 'glazing' in a window) by its particular keyword.
Utilities package

The Utility package contains those related classes that represent the interior or exterior utilities of the building and is illustrated in Figure 7.11. The utility objects can be defined independently or under a particular system (e.g. electrical, water, fuel or HVAC). Each utility assembly (_UtilityObject) may have an object type (defining its details), base height, damage status, replacement value and a material object associated to it. On the other hand, internal and external utilities are distinguished in the model since for damage analysis, the inside or outside depth of water should accordingly be selected. In terms of their spatial representation, utilities are commonly presented by either a GML solid or multiSurface. In this research, for the utilities, the focus was concentrated on the electrical system elements such as lights, outlets, meters, switches and distribution boards which are explicitly defined by abstract classes '_FlowTerminal' and '_FlowController' corresponding to IFC classes IfcFlowTerminalType and IfcFlowController. In the IFC model hierarchy, these classes are the sub types of IfcDistributionFlowElement defining the "occurrence elements of a distribution system that facilitate the distribution of energy or matter, such as air, water or power". Elements such as

electrical cables on the other hand are defined using the 'FlowSegment' and can further be represented by 3D line segments using a GML Curve. The '_ControlElement' class, on the other hand, is an abstract class reserved for future use to represent utility components that impart control over the other elements in the system.

The type attribute of utility elements are specified using the code types. Some of these types for various utility components are illustrated in Figure 7.12.

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80 Corresponding to IFC's IfcFlowSegment.
Building package

The building package consists of those classes that represent the building and individual or an aggregation of building components. The concepts and their relationships in this package are illustrated in parts in Figure 7.13 to Figure 7.15 and are discussed here.

The 'Site' class represents a single parcel characterised by an address and a 2D footprint gml:polygon which can contain zero or more buildings. This containment relationship is realised using 'ContainsBuildings' and a reversed relationship of the Building class, the 'ContainedInSite'. The building is represented using 'Building' class which has a number of attributes such as address, height, elevation and total net area. On the other hand, the building value is represented by a val:BuildingValue class associated with it using the 'value' relationship. A building can be represented by either its 2D footprint or via the aggregation of 3D geometries of its components (e.g. stories). Similar to IFC hierarchy, a building in here consists of at least one storey (BuildingStorey class) and may contain utility objects or systems (refer to Figure 7.11), as well as any subtype of the abstract class '_BuildingElement'. The containment relationship between storey and elements is realised indirectly using the core:SpatialStructure. The building also has utility systems/elements and connections to connect its different structural and non-structural aspects. The connections are separately included in the data model in the connections package (see Figure 7.16).

The building components are all considered as a sub type of an abstract concept, the _BuildingElement. Each of the building elements has a damage state attribute and a replacement cost (val:AssemblyCostObject) associated with them which as discussed in Chapter 6 can be used together for damage cost analysis for damage quantification. Additionally, each building element can be classified using standard taxonomies via the 'ClassificationReferenceObject'; can be covered by 'coverings'; and be further broken down into other elements as its parts (see the self relationship 'ConsistsOfPart' of the _BuildingElement class). The majority of the building elements are optionally associated with a 'mtl:_MaterialObject'. Therefore, the materials are considered as the attribute of each
relevant building element. The `_BuildingElement` in here can be directly mapped to the `IfcBuildingElement` concept in the IFC model.

The defined building elements in the model, according to the extracted data requirements in Section 7.3.1, include slabs (foundation slabs or floors), beams and columns, walls and its components, roof, stairs (represented as a single element or separately by its railings and stairflights), framing members (representing the structural framing of the building other than columns and beams), openings (windows, sliding doors, doors, airbricks, vents, or any type of void opening) (see Figure 7.14), ceiling, flooring, soffit, cornices and skirtings which are modelled as covering elements (illustrated in Figure 7.15). For some building elements (e.g. studs that can be modelled using columns or FramingMember), it is indicated if they are load-bearing or not. This attribute can facilitate the assessment of structural stability of the building in case any damage is received by building elements. 'BuildingElementPart' on the other hand defines a class for a generic part of any other element. Explicit classes for wall parts ('WallComponentElement' such as the cladding) or covering parts ('CoveringLayerElement' such as insulation and lining) are defined in the model to represent these objects. A specific case of WallComponentElement is the claddingElement defining the details of the wall cladding. It specifies if the wall is rendered (for infiltration calculation) and provides the dimensions of the brick in the brickwork (required for evaluation of its bending capacity).

The building model on the other hand defines a generic class, 'BuildingElementProxy' to be used for elements that are not explicitly defined in the current version of the model. A 'Slab edge' is an example of this element.

Wall ties, as discussed in Chapter 6, are important aspect of damage analysis of the external walls in the building. They are represented in the data model using 'WallTie' class and in addition to all the inherited attributes from its super type `_BuildingElement`, they define tension and compression capacity. WallTie element can be used in relation to 'ConnectionRealizingElement' in the Connection package to define the cladding-tie-frame connection in the veneer system (refer to Section 5.2).

The building package also defines the openings of the building including its doors, windows, airbricks, weepholes, and void openings. In this data model, building openings (bld:_Opening) are characterised mainly by their dimensions, position in the host element, and their net opening area. Windows and doors in the building can be defined as either a single object or a combination of a lining (its frame) and a minimum of one panel that may have their own geometry, material and cost.
(see Figure 7.14). Using the provided details of the window panels and lining information (including frame dimension, transoms and mullions and their position and thickness), the glass panels' dimensions can be extracted for damage analysis using the process discussed in Section 6.4.4. In addition, lining materials can be defined using the constituents concept at the window level. Windows and doors correspond directly to the IfcWindow and IfcDoor in BIM. Additional window and door attributes (e.g. 'isWeatherStripped' and 'isFramingCaulked') were also included in the data model since they are required for infiltration calculation through these openings. Glass layers were defined in the model to be used for window damage analysis according to the process discussed in Section 6.4.4. The glass layers details are mapped directly to 'Pset_DoorWindowGlazingType' in IFC4 model. The 'Space' class in this model defines those elements for representing the internal (e.g. room) or external (e.g. the backyard) building spaces.

Furthermore, building package defines the elements such as flooring, mouldings (skirting boards and cornices), eave linings (e.g. soffit), and ceiling as sub types of 'bld:Covering' class (see Figure 7.15). In addition to their type and possibly net area, skirting boards and cornices have additional length attribute as their installation cost is mainly based on their unit length.
Figure 7.13: Building package (part 1)
Figure 7.14: Building package (part 2) - openings
As discussed earlier in this Chapter, each building element in the proposed data model can be directly mapped to their corresponding class in the IFC hierarchy. Table 7.2 illustrates this mapping in more detail. On the other hand for a better clarity of the figures, the code types for the building elements and their damage states are omitted in the above UML diagrams. Appendix 13 provides these details in classes with "enum" suffix.

Connections package

As the last UML package (see Figure 7.16), the Connection package contains the 'Connection' class which is considered as the supertype for all connections (mechanical and non-mechanical) defining a link between two or more _BuildingElement objects. The 'MechanicalConnection' is a specialised connection type that employs an additional linking _BuildingElement for the explicit establishment of the connection. An example here is the brick cladding to timber framing connection using 'WallTie' (as the ConnectionRealizingElement). The connection between the 'RelatingElement' and 'RelatedElement' can be optionally detailed by its geometry type (point, curve, or surface) that either of the elements or the realising element connects to them. In the wall tie example, the connection is simplified by a PointConnectionGeometry class that has a GML point defined on both related and relating elements. The connection concept can easily be mapped to its counterpart in IFC model for integration purposes.
In this section, the design of the data model and its different packages were presented. As discussed in Chapter 4, for design of the data model, constant review of other data models such as CityGML and IFC were performed for matching their entities with the above model's entities for ease of mapping in data integration/transfer process. Where elevation, flood and core packages are designed similar to CityGML and WaterML, the building, utilities, materials, valuation and the connections packages were designed in with similarities to the IFC data model. Table 7.2 illustrates the mapping between the building components of the proposed data model to the IFC4.
### Table 7.2: Mapping between the proposed data model’s concepts and classes and IFC 4 classes

<table>
<thead>
<tr>
<th>Building element</th>
<th>Class in data model</th>
<th>Class in IFC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property, parcel</td>
<td>Site</td>
<td>IfcSite</td>
</tr>
<tr>
<td>Building</td>
<td>Building</td>
<td>IfcBuilding, Pset_BuildingCommon</td>
</tr>
<tr>
<td>Building storey</td>
<td>BuildingStorey</td>
<td>IfcBuildingStorey</td>
</tr>
<tr>
<td>Space</td>
<td>Space</td>
<td>IfcSpace</td>
</tr>
<tr>
<td>Building assembly</td>
<td>_BuildingElement</td>
<td>IfcBuildingElement</td>
</tr>
<tr>
<td>Roof</td>
<td>Roof</td>
<td>IfcRoof</td>
</tr>
<tr>
<td>Beam</td>
<td>Beam</td>
<td>IfcBeam</td>
</tr>
<tr>
<td>Column</td>
<td>Column</td>
<td>IfcColumn</td>
</tr>
<tr>
<td>Slab/floor</td>
<td>Slab</td>
<td>IfcSlab</td>
</tr>
<tr>
<td>Stairs</td>
<td>Stair, StairFlight, Railing</td>
<td>IfcStair, IfcRailing, IfcStairFlight</td>
</tr>
<tr>
<td>Wall</td>
<td>Wall</td>
<td>IfcWall, IfcWallStandard</td>
</tr>
<tr>
<td>Building element part</td>
<td>_BuildingElement, BuildingElementPart</td>
<td>IfcBuildingElementPart</td>
</tr>
<tr>
<td>Framing members</td>
<td>FramingMember</td>
<td>IfcMember</td>
</tr>
<tr>
<td>Windows</td>
<td>Window, WindowPanel, WindowLining</td>
<td>IfcWindow, IfcWindowPanelProperties, IfcWindowLiningProperties</td>
</tr>
<tr>
<td>Doors</td>
<td>Door, DoorPanel, DoorLining</td>
<td>IfcDoor, IfcDoorPanelProperties, IfcDoorLiningProperties</td>
</tr>
<tr>
<td>Glass layers</td>
<td>GlassLayers</td>
<td>Pset_DoorWindowGlazingType’</td>
</tr>
<tr>
<td>Weep holes/other void openings</td>
<td>Weephole, voidOpening</td>
<td>IfcOpeningElement, IfcVoidingElement</td>
</tr>
<tr>
<td>Proxy elements</td>
<td>BuildingElementProxy</td>
<td>IfcBuildingElementProxy</td>
</tr>
<tr>
<td>Mouldings</td>
<td>Skirting, Cornice</td>
<td>IfcCovering</td>
</tr>
<tr>
<td>Eye linings (soffit)</td>
<td>Soffit</td>
<td>IfcCovering</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Ceiling</td>
<td>IfcCovering</td>
</tr>
<tr>
<td>Flooring</td>
<td>Flooring</td>
<td>IfcCovering</td>
</tr>
<tr>
<td>Connections (e.g. wall tie)</td>
<td>Connection, Mechanical Connection,</td>
<td>IfcRelConnectsElements, IfcFastener, IfcMechanicalFastener</td>
</tr>
<tr>
<td>Spatial structures</td>
<td>SpatialStructure</td>
<td>IfcSpatialStructureElement</td>
</tr>
<tr>
<td>Classification</td>
<td>Classification, ClassificationDefinition</td>
<td>IfcClassification, IfcClassificationReference</td>
</tr>
<tr>
<td>Costs/values</td>
<td>AssemblyCostObject, BuildingValue</td>
<td>IfcCostValue, IfcCurrencyRelationship</td>
</tr>
</tbody>
</table>

#### 7.3.3 Data model implementation

Subsequent to the design of the data model discussed in Section 7.3.2, the physical data models were developed. Extensible Markup Language (XML) file was selected in this research to implement the integrated information model. Therefore, the physical model was developed as an XML schema and according to XML schema specifications and the described UML packages in Section 7.3.2. This XML schema, as presented in Appendix 13, defines the structure of the XML file and the required
rules for definition of objects in it. This schema comprises eight namespaces, each of which corresponding to and implementing one of the UML packages described in Section 7.3.2. These namespaces are separately implemented in different XML Schema files (refer to Table 7.3) and are presented in the Appendix 13.

<table>
<thead>
<tr>
<th>Data model package</th>
<th>XML Schema file</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core package</td>
<td>UrbanFloodBase.xsd</td>
</tr>
<tr>
<td>Terrain package</td>
<td>Terrain.xsd</td>
</tr>
<tr>
<td>Flood package</td>
<td>Flood.xsd</td>
</tr>
<tr>
<td>Valuation package</td>
<td>Valuation.xsd</td>
</tr>
<tr>
<td>Material package</td>
<td>MaterialDomain.xsd</td>
</tr>
<tr>
<td>Building package</td>
<td>Building.xsd</td>
</tr>
<tr>
<td>Utility package</td>
<td>Utility.xsd</td>
</tr>
<tr>
<td>Connection package</td>
<td>Connection.xsd</td>
</tr>
</tbody>
</table>

While in this Chapter the design of the information model and its implementation were explained. The process of bringing together the various required data form BIM and GIS will be discussed in the next Chapter.

7.4 Chapter Summary

In response to the second objective of the research, in this chapter a framework for a micro-level FDA on buildings was proposed, its design and components were explored, and its benefits for a number of use cases were discussed. By adopting the theories from ABV and dynamic vulnerability, this framework allows for assessment of the physical damage to the building and subsequently its quantification and visualisation. This chapter explored the design of the physical damage assessment process in which benefits from the explored infiltration and damage assessment theoretical knowledge that was presented in Chapter 6. The framework dictates that following the assessment of the physical damage to the building, with the information about costs of assemblies and their 3D geometries, their damage can be quantified in monetary terms and visualised in an interactive 3D GIS environment.

The framework also proposes that for an effective damage assessment and communication, a unified information model is the key for bringing together and harmonising the required spatial and non-spatial information for the abovementioned process. This chapter detailed the design and
development of this information model according to the data modelling methodology. It first analysed the data requirements of the designed framework from BIM and GIS and classified them into 7 main categories. According to these results, the conceptual and logical data models in support of BIM-GIS integration for micro-level FDA were designed. This data model comprises of UML classes (containing various concepts and their attributes) and their relationships which are organised into 8 packages; i.e. Core, Flood, Terrain, Valuation, MaterialDomain, Building, Utilities, and Connections. The logical model was further used to design the physical data model which was implemented using an XML Schema and is presented in detail in Appendix 13.

According to the presented design of the framework, the next chapter provides the details of its implementation into a proof-of-concept prototype system which was used later in the research to demonstrate the feasibility of implementation of the framework in support of decision making in a real case scenario.
Chapter 8

Prototype Implementation
8 Prototype Implementation

8.1 Introduction

This Chapter presents the implementation of the proposed FDA framework into a prototype system to address the third objective of this research. It begins with an overview of the desirable functionalities of the framework according to the use cases and the requirements presented in Chapter 7. This is followed by the presentation of the overall architecture of the prototype system. This system uses layered architecture which not only generates a well-formed system design, but also increases its flexibility and adaptability to change. This chapter further discusses the layers of this architecture and provides a detailed explanation of the implemented workflows in the prototype system design.

8.2 Prototype system for micro-level FDA on building

As a proof of concept for the proposed FDA framework, this section aims to design and present a semi-automatic prototype system for the assessment and visualisation of flood damages to a building. Referring back to Figure 4.10, the prototype design process follows - in part - the "prototyping" methodology. Prior to discussing the prototype design, its architecture and the technologies employed for its development, a brief overview of the system functionalities is provided in the next section.

8.2.1 Functional overview

The design of any information system requires the prior knowledge of its required functions. According to the discussed use cases pertinent to different potential users (refer to Section 7.2) and the scope of this research, a number of functionalities for the FDA prototype has been envisioned which will be considered in its design and development. The implementation of these functionalities in the prototype can be used to demonstrate the feasibility of the realisation of the framework. These functions can be summarised as follows:

a. The prototype should allow for importing the required data for FDA processes;

b. The prototype should function in a way to support dynamic analysis of damage to structural and non-structural building elements⁸¹ against water contact, hydrostatic and hydrodynamic actions;

⁸¹ Those that are discussed within the scope of the research (refer to Chapter 6 and 7).
c. The prototype should allow for damage cost estimation for individual building assemblies and also for the entire building.

d. The prototype should allow detailing and communication of the location and mode of damage to individual building assemblies; and

e. The prototype should provide support for interactive 3D visualisation of building damage.

The formalisation of the above functions lays the foundation for adoption of suitable technologies for implementing the prototype system and designing its overall architecture. The architecture of the prototype is presented in the next section. It is also important to note in here that although the proposed workflows and processes in the design of the prototype are discussed in full in this chapter, the implementation however did not intend to fully automate all these processes for the development of the system.

8.2.2 Implementation architecture

The prototype for a micro-level FDA on a building in this work uses a layered architecture which is composed of four generic layers; i.e. Data layer (DL), Data Access Layer (DAL), Business Layer (BL), and Presentation layer (PL) (see Figure 8.1). While the components of each layer are permitted to interact with each other, the hierarchy of layers only allows access to functionalities at the lower levels. The framework was mainly developed using Object Oriented (OO) development and using the C#.NET programming language. While the benefits of object oriented have been discussed numerously in the computer science community, the .NET language was chosen according to its power and flexibility for application development and also the researcher's previous experience with this technology. In the following sub sections, the layers of the prototype's architecture and their details are discussed.
Data layer

The Data layer of the prototype contains all the required spatial and non-spatial data to undertake the damage assessment and visualisation processes. The core aspect of this layer is an XML file which was designed in accordance to the presented information model (XML schema) in Chapter 7. While the XML Schemas were stored on a web server for accessibility purposes, the XML file was maintained locally in the processing environment. In addition to the XML database, other text, Shapefile or IFC files are also created or maintained within the overall process of damage assessment and are considered within the scope of this layer.
To use the stored information in these files and the database for analysis of flood damages, the "Data Access" layer, as an intermediate layer, was designed to interact with this database and is discussed next.

**Data Access Layer**

In the layered system architecture, the data access layer is generally a part of the system (or software) that provides simplified access to the data that is stored in the data storage (e.g. a database or files). This layer is generally responsible for managing the physical data storage and data retrieval\(^2\). In the presented architecture, data access layer manages the internal library of objects, that in addition to other required data structures for system's internal use, representing the concepts designed in the XML database (see the XML schema). These objects unify the view of data (that may be sourced in different formats) for the higher layers in the architecture. Data access layer is the intermediate layer between the data and Business Layer of the architecture and provides object manipulation functionalities, data import/export and some query capabilities for the analyses of flood damage to a building.

**Business Layer**

Business Layer is generally responsible for maintaining the business (in here FDA) logic, processes and rules. With direct interaction between Data Access Layer, the Business Layer modules fetch their required data from the XML database (using data access layer mediators) and according to the defined processes perform various functions of the prototype including infiltration analysis, damage and cost assessment, etc. According to the outputs of these processes, they are either transferred/requested to/from the presentation layer (for visualisation or data inputs for processes) or sent back to data access layer for export or storage purposes. The business layer also contains additional functionalities to further manipulate the system's internal objects at a higher level.

**Presentation Layer**

Presentation layer in this architecture contains the User Interface (UI) of the system that presents the necessary interactions with the users: i.e. capturing user inputs or presenting the outcomes of the [lower level] processes to the user. For the prototype implementation, presentation layer spans across three different software packages; i.e. the prototype UI, ANSYS (2009), and ArcGIS platform (ESRI, \(^2\)https://www.simple-talk.com/dotnet/.net-framework/.net-application-architecture-the-data-access-layer/
The UI of the prototype system was designed using Windows application forms and consists of three major tabs corresponding to the first three phases of the framework (see Figure 8.2).

The first tab (data preparation) provides the interface for the user to import the required data from external sources. The "Physical Damage Assessment" tab (see Figure 8.3) allows users to initiate the execution of the infiltration monitoring and dynamic damage assessment processes (see Section 8.2.3 for details) which can be presented to the user in real-time using the designed UI in Figure 8.4.
Prototype implementation

Figure 8.3: FDA prototype main UI (Physical damage assessment tab)

Figure 8.4: FDA prototype main UI (Infiltration monitoring and damage assessment)

The last tab (Results), as presented in Figure 8.5, allows users to export the outputs of damage assessment process to a suitable format; i.e. tabular (using CSV files) or 3D ShapeFiles to be visualised and queried in an interactive 3D GIS software. In addition, according to the principles of dynamic vulnerability, intermediate results (the damage lookup tables containing the building
elements’ damage status for that time step, the time steps that contact with water was initiated and ended) can also be further queried and inspected by the user.

![Figure 8.5: FDA prototype main UI (Results tab)](image)

As discussed earlier in this section, the ANSYS software forms a part of the UI of the prototype which is used throughout the failure analysis of window glazing. The user interacts with this software to simulate the loads on the panel and obtain the maximum generated stress ($\sigma_{\text{max}}$) in the glazing from the flood actions. Figure 6.15 and Figure 6.16 illustrate the UI of the ANSYS tool. In the glazing damage assessment process, the feedback of the user is required and is obtained using the designed UI in the prototype system (see Figure 8.6). By comparing $\sigma_{\text{max}}$ with $\sigma_d$, the user can feed in the analysis result for each panel of different size against different flood parameters.
Lastly, the ArcGIS platform (ESRI, 2015a), and particularly the ArcMap and ArcScene tools were used to provide an interactive [2D and/or 3D] visualisation of (a) the flood parameters around the building, and (b) the damage to the building assemblies. Figure 3.1 and Figure 4.7 presented the ArcScene and ArcMap UIs.

8.2.3 System processes

This section presents the design and implementation of its workflows according to the discussed processes in the proposed framework (see Section 7.2) and the guidelines provided for FDA calculations (see Chapter 6). These workflows are classified into data import, damage assessment, and export (and presentation).

Data import

As part of the data preparation phase in the framework and in response to the first functional requirement of the prototype, a set of different processes are designed to bring together the FDA data requirements (refer to Section 7.3.1) into the designed XML database. It was found in this research that direct import of such data requires some degree of data preparation and pre-processing. In here, pre-processing and importing of the information from GIS and BIM for building information, flood, elevation, parcels, costs, etc are presented.

The first set of information to be acquired includes the elevation model. As indicated in Section 7.3.2, the Terrain package of the designed information model allows for elevation representation in
either TIN model (a series of triangles) or the spatial distribution of a set of 3D points. Depending on the elevation source (contours, TIN layer, etc.), the presented process in Figure 8.7 (using UML sequence diagram) was adopted to import the elevation data into the XML database. This diagram shows two alternative processes that are pertinent to situations where the elevation input is a TIN or in point form.

Figure 8.7: Import process of elevation data into the XML database

Depending on the elevation source, it must first be converted to either triangles or points for further conversion to GML format. This process is performed using the ArcGIS toolboxes and is schematically illustrated in Figure 8.8. On the other hand, FME (as part of the ArcGIS Interoperability Extension package) was employed to convert between the triangle shapes and their GML representation. The prototype system uses this input to recreate these triangles in the TinTerrain format and store this information in the XML database. For the 3D points in Shapefile format, they can be transformed directly into their gml:point equivalent within the MassPointTerrain template. The CatFood project provides powerful libraries for parsing and manipulating 2D ShapeFiles. Since limited functions are available for 3D geometry manipulation within this project, in this research the libraries of this project were extended to support read/write and some limited manipulation of 3D ShapeFiles (3D points and ESRI Multipatch geometries).

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83 Or it can be converted to point distribution (e.g. DEM or contours).
Figure 8.8: Elevation pre-processing conversions

Figure 8.9 illustrates the designed UI for importing the elevation surfaces (a similar dialogue was designed for elevation points).

Another crucial data input for the prototype includes the flood parameters. As discussed in Section 4.5.4, this research has adopted MIKE software package for simulation of the flood; therefore, the flood data acquisition processes were designed according to the output of the MIKE software. MIKE, using its embedded Mike2Shp tool, allows for export of the model outputs into one or more Shapefiles depending on the number of time steps in the flood simulation. Each output Shapefile contains a set of triangles that each has attributes pertaining to the flood parameters (i.e. flood depth and its velocity vector components) in its vicinity. The initial investigation of the output of the Mike2Shp showed that the exported polygons (triangles) were not generated properly\textsuperscript{84} and on the other hand the export function does not provide the point distribution of flood parameters. Therefore,

\textsuperscript{84} The triangles miss a line to close the geometry as a polygon.
a geo-processing workflow was designed using "ArcGIS ModelBuilder" to iterate through each ShapeFile, manipulate and transform the data, and generate two sets of outputs (see Figure 8.10) which include (a) the flood surfaces by direct extraction of the triangles from the original MIKE outputs, and (b) a point distribution of flood parameters for each time step via adopting the centroid of each triangle as the representative of the flood parameters in that vicinity.

Figure 8.10: Pre-processing workflow for flood parameters extraction

The "shape manipulation and transformation" mode in Figure 8.10 is the main responsible component to fix the geometry and generating point distribution of flood parameters. The details of this process are illustrated in Figure 8.11. Where the blue steps intend to parse the shape files in the directory, the yellow, green, purple and orange are responsible for fixing the geometry, calculate additional information (i.e. velocity and magnitude of velocity), and create point and triangle representation of flood data. It is noted that those circles marked with [P] are input parameters of the model and appear in its UI.

Figure 8.11: Workflow for fixing exported geometries and their conversion to triangles and points representation in the ArcGIS environment

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86 Representing the center of mass of the geometric object.
Once these two flood parameter representations were extracted, they would be imported using the tools provided in the designed prototype UIs. Figure 8.12 illustrates the import process of the maximum flood surface (for visualisation only) and the point distribution of flood parameters for different time steps.

Figure 8.12: Pre-processing workflow for flood parameters extraction

In the first step, the designed pre-processing workflow in ArcGIS fixes the geometry of the outputs of the MIKE simulation and generates the flood surfaces and points and finally stores them in two separate folders. For importing the point distribution of flood parameters, the user opens the "Flood Point Extraction" dialogue window (see Figure 8.13 [bottom]) and subsequent to entering the required
inputs (including the directory of flood point ShapeFiles) the form can be submitted. This form executes the import module in the BL, and using the CatFood project, the values of each point for different time steps are extracted.

![Flood Surface Extraction Form](image1)

![Flood Point Extraction Form](image2)

Figure 8.13: Flood surfaces extraction for a particular time step (top); flood point time-series extraction (bottom)

Furthermore a gml:MultipointCoverage object containing its information is created according to the guidelines in the designed XML schema (refer to Section 7.3.3). An example of this data is presented in Figure 8.14. This object is then stored in the XML database and the user is further notified using the PL modules about the result.
Figure 8.14: Example of generated XML code for point distribution representation of flood parameters

On the other hand, for importing the maximum flood surface (or in a similar way for a series of surfaces for each time step), the exported triangles (polygons) from Mike2Shp outputs are first converted to their equivalent CityGML polygons. These polygons are then imported and converted to a flood body (RepresentedBySurface) using the "Flood Surface Extraction" dialogue window (see Figure 8.13 [top]). For this purpose, by entering the time step containing the highest water level and indicating the input folder containing the surface representation of MIKE outputs by the user, this information is passed to Business Layer import module and the flood surfaces are stored in the XML database. Similar to above, the user is notified regarding the result of this process.

The next information to import includes the parcel (site) information. According to the nature of the parcels ShapeFiles (simple polygons with attributes), their semantics and geometries (polygons) can be extracted and transformed into the XML database directly using the CatFood project libraries. This process is summarised and illustrated in Figure 8.15.
On the other hand for the building information, a workflow was designed for extraction of its assemblies, their classification, materials and assembly costs and their transformation into the structure of the designed information model. Although these processes (see Figure 8.16) can be automated where sufficient time and resources are available, yet for this research they were performed manually. The manual extraction of this information was feasible for this research since the data was extracted only once for use in one case study (see Chapter 9). However, for the regular use of the prototype for different buildings and cases, manual data import is too costly and labour-intensive and the automation process would be a crucial requirement. In the designed process, first the BIM model is exported to its standard IFC format, and on the basis of the IFC model, two sub-processes are followed to extract and transform (1) geometry and (2) attributes, classification (if exist), materials, and costs of building assemblies from IFC to the GML format.

For geometry transformation, with the support of FME engine in the ArcGIS Interoperability Extension, the IFC file is first converted to an ESRI geodatabase file. For each FeatureClass (type of building element) in the geodatabase, the "Quick export" tool is used to convert each feature to its CityGML equivalent. Since no prior mapping has been done between the feature classes and CityGML in the FME engine, all output objects are in the form of "GenericCityObject" with a TAG attribute (their unique identifier) which was derived from the original IFC. The next step in the process is to combine all the separately generated CityGML files into one single file that contains the geometry of all building elements in GML format.

87 For more information about the ESRI geodatabase and feature classes visit http://webhelp.esri.com/arcgisserver/9.3/DOTNET/index.htm#geodatabases/an_ove-2050156920.htm
On the other hand for transforming the assembly attributes, SpatialStructures, classifications, materials, and costs to the format of the designed information model, first the IFC file is converted to its equivalent IfcXML format\(^{88}\) (see Section 3.3.4) to facilitate the querying process using the existing XML libraries in the .NET framework. Via querying the building elements in the IfcXML file, the classification, material, and cost objects, as well as the other relevant attributes of the assemblies are extracted. Once this information and their geometries are separately obtained, according to the rules defined in the Schema of the XML database (and the mapping provided in Table 7.2), the building and its elements are reconstructed in the new format. This information is separately stored in the XML database (according to the guidelines presented in the Core package in Section 7.3.2), therefore for preventing redundant definitions, these descriptions (or their reference) in each assembly is replaced with a reference to their new corresponding unique identifier in the database.

The process of extracting the utilities and storing their information in the XML database is similar to above. For each building and utility element an empty record (no damage to the assembly and with water contact initiation and ended time step set to -1\(^{89}\)) with the ID of the element is stored in the Damage-LookUpTable of the XML database.

\(^{88}\) Using the direct export or open source BIMServer (2015)

\(^{89}\) Representing the situation that water has not contacted the element yet.
It is important to note that the building elements and the flood parameters are not well-linked with each other and an additional piece of information would be required to establish that missing link for determining the associated loads and water contact with elements. This linking information is extracted and stored separately from the XML database and using a designed geo-processing workflow in ArcGIS ModelBuilder (see Appendix 14). In this workflow, following the extraction of the point distribution of flood parameters, the external facade of the building (extracted from the outside lines of the external walls from the BIM model) is used as an input to extract the closest set of flood points to the building. These flood points were identified by creating a 2-3 meter buffer around the external walls. The building facade lines are first broken on the basis of their vertices. Further, a "Voronoi" diagram\(^90\) (O'Sullivan and Unwin, 2003, pp 127) of the identified flood points is generated that subdivides the plane in the way that the created regions correspond to areas that are closest to each point. Using the generated regions in the GIS environment and offsetting them with building facade elements, these elements are further broken down to smaller segments each of which representing the effective application areas of flood points on the facade of the building. These elements are created for each time step of the flood and are stored in a folder. By employing the developed libraries in the Business and the Data Access layers, these separate ShapeFiles were parsed and a separate XML file was created that contain the flood parameters of different time steps for each unique building facade element. An example of the data in this XML file is illustrated in Figure 8.17 for a building facade element for time steps 436 and 437 of an example flood simulation.

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\(^90\) It is also known as "Thiessen diagram".

![XML Format Example](image-url)
Prototype implementation

Complementary to the above XML file, a simple list data structure was also designed as an internal object in the data access layer to maintain the reference of each external building element (e.g. walls or windows) and their corresponding building facade element object reference. This facilitates quick access to flood parameters pertaining to individual external building elements (e.g. walls, external utilities, windows, doors and other openings) at each time step. The linkage between the two was established and the above list was manipulated in the data preparation phase by testing the geometry overlap between every 2D footprint of building element and the 2D facade element line segments. The overlay spatial analysis was performed using the embedded functions of the ArcGIS .NET development kit adopted in this project.

**Flood infiltration and damage assessment**

In the previous section the implemented process of preparing the required data for micro-level FDA on building was discussed. This section on the other hand presents the implementation of the damage assessment process which is illustrated in Figure 8.18. This function addresses the second functional requirement of the system.
Figure 8.18: Implemented damage assessment process in the prototype system

In the damage assessment process, the user first loads the prepared data in the data preparation phase using the load project UI accessible in the main menu of the prototype (see Figure 8.19). Using the provided window, the user must indicate the path to the XML database and the related files for flood parameters for building facade elements. At this step, the user also sets the output folder of the calculations using the provided window "set project outputs" in the Figure 8.19. The loading process calls the "Load" module in the business layer and relevant components in the data access layer are activated. The required information is fetched from the database and the other relevant files and is loaded into the internal objects of the system. The loaded objects are then transferred to business layer and the user is further notified about the result of the loading process using presentation layer components in the UI.
Once the required data are obtained at the business layer and the previously discussed intermediate XML and ShapeFiles are created, in the next step the user executes the damage analysis process using the provided button in the Physical Damage Assessment tab in the UI of the prototype (see Figure 8.3). This component of the presentation layer executes the damage assessment module in the business layer which evaluates the damage to each component in two overall steps; i.e. (1) calculation of infiltration and depth of water for each time step, and (2) evaluation of damage to each building assembly dynamically and for individual time steps. According to the methods provided in Chapter 6, a loop was implemented for each time step to first calculate the infiltration through wall panels, weep holes, air bricks, windows, doors and sliding doors and then to evaluate the damage according to the calculated depth of water for outside, inside and for the wall cavity spaces. As Figure 8.18 illustrates, this process is mainly undertaken in two business layers' modules, the infiltration and damage components.

In the first module, following the calculation of infiltration (discharge) from each discussed building assembly (see Section 6.3), the relevant modules in the business layer for calculation of depth of water inside of the building and in each wall cavity space is used. These water depths are stored in an internal object and are used along with the time step number as parameters for the damage assessment module. These water depths are visualised and presented to the user in the real time using the user interface that was previously presented in Figure 8.4.

The damage analyses for building components and utilities are implemented and performed according to the provided processes discussed in Chapter 6. Except for the failure analysis of window and door glazing panels, the damage assessment process regarding the other building assemblies can be automatically performed using the prototype system. As discussed in Section 6.4.4, the user feedback is required to determine the failure of a glazing panel of a particular size against the specific
water velocity and the depth differential between the inside and outside. This information is extracted in the damage assessment process according to the base height of the panel and the obtained flood parameters are reported to the user (see Figure 8.6). They are further used to run the ANSYS model and identify $\sigma_{\text{max}}$ for the panel to be compared with $\sigma_d$ from the standards. The result of the analysis is submitted by the user. The BL captures the information and incorporates the result in the look up tables.

Once the damage to all the building elements was evaluated against the flood actions for a particular time step, the damage look up tables and the internal objects are updated and the analysis moves to the next time step until no more time steps remain. The damage lookup tables are further stored and updated in a designated folder for later inspection by the user. Figure 8.20 illustrates an example of damage lookup table file. Subsequently, the user is notified using the PL that the analysis is completed and can export the results according to his/her needs.

**Data export**

As discussed earlier in Section 8.2.2, the results of the damage assessment process can be exported to 3D ShapeFiles for visualisation purposes, or to tabular format for details of the damage. For the first export, the geometry and other details of building elements (including their mode and cost of damage) are transformed and stored in ESRI ShapeFiles using the steps depicted in Figure 8.21.
In this process the user first opens the "Write to Shapefile" window in the "result" tab of the prototype UI. By indicating the output folder for storing the generated ShapeFiles and submitting the form, the exporter module in the business layer is activated and executed. The exporter module extracts the geometry and attributes (that may include the reference to other elements based on the relationships) from the cached internal objects and passes them to the data access layer shape exporter module. Each ESRI Shapefile contains a .SHP, .DBF, and .SHX as mandatory files. Where the SHP file contains zero or more shapes (geometries), DBF files have attribute records linked to their geometries in the SHP file. The building elements are grouped into their general types (e.g. switching devices and electrical distribution boards into electrical utilities) which are all stored in one single
Shapefile (e.g. utilities). This module creates ESRI geometry types as shapes (with unique ID of the object) and stores them for each building element in its .SHP file. On the other hand, for each record (identified using its ID), attributes are stored separately in ".DBF" file. Other relevant files (i.e. .PRJ for projection and .SHX for indexing) are also created and stored to generate the Shapefile. This addresses the fourth functional requirement of the system. The write Shapefile module stores the information according to the guidelines provided by ESRI (1998).

In addition to the building elements, for the flood and elevation, the stored triangles are extracted in the same way and their relevant ShapeFiles are created and stored in separate folders under the indicated output location. Once ShapeFiles are created for all building elements, utilities, flood and elevation, a message is sent back to the business layer and subsequently the presentation layer to notify the user about the results of the export process.

For exporting the overall building damage or damage cost of its assemblies, as Figure 8.22 illustrates, first the "Export Tabular" dialogue window is loaded from the "Results" tab of the prototype. Via indicating the output folder, the user can submit the form which creates a request to the exporter module of the business layer. This module identifies the damaged building elements in the simulation by inspecting the final damage lookup table. For each damaged building element (where its damage state is greater than zero) in the lookup table, the module extracts the information about the building element, its unit costs and calculates its damage cost. This process is repeated for all damaged assemblies and then the total cost is calculated in the system and according to Equation 7.3. Following this step, a table with records of assemblies, their details and costs is created and using the export module in data access layer, its details are saved in Comma Separated Values (CSV) format within the output folder. The user is then notified about the result of process using the presentation layer. This function addresses the third functional requirement of the prototype.
In addition to GIS export and tabular outputs, the damage look up tables generated during the damage assessment can be accessed and inspected for better understanding of the damage generating mechanisms on the building. Where a specific folder in the system is dedicated for these lookup tables, the user can click on the button "View Damage Lookup Tables" in the prototype to open an explorer window showing the created damage lookup tables for each time step of the analysis. These files are tab delimited text files (as illustrated in Figure 8.20) containing the unique identifier of the building elements, time steps that water contact with the element was initiated and ended[^1], the duration of water contact with the element, and the damage state of the element until that time step.

**Presentation of outputs**

Following the export of the ShapeFiles for each building element type, these ShapeFiles can be opened using ESRI ArcScene and be added to a map as a layer. They can be styled and colour coded according to their damage states and the preference of the user. Furthermore, the user can obtain more information about the mode of damage, its cost and other details of the element by using the “identify”

[^1]: If it has not ended yet, value -1 is indicated.
tool or opening the attribute table of the layer. On the other hand, the tabular CSV file can be presented using Excel for further manipulation by the user. These capabilities address the fifth functional requirement of the prototype system.

8.3 Chapter Summary

This chapter presented the development of a prototype system for assessment, quantification and visualisation of the flood damage to building at a micro level. This system was developed as a proof of concept of the concepts and processes in the presented framework in Chapter 7. This chapter first explored the desirable functions of the system and further presented the design of its layered architecture. Each layer in the architecture of the system was discussed and various processes within each and their interactions for infiltration and damage assessment as well as data import/export were presented.

In the next chapter, the application of the framework and the designed prototype system for assessment and visualisation of the flood damage to a proposed building in a real life scenario will be presented. In addition, the result of validation of the framework on the basis of expert feedback (face validity) will be reflected and discussed.
Chapter 9

Framework Evaluation


9 Framework Evaluation

9.1 Introduction

This chapter, to address the fourth objective of this research, presents and discusses the outcome of the framework evaluation. As discussed previously in Section 4.5.4, the evaluation in this research is two-fold and intends to

a) Demonstrate the framework in a real life scenario for assessment of the potential damage and risk to a proposed building in a flood prone area; and

b) Validate and verify the framework.

To present the outcomes of each aspect of the evaluation, this chapter is divided into two separate parts. While the first part demonstrates the application of the framework in a case study in the City of Maribyrnong in Melbourne, the second part of this chapter presents the result of verification process and the validation of the framework design from experts' point of view. The chapter is subsequently summarised and the conclusions from the evaluation process are elaborated.

9.2 Case study

In this section, the demonstration of the application of the proposed framework for assessment of flood damage and risk to a proposed building in the Maribyrnong council is presented. As discussed in Section 4.5.4 this study was conducted in collaboration with the Maribyrnong council and the floodplain management authority in Melbourne metropolitan area, the Melbourne Water.

9.2.1 Case study setting

The statistics in the state of Victoria in Australia and specifically in the Melbourne Metropolitan area show that over 82,000 properties within this jurisdiction are at risk of floods. More than 40,000 of these properties contain dwellings with risk of above-floor inundation (Melbourne Water, 2013). This significantly increases the importance of the flood risk management in this region for both the existing settlements and the future developments. The Maribyrnong council is one of the flood-prone local governments within this area that as discussed in Section 4.5.4, it has been affected severely for a number of times in the last century. Therefore according to the existing risks in this area, many flood-prone properties have been acquired by the council to prevent the construction of settlements of any type in them. In addition, as part of the planning and building permit issuing process within the
overarching land development process, Maribyrnong council requires the assessment of flood risk to any proposed development prior to its construction. This risk assessment is undertaken in collaboration with Melbourne Water as the primary referral authority for managing the flood risks to buildings in the area. In this process, one of the major questions to be answered is that “if a particular proposed development in the flood prone area like Maribyrnong was designed to be resilient to the potential flood risks and if it can be permitted for construction?” However, in their current practice, the council and Melbourne Water use *Freeboard*[^1] as the primary decision making tool for assessing the suitability of a proposed building for construction in this area. The maximum threshold for the freeboard in this council is set to 300mm (Melbourne Water, 2014). Therefore if for any proposal this threshold is exceeded, the building cannot be allowed for construction. In this way, by not accounting for the resilience of the building construction and potential damages, the evaluated risk is based on assumptions and not evidence-based.

With the interests and collaboration of both parties in this research, an area within the Maribyrnong council was selected (see Figure 9.1) and a case study was conducted to assess the benefits of this research to their process. Accordingly, the potential flood damages and risks to a proposed single-storey brick veneer house with slab-on-ground foundation were estimated against a design flood with 1% probability of occurrence. The council and Melbourne Water, as the common planning instrument, require any new development to be resilient to flood events of this magnitude (Melbourne Water, 2014).

[^1]: *Freeboard* is the above inhabitable floor inundation level.
9.2.2 Damage assessment to a building in Maribyrnong

The building of focus in this study is the most common Australian type (Geoscience Australia, 2014). It is a brick veneer construction with plasterboard lining and integral garage that are built on a slab-on-ground foundation. As illustrated in the Appendix 15, the slab of the house is raised to about 0.7m to reduce the flood damage to the building. According to the provided guidelines in Chapter 7 and via using the developed prototype system (refer to Chapter 8), the damage and subsequently the risk to this building was assessed and presented. In the following sub sections, the process of conducting this case study and its outcomes are presented.

Data Preparation

The data preparation phase intended to gather all the data requirements discussed in Chapter 7 and bring them together for storage in a unified XML database and for use in the damage assessment. In here, different aspects of this phase for this case study are explained.
Building and property information

The building information, as discussed in Chapter 7, is a crucial data requirement for this case study. Following an initial survey of the existing buildings as well as the investigation of the proposed buildings in the case study area, with collaboration of the council, a proposed building was selected and its respective planning documents were provided for this research. These documents are as follows and contained various aspects of the building as well as the details of the materials used for its components.

- The design and engineering plans\(^9\) submitted to the council by architects, engineers (including civil and geotechnical); and
- The sustainability analysis report by a local consultancy firm.

Where the BIM model of the building was not submitted to the council, the abovementioned documents along with the council's property information (in GIS format) were used for the development of a geo-referenced 3D BIM model of the house (see Figure 9.2) using Autodesk Revit (AutoDesk, 2015). The property information included the council parcels, their address and respective spatial data (i.e. polygon geometries). In addition, based on the type of the building components used for construction of the house, their replacement costs were acquired from the up-to-date Australian construction cost guide (Rawlinsons, 2014) and stored in the BIM model. On the other hand, the value of the building was obtained according to the cost of construction of the building in the submitted documents to the council.

\(^9\) Refer to Appendix 15 for some of the received plans from the council.
Hazard simulation and extraction of the flood parameters

To obtain the flood parameters, as discussed and justified in Section 4.5.4, MIKE 21 hydrodynamic simulation software (DHI, 2015) was employed and a 1-in-100 year flood in the study area was simulated. The discharges from the Maribyrnong River and the other required parameters (e.g. boundary conditions) for the simulation were provided by MW based on their previous flood mapping studies. The river discharges at the north boundary of the case study area (indicated by NB in Figure 9.4) for a 1-in-100 year flood was calculated using the rainfall and runoff modelling software RORB and provided by Melbourne Water. The modelled discharges are illustrated in Figure 9.3(right).

![Graph: South boundary rating curve (left); North boundary river discharges for the case study area (right)]

Figure 9.3: South boundary rating curve (left); North boundary river discharges for the case study area (right)

On the other hand, for the south boundary condition (SB in Figure 9.4), a rating curve (a diagram for relating discharge to their corresponding stage for a given point on the river) from previous Melbourne Water studies was provided and used (see Figure 9.3[left]).
The simulation employed a detailed elevation model of the study area (0.5m contours). The spatial distribution of building footprints was on the other hand employed to illustrate the building effects on the flood characteristics. By employing the most suitable method of representing buildings in flood simulation (amongst the alternatives illustrated in Figure 7.3), as indicated by Schubert et al. (2008), the buildings were blocked out from the used elevation model and accordingly a flexible mesh was created in the MIKE software for the bathymetry of the case study. Their flexible sizes - as opposed to fixed-size rectangular grids - allowed the topography triangles to be denser in the vicinity of the buildings and coarser in the other locations for computational efficiency. The resulting mesh is illustrated in Figure 9.5 and Figure 9.6 which in detail show the elevation in the mesh as well as the excluded buildings using polygons (represented in white with highlighted vertices and a green point inside to indicate their exclusion from the elevation model).
Figure 9.5: The generated mesh with buildings blocked out of the elevation model for the entire study area

Figure 9.6: Details of the generated mesh with buildings blocked out of the elevation model
By using the generated mesh, the boundary conditions, the surface roughness, and specifying the output time steps (set to 10 minutes interval) the model was set up (see Figure 9.7) and the flood was simulated.

![Figure 9.7: Flood model set up in MIKE 21](image)

In addition, to test the influence of the presence of the buildings on the flood parameters, the simulation was executed once more using a separate mesh without the consideration of buildings (refer to Figure 9.8). The results of this comparison revealed some notable differences between the spatial distribution of the depth and velocity of water at the location of the building under investigation. Such effect may adversely impact the damage assessment and for this reason only the outputs from the simulation with buildings were used in this case study.

![Figure 9.8: Modelling the flood without (left) and under the influence of buildings (right)](image)
The outputs of the simulation comprised the spatiotemporal distribution of water depth and velocity for 1170 time steps (approximately 8 days of flooding). As discussed in Section 8.2.3, the output of the simulation was exported to GIS (Shapefile) using Mike2Shp toolbox in MIKE package, creating a Shapefile for every time step. The triangular surface output of the MIKE simulation was exported to GIS and visualised in ArcMap software. It was realised that the simulated flood was in good agreement with the Melbourne Water’s previous flood study in this area highlighted by red (see Figure 9.9[left]). Also, the velocities of water were inspected to ensure they are reasonably modelled (see Figure 9.9[right]). Subsequent to this initial check, the spatial distribution of depth and velocity vector-components (points and triangles) were extracted and imported to the XML database according to the process discussed in Section 8.2.3.

The elevation model was extracted using the process illustrated in Figure 8.7 and both TinTerrain and MassPointTerrain representations were stored in the XML database. On the other hand, the parcels and building information (including the building assemblies, their costs, classification, and connections) were extracted from the BIM model of the house using the processes illustrated in Figure 8.15 and Figure 8.16.

As the last step in the data preparation phase, the building facade elements and their respective flood parameters were extracted and stored in a separate XML file. For this purpose, the point distribution of the flood parameters was retrieved from the GML file, imported to ArcGIS tool and then a Voronoi diagram of these points was generated using the ArcGIS toolboxes (see Figure 9.10). Using this diagram in the GIS environment and overlapping it with the building facade line elements...
(obtained from external walls outline in BIM), the effective application areas of each flood point could be identified. According to these application areas, the facade lines were broken down into these smaller elements and assigned a particular depth and velocity value at each time step. The visualisation of these elements in GIS environment is illustrated in Figure 9.11 (see Figure 8.17 for the XML representation of this data).

![Figure 9.10: The Voronoi diagram of the flood parameters point distribution around the building](image)

![Figure 9.11: Flood parameters for individual facade elements of the building](image)

Using the flood parameters along with the referred methods in Section 6.2, the pressure distribution (as a result of combined hydrostatic and hydrodynamic actions) on each external building component
could be estimated. This information was then used to assess the physical damage to the building assemblies. The outcomes of this phase will be presented next.

**Physical damage assessment and quantification**

The physical damage assessment, as the second phase of the proposed framework, involves a number of interlinked tasks; i.e. calculation of volume of infiltrated water to inside the house and cavity spaces, calculation of flood actions, and lastly assessment of damage to individual components of the building. These tasks were performed for the case study according to the implemented guidelines of the framework in the prototype system discussed in Chapter 8.

The infiltration monitoring module in the prototype system calculated the FIR, FRR and accordingly the depth of water for the house interior and each of the veneer walls' cavity space. At the end of each time step a separate file was created and/or updated for each wall to be used for calculation of flood actions. An example of this information for a wall with unique identifier "Vbd89r0b" is presented in Figure 9.12. This information in addition to the water level inside each wall's cavity space was communicated to the user at the end of each time step using the UI provided in the prototype system. Figure 9.13 presents a snapshot of these outputs while the simulation was in progress at time step 172.

![Figure 9.12: Water depth outside and inside cavity for each wall and for different time steps of infiltration modelling](image)

The output of the completed simulation of water infiltration and the calculated water depths for the house in the case study is illustrated in Figure 9.14. While the depth of water inside (orange line in the
figure) is a representative of the absolute depth above the floor level, the water level value (red line) shows the depth of water with the ground elevation as its base. This figure illustrates the flood depths inside and outside the house for only four days of the flood. This is because the water depths below the floor level were unlikely to cause damage to any of the building components.

At the end of each time step, the damage to each building assembly was evaluated, the damage lookup table was updated, and the results were logged for review of the user at later stages. Figure 9.15 shows an example of the log file for step 111/1170 of the damage assessment simulation in this study.
Once the damage assessment process was completed for all time steps, the ultimate damage state of building assemblies are obtained at the end of last time step and those damaged assemblies are filtered and extracted. As discussed in Section 8.2.3, the intermediate damage states can also be accessed and inspected by the user via the provided UI in the prototype system.

For each of the damaged assemblies, according to their details, a list of damage costs for individual assemblies as well as the whole building is generated and exported (via request of the user) to a CSV file. In addition, the outputs are then exported to GIS format using the provided function in the prototype system (refer to Section 8.2.3) for further inspection of flood damages to the building. These outputs are discussed further in the next Section and can be communicated to the relevant stakeholders (refer to Section 7.2) for decision making.

**Communication and reporting**

Once the outputs of damage assessment were successfully exported using the provided functions in the prototype system, the user can further inspect the outputs using a suitable tool.

To visualise the flood around the building, the exported GIS ShapeFiles were opened in ArcScene and colour-themed according to the preference of the user. The elevation, buildings and the surface representation of the flood were used to present the overview of flooding situation in the case study as shown in Figure 9.16.
By increasing the zoom level to the building under investigation and turning on the exported building layers as well as the point and surface representations of the flood in ArcScene, this information were also visualised in 3D using this GIS software (see Figure 9.17). This interactive visualisation can provide a better understanding of the flooded house for a range of decision makers and beyond the 2D visualisation capabilities. It further creates a strong visual impression of the 3D world, improves the communication of risks, and provides a better tool for inspection and the analysis of data (Ross, 2010; Pouliot et al., 2011; abdul-Rahman et al., 2011).

On the other hand, the exported CSV files were opened in Microsoft Excel and the details of the damages to the building and its components were further presented to the user. These results, as Table 9.1 illustrates, indicate the total damage of AUD$51,410 to the building under investigation from the simulated flood and further details the breakdown of the damages to its assemblies. In here, the
significant contribution of the timber flooring and wall linings to the overall damage costs (approximately $32,650) is notable. By knowledge of such impacts, the designer can modify the design of the house or use alternative components’ materials to mitigate such damages. On the other hand, where damage is inevitable, by selecting components with lower replacement costs, they can reduce the overall damage costs to an acceptable level.

Table 9.1: Summary of damage to the building (the unit costs are based on Rawlinsons, 2014)

<table>
<thead>
<tr>
<th>Item</th>
<th>Building Component</th>
<th>Type</th>
<th>Count</th>
<th>Overall units</th>
<th>Unit of Measurement</th>
<th>Unit costs (AUD$)</th>
<th>Total cost (AUD$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Timber-framed highlight window with sliding (25% opening), one operator to open (one sliding sash)</td>
<td>Window</td>
<td>1</td>
<td>1</td>
<td>each</td>
<td>420.00</td>
<td>420.00</td>
</tr>
<tr>
<td>2</td>
<td>A &amp; L aluminium Timber Entry Frame double sidelight (Entry door solid core)</td>
<td>Door</td>
<td>1</td>
<td>1</td>
<td>each</td>
<td>227.00</td>
<td>227.00</td>
</tr>
<tr>
<td>3</td>
<td>Hollow core door (standard 35m thick)</td>
<td>Door</td>
<td>13</td>
<td>13</td>
<td>each</td>
<td>151.00</td>
<td>1,963.00</td>
</tr>
<tr>
<td>4</td>
<td>CSD pocket sliding door (single panel)</td>
<td>Door</td>
<td>2</td>
<td>2</td>
<td>each</td>
<td>211.00</td>
<td>422.00</td>
</tr>
<tr>
<td>5</td>
<td>CSD pocket sliding door (double panel)</td>
<td>Door</td>
<td>1</td>
<td>1</td>
<td>each</td>
<td>305.00</td>
<td>305.00</td>
</tr>
<tr>
<td>6</td>
<td>Electric meter box</td>
<td>Electrical</td>
<td>1</td>
<td>1</td>
<td>each</td>
<td>855.00</td>
<td>855.00</td>
</tr>
<tr>
<td>7</td>
<td>Double power point</td>
<td>Electrical</td>
<td>30</td>
<td>30</td>
<td>each</td>
<td>45.00</td>
<td>1,350.00</td>
</tr>
<tr>
<td>8</td>
<td>Single lighting switch</td>
<td>Electrical</td>
<td>15</td>
<td>15</td>
<td>each</td>
<td>24.00</td>
<td>360.00</td>
</tr>
<tr>
<td>9</td>
<td>Timber skirting</td>
<td>Joinery</td>
<td>55</td>
<td>137.88</td>
<td>m</td>
<td>15.10</td>
<td>2,081.98</td>
</tr>
<tr>
<td>10</td>
<td>Ceramic tile skirting</td>
<td>Joinery</td>
<td>21</td>
<td>45.22</td>
<td>m</td>
<td>21.50</td>
<td>972.23</td>
</tr>
<tr>
<td>11</td>
<td>Carpet flooring (rubber underlay included)</td>
<td>Flooring</td>
<td>6</td>
<td>77.181</td>
<td>sqm</td>
<td>58.50</td>
<td>4,515.08</td>
</tr>
<tr>
<td>12</td>
<td>Timber flooring</td>
<td>Flooring</td>
<td>1</td>
<td>101.027</td>
<td>sqm</td>
<td>205.00</td>
<td>20,710.53</td>
</tr>
<tr>
<td>13</td>
<td>gypsum wall board</td>
<td>Lining</td>
<td>82</td>
<td>418.919</td>
<td>sqm</td>
<td>28.50</td>
<td>11,939.19</td>
</tr>
<tr>
<td>14</td>
<td>gypsum wall board - Water resistant</td>
<td>Lining</td>
<td>26</td>
<td>93.32</td>
<td>sqm</td>
<td>32.50</td>
<td>3,032.90</td>
</tr>
<tr>
<td>15</td>
<td>Insulation (Rockwool batts for wall timber framing)</td>
<td>Insulation</td>
<td>21</td>
<td>171.56</td>
<td>sqm</td>
<td>13.15</td>
<td>2,256.01</td>
</tr>
</tbody>
</table>

Total damage: 51,409.95

As discussed in Section 7.2.4, by colour-coding the building assemblies according to their damage states, their damage level could also be visualised in 3D using ArcScene. Figure 9.18 visualises the damage to different building assemblies including the walls, doors, flooring, moulding and skirting, electrical elements, and the windows. The user not only could visually inspect the damaged assemblies, but also could query the details of the damages and their location (see Figure 9.19).
Figure 9.18: A 3D Visualisation of Damaged Walls (top left), Doors (top middle), Flooring (top right), moulding and skirting (bottom left), electrical elements (bottom middle) and windows (bottom right) in ESRI ArcScene
On the basis of the estimated damage costs to the building, the flood risk to the building was additionally quantified according to the Equation 7.4. The risk in this case study was calculated for a 1-in-100 year flood (1% probability of occurrence) as $0.01 \times 51,490 \approx 514$. In addition to the calculated damage for 1% probability of occurrence, by estimating the damage for other events with different probabilities, the AAD diagram can be created. However, such comprehensive analysis of risk was beyond the scope of this research.

Figure 9.19: Querying damaged assemblies using "identify" tool in ArcScene for (top) doors and (b) wall linings
The results of the case study were presented to and discussed with the principal building surveyor of the Maribyrnong council and three of its senior staff\(^94\) in its Building and Planning department. This discussion underlined that

- The automation of the assessment of flood damages and risk to the building provides an added value for Maribyrnong council and possibly for other local governments. However, the integration of such process with the current processes of the council would be challenging.

- The inclusion of BIM in the development process and its integration with GIS can effectively benefit the decision making for improving the resilience of buildings against floods and also other aspects of planning. However, current policies do not mandate the owners and developers to submit BIM models to the council.

- The interactive 3D visualisation of the potential impacts of a flood on the building and also the provision of querying functionalities in the system are beneficial for the council. However, the cost of damage would not be an added value. It was discussed that such outputs would be more of an interest of the designers/engineers, building owners, and insurance companies.

- With such tool the council can investigate opportunities to utilise the unused flood-prone land within the council areas.

On the other hand, it was discussed that there are often disputes between the council and owners regarding the decisions made for accepting or rejecting the development proposals. These disputes are generally handled at higher level in the Victorian Civil and Administrative Tribunal (VCAT). It was highlighted that a 3D visualisation can provide an easy to understand medium to replace the complex engineering language for an effective communication of the building risks to the owner.

In addition to the potential benefits of the framework to the council, a number of challenges in its adoption were raised during the discussion which include

- Translating the framework processes in the planning scheme and justification of the need for their inclusion in the daily activities of the council;

\(^94\) including the principal planner of the council
Policy changes to necessitate the submission of BIM models as part of the new developments submission requirements;

Allocation of time and resources for implementation of the system in the council; and

Allocation of the required resources (e.g. financial and skilled personnel) to support the operations of the system.

9.2.3 Summary of case study

The case study for the assessment and 3D visualisation of damage to a residential building in the Maribyrnong council was successfully implemented and its results were presented. In addition, the feedback of the Council for benefits and challenges of the implementation of the framework in this council was provided. According to the provided feedback, although the implementation of the framework would be associated with a number of challenges in the current set up in the council, it was discussed that they can increase the confidence in their decisions for evaluating the proposed development for issuing planning or building permits in flood-prone areas.

The next section presents and discusses the results of the verification and validation of the proposed framework.

9.3 Verification and Validation

The additional steps for completing the framework evaluation include its validation and verification. As explained in Chapter 4, the verification process intends to ensure that the adopted theories are correctly implemented in the designed framework's processes. On the other hand, the purpose of the validation is to provide an indication of effectiveness and reliability of the framework in assessing the flood damages to a building. In the following sub sections the outcomes of these steps are presented and discussed.

9.3.1 Verification

The verification of the framework in this study adopted one-step analysis (see Chapter 4) and used hand calculations to compare the results of each implemented function in the prototype against hand calculations. The verification was performed twice; i.e. once during the development of the prototype where the implemented code was compared with the required calculations presented in Chapter 6 and
Chapter 7; and again in a similar way during the case study. The output of the verification process showed that the functions in the prototype were correctly implemented with similar outputs as the manual calculations.

Following the verification process, the framework was validated on the basis of experts’ opinion. The next section will present and discuss the result of the validation of the framework.

### 9.3.2 Validation

The validation of the framework was undertaken according to a number of defined criteria that were explained in Section 4.5.4. These criteria included the validity of the formulated problem, framework structure and its logic, the effectiveness of its data sources, and lastly its outputs. The structured face-to-face interview method (based on the questionnaire presented in Appendix 6) was employed to obtain the feedback of a number of experts on the proposed framework. The questionnaire in the interview comprised nine open-ended questions each of which was tailored to individual or a number of the abovementioned criteria. Table 9.2 illustrates the mapping between the designed questions and their corresponding face validity criteria.

<table>
<thead>
<tr>
<th>Face validity criteria</th>
<th>Relevant questions in questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Problem formulation</strong></td>
<td>Question 1.</td>
</tr>
<tr>
<td><strong>Framework structure and logic</strong></td>
<td>Question 2(a, b), 4, 6, 7(a), 9.</td>
</tr>
<tr>
<td><strong>Data sources</strong></td>
<td>Question 2(c), 3, 5.</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td>Question 7(b, c), 8.</td>
</tr>
</tbody>
</table>

In overall, 10 people with expertise in the field were interviewed for validation of the framework. Table 9.3 presents the list of participants and their affiliation. These participants were selected according to the criteria discussed in Chapter 4 (e.g. expertise in the field of civil engineering as well as previous experience designing or evaluating building design in flood prone areas). On the other hand, special emphasis was made to include Geoscience Australia in the study. This was mainly due to their expertise and experience in flood damage assessment to buildings as they constitute the main body to investigate and develop the damage curves for different building types across Australia.

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95 Criteria for being considered as expert was defined in Chapter 4.
As discussed in Chapter 4, following these interviews an evaluation of the responses was undertaken and it was found that a point of saturation was reached due to a minimal variation amongst these responses. Therefore no further interviews were performed. The thematic classification of the questions (illustrated in Table 9.2) was further used to summarise the responses of the participants for the evaluation of the framework. The subsequent sub-sections will present and discuss the results.

Table 9.3: List of participants in the framework evaluation

<table>
<thead>
<tr>
<th>Category</th>
<th>Participant</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Researchers</td>
<td>Dr Matthew Mason</td>
<td>The University of Queensland, Australia</td>
</tr>
<tr>
<td></td>
<td>Professor Anne Steinemann</td>
<td>The University of Melbourne, Melbourne</td>
</tr>
<tr>
<td></td>
<td>Dr Massoud Sofi</td>
<td>The University of Melbourne, Melbourne</td>
</tr>
<tr>
<td>Building</td>
<td>Mehran Khademollah</td>
<td>Maribyrnong, Melbourne</td>
</tr>
<tr>
<td>Surveyors</td>
<td>Armin Eftekhari</td>
<td>Enrik, Melbourne</td>
</tr>
<tr>
<td>Engineers</td>
<td>Dr Vidal Paton-Cole</td>
<td>Fine Design Engineers, Melbourne</td>
</tr>
<tr>
<td></td>
<td>Daniel Szych</td>
<td>Maribyrnong council, Melbourne</td>
</tr>
<tr>
<td></td>
<td>Wayne Bryson</td>
<td>Home and Industrial Pty, Melbourne</td>
</tr>
<tr>
<td></td>
<td>Nick Manesh</td>
<td>Enrik, Melbourne</td>
</tr>
<tr>
<td></td>
<td>Martin Wehner</td>
<td>Geoscience Australia, Canberra, Australia</td>
</tr>
</tbody>
</table>

Problem formulation

The research problem discussed in Chapter 1 was presented to the participants using a formal presentation and then they were asked if such problem exists from their point of view and if addressing it can provide benefit to the community. The answer to this question was valuable to this research from two points of view; one is to partially verify the relevance of the problem in the Design Science methodology, and the other to be used for framework evaluation. As illustrated in Figure 9.20, the responses were positive and all the participants agreed (60% strongly agreed and 40% agreed) upon the existence of the gap and the importance of addressing it.
Framework structure and logic

Following the confirmation of the problem, the participants were asked to provide their feedback regarding the framework structure, processes, and its logic by responding to the relevant questions highlighted in Table 9.2. Where question 2(a) directly inquired about the design and logic of the flow, the questions 2(b) and 7(a) asked the participants to evaluate the relationships between the framework components and their inputs and outputs. In this part of the interview, the framework was presented to the participant and its flow and components were explained in detail. Figure 9.21 summarises the responses to these questions and presents the percentage of different answers separately using a stack column diagram.

![Stack column diagram](image)

Figure 9.21: Summary of participants’ responses regarding the framework structure and logic

Regarding the question 2a, all the participants agreed on the appropriateness of the design of the framework, its structure and logic. On the other hand, except only the 10% of the participants, the rest...
also agreed upon the accounted interrelationships between the components of the framework and their inputs and outputs. Furthermore, the participants were asked to express their opinion about if the interrelationships between the building components damage (e.g. failure of host component like wall would result in failure of the component such as window or door) were considered properly. Where 70% of the participants provided positive feedback, the remaining 30% were neutral.

Furthermore the participants provided their feedback on the appropriateness of the adopted methods and their assumptions for assessing the damage to building components. Each method for the analysis of damage to windows (and also the sliding doors), doors, ceiling, utilities (the electrical components), soffit, mouldings, internal and external wall components (i.e. cladding, lining, frame, and insulation) and the assumptions for each were presented to the participants for validation. Thorough discussions were held in this regard and the conclusions were made. Figure 9.22 presents the outcomes of the participants' responses which underlined the appropriateness of all the methods and their assumptions (100% of the responses were yes for them) for analysis of damage to the building components.

![Figure 9.22: Responses of the participants for the damage assessment methods and their assumption](image)

Although it was discussed that the adopted methods could provide a good assessment of damage, yet additional suggestions were received for

- Extending the structural frame analysis for evaluating the behaviour of the entire frame (the interaction of loads with other aspects of the frame) when building is subjected to flood loads;
- Extending the window failure from its connections to the wall; and
- Extending the door failure according to the failure of its locks, latches and hinges.

\[96 \text{“A” represents “Assumptions” and “M” indicates the “used Method”.} \]
The criteria (thresholds) for damage to building components were further validated by the participants. Although 100% of the answers were positive about the defined threshold for damage against water contact and flood loads (refer to Figure 9.23), yet additional comments were received. It was discussed that in some literature and also based on the previous experience of some participants, although the material of floor tiles are water resistant, yet the joint between them (e.g. cement) may not be and therefore allows for entrapment of floodwater. In this way, the removal of the tiles would be necessary. On the other hand, where parts of the wall lining or finishing may be damaged, the wall finishing (e.g. paint, wallpaper, etc.) should be fully replaced - which was not accounted for in the presented case study. Hence, a need was highlighted for further investigation of the damage threshold for bathroom/kitchen floor tiles and also the wall finishes.

In addition, some responses suggested that while the threshold for water contact damage have been properly set, yet the thresholds for load-resistance analysis were discussed to be conservative due to the similar adopted 95% confidence level for analysis in the Australian Standards. The feedback indicated that due to the probabilistic nature of failure of the assemblies against loads, a probabilistic analysis method would be a better option in the framework and can take into account the additional uncertainties.

Figure 9.23: Summary of the responses for validating the appropriateness of the damage threshold for assemblies
Data sources

The third criteria for validation of the framework included the effectiveness of the data sources as the input of the framework. This criterion was tested to (a) check if the key parameters for FDA are provided as inputs; and (b) whether the BIM and its integration with GIS can provide the necessary inputs for the envisioned analysis of flood impacts on the building. As illustrated in Figure 9.24, all the participants agreed that the key flood parameters were accounted for in the inputs. However, it was discussed that the inclusion of shrink and swell effect may provide additional benefits for the model since this situation can be observed in floods of extended period. On the other hand, the 20% of the participants suggested that additional building components should be included in the framework. It was indicated that cabinetry, kitchenware and other fittings, the garage doors, as well as the other utilities should be included to complete the model.

The participants also suggested incorporating the variation of velocity in the z axis in the analysis of damage. It was discussed that despite the insignificance of such variation for the flood type in this research, yet future research on high velocity water in flash flood situations should account for this factor.

Figure 9.24: Summary of responses for inclusion of the key flood and building parameters in the framework

The participants were also asked to provide their feedback regarding the inclusion of BIM and its integration with GIS for satisfying the data needs of the framework. All the participants had previous familiarity with BIM and agreed that it, along with GIS, can provide rich and effective inputs for a detailed analysis of damage to a building (see to Figure 9.25).

97 Without considering those outside of the scope of the research.
Outputs of the framework

As the last criteria of the face validity method for validation of the framework, the participants were asked to validate the outputs of the framework in the conducted case study. In regard to question 7(c), all the responses were positive (refer to Figure 9.26) and underlined that the adopted theories could effectively simulate the water infiltration to inside the house as well as in the cavity space of the external walls. On the other hand, as illustrated in Figure 9.26, 100% of the responses to the question 8 underlined the output of the framework (consists of the tabular damage costs as well the 3D visualisation of the location and mode of damage to building assemblies) can effectively communicate the assembly damages and their costs to the user. However, it was raised by one of the participants that further investigation would be required to take into account the human element in perceiving the different aspects of the visualisation to explore the areas of improvement.

In regard to the prediction capacity of the framework to assess the damages, 70% of the responses indicated that the framework could effectively predict the potential damages to building components. Where 20% of the responses were neutral, 10% of the participants underlined the incompleteness of these predictions and highlighted that the framework intends to underestimate the total damage. This was majorly due to not taking into account the damage costs of excluded building elements like garage doors, other utilities, cabinetry, curtains, and those discussed in Chapter 5. In order to provide a complete damage assessment, these building elements were highlighted to be included in future studies.
In additional to the above responses, the participants provided their overall assessment of the proposed FDA framework. All participants underlined that the framework is beneficial for various applications by allowing an automatic assessment of potential flood damages and risks at building level. The design of the framework was found to be a good starting point with potential for extension to incorporate other aspects of the building and the remaining flood parameters. It was also highlighted that although the ABV method was used to quantify the building damage, yet it only focuses on the damage costs of the building assemblies. The framework validation revealed that additional items such as clean up or labour costs should be included for more complete flood damage estimation. Lastly, the importance of further validation of the framework in the future using experimental model testing was highlighted by a number of participants.

9.4 Chapter Summary

This chapter provided insight into the evaluation of the framework from two perspectives; i.e. demonstration of the framework using a real world case study, and its formal validation using expert opinion.

In the first part of this chapter, a case study was presented to assess the potential damages of a riverine flood in the Maribyrnong council on a proposed building. The BIM of the building was created according to the 2D plans and the flood was modelled using the MIKE 21 simulation package. This information along with the elevation model and the other building footprints were imported using the prototype system and the physical damage assessment was performed. Following the
completion of the analysis, the results were provided to the user using tabular breakdown of damage costs and a 3D visualisation of the location and mode of damage to individual building assemblies. The feedback from the Maribyrnong council was positive and a number of benefits were highlighted for the framework at the building design and planning phases.

In addition to the case study, a formal validation of the framework was undertaken using the Face Validity method. The framework and its details were thoroughly presented to a number of participants and their feedback on different criteria of the face validity was acquired. Following the confirmation of the problem in this research, it was recognised that the structure, logic and the methods used for calculation of the infiltration volume as well as the estimation of the damage to the building assemblies were designed effectively. On the other hand, although there is a need for further extension and validation of the framework for inclusion of the other flood and resistance parameters, it was discussed that the framework, as a good starting point, can provide a reasonable estimation of damage to a building and can effectively communicate and present the flood damages and their costs to the user. Further suggestions were also received from the participants in the validation process which will be further classified and discussed as future work in the next chapter.

The next chapter, as the concluding chapter of this thesis, will present the achievements and findings in this research, our conclusions and also the future research directions in this field.
Part 4: Synthesis
Chapter 10

Conclusions and Recommendations
10 Conclusions and Recommendations

10.1 Introduction

This chapter summarises the achievements in this research and also reflects on the conclusions. It additionally demonstrates that the main aim and objectives of the research have been achieved and the research problem put forward in Chapter 1 is addressed. This chapter also highlights the main contributions of this research to the FDA and FRM body of knowledge; and furthermore proposes and discusses the areas of improvements as well as the future research directions.

10.2 Addressing the research aim and objectives

The primary aim of this research, as specified in Chapter 1 was set out to

"Design and develop a new framework for a detailed micro-level analysis and communication of damage to a building based on its unique characteristics and behaviour against the flood impacts."

As presented in Chapter 7, this aim was achieved and a framework for a Micro level assessment and communication of flood damage to a building was designed. This framework, as the main artefact of this research, was developed by employing a combined use of Design Science methodology and Data Modelling technique. The proposed framework defines the processes for a detailed physical as well as monetary assessment of flood damages to a building at its individual assembly level. In this way not only the mode of building damage can be determined but also the breakdown and the overall cost of building damage can be obtained. On the other hand, the framework allows for a 3D visualisation of damages for presenting their location in the building.

The effectiveness of the framework was evaluated and its application for a real-life problem was further tested. The framework as a decision support tool can be effectively used for a number of theoretical and practical applications at individual building level which the current FDA methods are not sensitive towards. The positive feedback from the Maribyrnong council suggested the value of the framework in the building planning and design stages for improving the resilience of communities against floods. This feedback and the derived conclusions from the literature indicated that councils and relevant authorities can increase the confidence in their decisions for evaluating the proposed developments for issuing planning or building permits in flood prone areas. The discussions with
engineers and building surveyors also underlined the benefits of the framework for assisting building designers and engineers to evaluate their designs for identification of flood risks and to seek appropriate alternative designs or mitigation measures for their treatment. This can accommodate the evident shift in practice from the classic code-conforming designs to the performance-based methods where buildings are tailored to the performance requirements of the owner or a particular application. In addition, by providing not only the physical vulnerability but also the costs of damage to components, a cost-benefit analysis can be employed for the selection of the most effective alternatives. Also, by incorporating the concept of dynamic vulnerability in the analysis of flood damages, the framework accounts for the intermediate impacts on the building assemblies and also their influence on the overall damage to the building. This can unveil the flood damage generating mechanisms on different components and the use of counter measures for their prevention. Similarly, via use of the distinct design of buildings in the analysis, and distinguishing their detailed risk levels, insurance companies can differentiate their premiums for policy holders. Finally, replacing the use of complex engineering language with an easy-to-understand 3D visualization of potential vulnerabilities, the owners can make more informed decisions for adoption of flood resilient building materials or suitable risk reduction measures.

Accordingly to the above benefits, as discussed in Section 2.6.2.3, the framework can translate the concept of FDA beyond a simple analytical tool for assessing damages towards the identification of optimal management options, and extend its to an exploratory planning toolkit.

For the design of the framework, as required by the Design Science methodology, a number of steps were completed in five phases of this research (refer to Section 1.4). These steps were discussed in detail in Chapter 4 and included (a) formulating the problem in the FDA domain, (b) populating the knowledge base of the research and the identification of possible solutions from the other domains, (c) design and development of the framework, (d) demonstration of its application in real life, (e) its evaluation, and finally (f) its communication using suitable channels. Except the step (f) which was addressed by various publications and presentations, the individual or combinations of these steps were translated into four major objectives (and sub objectives) of this research. In the following subsections these objectives and how they were achieved in this research are revisited and discussed.

10.2.1 Objective one

The first objective of this research comprised two components and intended to investigate and understand
a. The current status of FDA on building in support of the flood risk management; and

b. The state-of-the-art technologies that can potentially benefit FDA by providing a more effective data input for covering all the requirements of a detailed micro-level FDA on buildings;

As the first step in this research, in correspondence to the objective 1(a), a thorough and exhaustive narrative review of literature in the FDA domain was undertaken. The outcomes of this investigation were presented in Chapter 2 which detailed the drivers of undertaking a FDA and its applications in FRM. It further highlighted different aspects of the FDA and investigated various methods for assessment of damage to building at a micro-level. According to the findings, a number of knowledge gaps and also the problems in this research were unveiled. It was realised that while FDA at Macro and Meso scales have received much attention and the existing models can reasonably satisfy the stakeholder needs at those levels; however, the detailed analysis of the flood damage to buildings at micro level is still immature and the existing methods cannot currently provide an effective evaluation of flood damages to an individual or a small cluster of buildings. This problem was mainly identified in terms of the input data available for the analysis of damage which could not reflect the unique design and construction of the buildings, and accordingly its unique behaviour against floods. On the other hand, the existing methods for damage analysis were found related to the analysis of either structural damage from water loads or the water contact damage and not together. Therefore, a need for a new method for the analysis of both damages according to the uniqueness of a building was identified. This comprehensive review answered the research question 1.

In order to identify possible solutions for the above problems in the FDA domain (corresponding to the second step in this research), the other disciplines including the Geospatial and AEC/FM domains were visited and explored. An exhaustive review of literature was undertaken in these domains to identify potential data technologies that could benefit a detailed FDA model at the building level. The outcomes of the investigation were presented in Chapter 3 and suggested that a separate adoption of GIS or BIM technologies would not effectively satisfy the requirements of the envisioned detailed FDA model. Where it was previously discussed that a combined use of BIM and GIS together can benefit the assessment of flood damage to buildings, this claim was further investigated in Chapter 3 and a comprehensive review of different BIM-GIS integration methods at different levels was undertaken. Section 3.4.4 provided a summary of this investigation and illustrated the insufficiency of the existing BIM-GIS integration models in support of the requirements of the envisioned FDA model.
Conclusions and Recommendations

at a micro level. It further highlighted a need for a new model for this purpose as the answer to research question 2b.

In the next step in this research, the framework was designed to fill the identified gaps in terms of data inputs as well as the processes for an effective micro level FDA on the building. This step was translated to the second objective of this research that will be revisited next.

10.2.2 Objective two

The second objective in this research was defined as follows:

"To design a framework for a detailed assessment and visualisation of flood damage to a building for allowing the analysis of the building damage based on its unique characteristics."

To achieve this objective, as the core of this research, four sub-objectives were defined and addressed. These sub-objectives include

a. To understand the potential impacts of flood on different aspects of the building;

b. To identify the required analytical methods for assessment of the damage to the building and its components;

c. To extract the data requirements for the designed processes in (2b); and

d. To integrate the required components into the body of the framework and outline its design.

For achieving the first sub-objective, a thorough systematic review of the existing body of knowledge was undertaken to understand the possible flood impacts (what damages and how) on the building type under investigation and its components. The output of this investigation underlined over thirty different vulnerable components (and their sub-components) in the building that can potentially be damaged from a flood. These elements are summarised in Section 5.4. A subset of these components were selected and justified for inclusion in this work according to the type of flood in this study.

Furthermore, a systematic literature review was employed to identify suitable analytical methods for the assessment of damage to each of the selected components of the building. The relevant flood actions, the damage criteria, damage assessment processes for individual building components, and various possible damage states of the components for damage analysis against flood loads as well as
the water contact was formalised and presented in Chapter 6. In this way the objective 2(b) was achieved and the research question 2a was answered.

Subsequent to the formalisation of the damage analysis methods for each component as well as the overall processes required for the framework, the data requirements of this process were extracted to be used for creating a data foundation within the overall framework structure. In this way, the objective 2(c) of the research and the second part of research question 2b was addressed. These requirements are presented in full in Section 7.3.1.

The design of the framework was completed based on the careful integration of various concepts and methods like the ABV concept, the Limit State Design paradigm, and the use of the Australian Standards. Chapter 7 is dedicated to present and explain the details of the framework for achieving the research objective 2(d). As part of this framework, a new method for integration of BIM and GIS at a data level was designed and implemented according to the previously identified data requirements. This method includes a data model as an application schema of GML and includes eight packages to satisfy the data requirements of the proposed FDA framework. This design was also mapped to OGC and BuildingSmart standards (i.e. IFC and CityGML) for facilitating the data integration processes. The design and implementation of the data model was found feasible and performed according to the provided guidelines of data modelling technique (see Section 7.3.2 and the Appendix 13). The integration of BIM and GIS provides a better representation of the resistance and flood parameters for FDA at a building level. By providing more detailed and accurate inputs, a more effective solution for micro-level FDA was developed.

10.2.3 Objective three

The third objective of this research included the development of a prototype system. To achieve this objective, a multi-tier semi-automatic prototype system was implemented according to the framework guidelines. The layers of the system included the Data Layer, Data Access Layer, Business Layer, and the Presentation Layer which were detailed in Section 8.2.2. While the first two were responsible for storage of the required data and provision of access to this data, the business layer contained the business logic and those core processes for water infiltration calculations, flood damage analysis, and quantification. Presentation Layer on the other hand spanned across ANSYS, ArcGIS and the UI of the prototype system for acquiring the user inputs as well as the presentation of the results.
This developed system enables the user to import the inputs of the analysis, estimate the infiltrated floodwater to inside the house and its other confinements, assess the damage to its individual components, and finally export of the results to 3D GIS or tabular formats. The estimation of the damage in this prototype is deterministic and is performed using the concept of dynamic vulnerability discussed in Section 2.6.2.3. The exported results can be visualised in 3D in the GIS environment; or presented in Microsoft Excel. In addition, the system enables access to the intermediate results for different time steps of the analysis for better understanding of the damage generating processes. The prototype facilitated the achievement of the objective 4 of this research and was presented in detail in Chapter 8.

10.2.4 Objective four

The fourth and the last objective in this research (corresponding to research steps [d] and [e] in Section 10.2) was to evaluate the framework in a two-step evaluation process:

- *The demonstration of the designed framework in a real life scenario;* and

- *The validation and verification of the framework.*

These step were used further to respond to the research question 3. For the first step of the evaluation, the application of the framework was tested in a case study for assessment and 3D visualisation of damages and risk to a single-storey brick veneer house with slab-on-ground foundation in the Maribyrnong. The results of this case study were presented in Section 9.2 and showcased the strength of the framework and the developed prototype system in assessing the flood damages at the building and its assembly level. The initial feedback from the industry (i.e. the Maribyrnong council and the Geoscience Australia) in Chapter 9 illustrated the benefits of this framework for improving the flood resilience in the community.

For achieving the verification aspect of the second component of framework evaluation, its processes as well as its implementation were verified by one-step analysis (refer to Chapter 4) and manual calculations to ensure the correctness of processes for estimation of damage. On the other hand, the Face Validity method was adopted for validating the framework. For this purpose, feedback from ten knowledgeable individuals in the field was collected on various aspects of the framework and they were validated using face-to-face structured interviews. The formulated research problem, the data inputs for the framework, the structure and logic of the framework processes and its intermediate and overall outputs of the framework for the case study were presented to and validated
by the participants. The presented results in Section 9.3 illustrated that the framework was logically designed and the results of the case study can be reasonably matched with expectations of the experts. On the other hand, although BIM is still not fully implemented in the land development process in the Australian context, it was found that its integration with GIS can provide effective data inputs for the analysis of flood damages to a building at this scale; that result in a better analysis, quantification, and visualisation of flood damages to a building. As illustrated earlier in Section 10.2, the proposed framework provides applications at individual building level which are beyond the reach of the existing FDA models.

The outcomes of the validation also highlighted a number of required improvements to the framework and its implementation. As discussed in Chapter 4, Design Science provides a loop back to the design of the artefact for its improvement base on its evaluation process. According to the decision of the researcher, this improvement can either be made in the context of the same study or the research is finalised and communicated with highlighting the existing limitations and shortcomings of the framework. In this research, the second option was selected due to the time and resource constraints. Section 10.5 details the future research directions and the areas that the framework can be further improved.

The presented accomplishments in each objective of this research led to achieving the aim of this research, and subsequently addressing the formulated research problem.

10.3 Responding to the research problem

The research problem defined in Chapter one (refer to Section 1.2.1) recognised that despite the benefits of existing FDA models for medium- to large-scale applications, they, and also those proposed for micro level, are limited to support important micro-level applications like designing/engineering flood resilient buildings, or approving development proposals in the flood prone areas. These micro-level applications require detailed analysis of potential impact of flood actions on a specific building and according to its unique construction. The existing models however have limitations for taking into account the distinct building characteristics for analysis of damage due to their data inputs or assessment methods. This research confirmed the existence of the problem in the FDA domain which hinders an effective decision making for abovementioned applications in support of an effective FRM.
To address the highlighted problem and the underlined need for more rigorous and detailed analysis according to higher spatial resolution inputs for the abovementioned applications, various technologies and methods from different domains were identified and a multidisciplinary framework for FDA was designed. This framework could address the fundamental building blocks of the defined problem (refer to Section 2.8) by

- Providing detailed data inputs about the building, flood and other relevant concepts by the integration of BIM and GIS to enable an effective flood damage assessment at a building level and according to its unique design;
- Allowing for the analysis of damages from both water contact and also from flood loads on the building elements;
- Utilising dynamic vulnerability concept to account for intermediate damages that may change the course of damage generation processes; and
- Providing a method for an integrated assessment of the physical damages to the building and their monetary costs damages.

The development of the prototype according to the framework and its evaluation in a case study suggested the feasibility of use of the framework and its effectiveness for the discussed applications at a building level. The proposed framework is a complement to the current FDA approaches (e.g. damage curves) where their capabilities fall short in providing effective outcomes at building scale. With consideration of the benefits of each for their effective scale and applications, a multi-scale framework can be further developed to provide a more comprehensive understanding of flood risks at different levels of the community as well as facilitating more informed decisions towards improving its resilience against floods and their adverse impacts.

### 10.4 Main outcomes and the contributions to the knowledge

This research led to a number of outcomes which also considered as its contributions to the knowledge. These contributions were made to different disciplines and include

- Development of a methodology to conduct research for detailed assessment of flood damage at building level;
Revelation and classification of factors that influence the impacts of flood on a building and specifically the type under investigation;

Identification and classification of the potential flood damages to a single-storey veneer house in the Australian context; and determination of the methods/processes and information inputs for assessment of these damages;

Development of a new framework for assessment of flood damage to a building according to its unique design and construction. This model contributes to knowledge in different ways:

- Integrating the dynamic assessment of building damage from water contact and the flood loads into a single process which has not been addressed before;

- Assessment of the mode of physical damage to individual components of the building and its monetary cost estimation

- Providing the 3D visualisation of potential flood damage to a building; and

- Provision of intermediate damages to provide a better understanding of damage generation processes;

Development of a prototype system confirming the feasibility of the implementation of the framework;

Identification of a new source of detailed information (i.e. combined use of BIM and GIS) for assessment of flood damage to building98;

Design and implementation of a new BIM-GIS integration method in support of micro-level assessment of flood damage to building;

Design of a new model to assess the damage to the brick veneer wall system from flood lateral loads;

Formalising the water contact damage assessment in the context of dynamic vulnerability;

98 Other sources are discussed by Messner et al. (2007).
10.5 Recommendations for future research

Throughout conducting this research, a number of future research opportunities were identified that could not be addressed within the scope of this research. Where some of them would contribute to addressing the limitations in this study, others underline the areas which this work can be extended to.

➢ Validation of the designed framework via empirical data

The framework in this work was validated using face validity method which is usually considered as the first step for a more thorough validation. The outcomes of lab experiments or previously collected empirical data can be compared with the generated outputs of model and can lead to a more effective validation of the framework. In addition, a crucial future research should thoroughly validate the water infiltration theories discussed in Chapter 6. While previous research only provided a qualitative validation of flood infiltration using expert opinion, however the outputs should be validated in a similar way using the abovementioned methods.

➢ Inclusion of additional factors in damage assessment

This research limited the scope of analysis and accordingly only a justified subset of the flood and resistance parameters were considered for the application of the framework. As recognised in Chapter 9 while the key building components were accounted for in here, yet, a complete analysis of damage to a building requires a full range of permanent and temporary resistance parameters at building level. On the other hand, the inclusion of those excluded but relevant flood actions (including shrink and swell, scour, contamination and debris) is crucial for extending the proposed framework in the future research. The prospect studies should additionally include non-content elements of the building which are often perceived as content (i.e. cabinetry and fittings) as well as the other utilities beside the electrical components. The feedback from the evaluation of the framework in this research also revealed that the analysis of the failure of garage doors and joints between the windows and wall should be included in the model. In addition, foundation, and with less priority the building roof and a full frame response analysis should be considered to be accounted for in the future research. The inclusion of the building foundation was underlined during the framework evaluation due to its vulnerability to shrink and swell impacts especially in the reclaimed land\textsuperscript{99} which is common in Australia. Lastly, factors like the age of the building, workmanship in its construction, its previous

\textsuperscript{99} Reclaimed land includes those new land created from the bed of water bodies like the oceans, rivers or lakes.
damage from other events, fatigue in its elements, as well as the precautionary measures should also be considered in the analysis of damage to building.

In addition, the presented research was limited to the permanent resistance of the building components and did not consider the influence of property-level features such as fences or walls that may potentially change the water flow and its impacts. Future extension of the model would require such parameters to be accounted for in the modelling of the flood as well as the analysis of damage to the building.

Finally, the building damage bill in this research as the ABV methodology instructs, was generated by accumulating the damage cost of individual building assemblies. However, other costs like clean up and labour costs can be included in the future research for more realistic damage quantification.

- **Damage assessment from probabilistic point of view**

  The nature of damage assessment in this research was deterministic. Although the expert feedback for this research indicated that this approach provides reasonable results, yet the failure of building components against flood actions would still include some degrees of uncertainty. Therefore, it is suggested to adopt a probabilistic method to resolve such uncertainties in the calculations for a more realistic evaluation of damage.

- **Exploration of the application of alternative methods for detailed flood modelling**

  The hydrodynamic action in this research was calculated using an average velocity vectors for all depths. Although this information can provide a reasonable input for damage assessment and has been used in all previous FDA models, there may exist various factors that can affect the flow and result in variations in the magnitude and direction of velocity in the vertical axis in the vicinity of the building. Therefore, the application of more efficient approaches (e.g. CFD modelling) for modelling of the flood at a micro level for taking into account such potential variations is suggested to be explored in future studies.

- **Enriching the data model according to the additional requirements for the framework**

  The data model for integration of BIM and GIS was designed and implemented according to the extracted data requirements of the adopted or designed method for damage assessment to a limited set
of resistance and flood parameters. Future studies that extend the framework based on the recommendations presented in this section should also augment the data model in support of the required concepts.

- **Extending the research to other flood and building types**

  This research only focused on the damages from slow-rise riverine flood and its impacts. On the other hand, this study is limited to only one building type of the 19-type GA building classifications in the Australian context. Future research can apply the presented methodology to extend the framework for other building types (in Australian or international context) and flood types including flash floods, overland (pluvial), coastal flood, groundwater flood, debris flow, as well as floods from failure of artificial water systems. This would broaden the transferability of the framework in space, time and also to all flooding events.

- **Consideration for second- and third-order damages and cascading impacts of flood**

  Although the generic framework proposed in this research can potentially account for second- and third-order flood damages, yet such damages were not investigated in this research. These damages occur in real flooding situations and can possibly increase the damage bill of the building. Therefore, future research should account for such impacts on the building and include them in the calculations.

- **Extending the framework according to user-specific needs (LoA 2 and LoA 3)**

  The proposed framework in this research was designed for LoA1 to assess the potential damages to a building from flood actions. This framework is generic and addresses the overall needs of its potential users (refer to Chapter 7). However, for extending the application of the framework for specific or a group of users (LoA2 and LoA3), further investigation would be required to understand and incorporate user requirements in design and evaluation of the framework. Similar methodology in this study can be adopted with an additional step for understanding the user needs to design the framework and a decision support tool for estimation of potential flood damages to a building.

  Furthermore it is crucial that future studies systematically investigate the value of extra and detailed information to the stakeholders in the defined use cases in this research (see Section 7.2). Such investigation, depending on the type of study, can provide a qualitative or quantitative indication.
for a cost-benefit analysis of future investments in the implementation of the framework in different jurisdictions.

- **Extending the material resistance guidelines for shorter water contact durations**

  In this research a number of literature and guidelines were used to determine the floodwater resistance of materials (R function) for evaluation of the water contact damage. Although these guidelines provide useful information for water contact of longer than 48 hours, yet for smaller events like flash flooding that may last only a few hours, these guidelines are limited to indicate the material resistance and the use of existing information would bring large uncertainties into the analysis. Therefore, further research in FDA domain should consider extending these guidelines with the resistance of the assembly materials against shorter water contact durations.

- **Translating the research findings to BCA best practices**

  The discussions with engineers and building surveyors in this research illustrated that although there exist requirements for design of a house against flood loads, yet the current practice and the building codes provide many details about the design against wind and earthquake but very little information about floods. On the other hand, despite their vulnerability in flood situations, veneer wall systems in Australia are not currently engineered to resist flood loads. Therefore, the methods proposed in this research can be further employed for development of guidelines and best practices for flood resilient design of the buildings. Future studies should investigate pathways to translate the presented theories in this research to best practices commonly presented as Australian Standard documents.

- **Exploring the proposed 3D visualisation of damages from human psychology perspective**

  As part of the evaluation of the framework it was recognised that the 3D visualisation of mode and location of damage can benefit the users. However, a more detailed investigation of the positive and negative aspects of this medium of communication from a user's point of view is required and proposed as a future research area.
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Appendices
### Appendix 1: Flood Disaster Statistics (source: EM-DAT)

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</table>

**Average (1980-2014):**

- **Value 1:** 109.7
- **Value 2:** 6654.8
- **Value 3:** 92497672.69
- **Value 4:** 33929.2
- **Value 5:** 2046146.6
- **Value 6:** 94577748.49
- **Value 7:** 18613058.11
Appendix 2: Personal Communication with Steven Tsikaris

From: Steven.Tsikaris@dtf.vic.gov.au [Steven.Tsikaris@dtf.vic.gov.au]
Sent: 07 October 2014 11:42
To: Sam Amirebrahimi
Subject: Re: Resource

Hello Sam

I definitely recall being introduced to you by Abbas. A pleasure to meet you too.

The material you're after was recently published by the Productivity Commission, as part of an Inquiry into natural disaster funding. Go to ...

http://www.pc.gov.au/projects/inquiry/disaster-funding  (background along with the Inquiry's terms of reference and a number of public submissions)

.. and some commentary around the recently released draft reports (which can also be downloaded) at ...


The relevant stat in the exec summary of the first volume, is that some 2% of disaster related funding (as reported by the Commission) is for mitigation, and the rest as a result of an event.

I said in my presentation that the numbers quoted probably don't capture some additional State level expenditure, hence my comment that when you take into account some additional spending it's more likely a 5% and 95% split.

Feel free to contact me if you want to discuss further.

Kind regards
Steven
Appendix 3: Damage curves for direct monetary estimation of damage to building at micro level

<table>
<thead>
<tr>
<th>Work</th>
<th>Flood type</th>
<th>Assessment type</th>
<th>Influencing parameters</th>
<th>Model construction</th>
<th>Curve type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nadal et al. (2010) (more details available in Nadal (2007))</td>
<td>R, C, FF, TS</td>
<td>Economic, financial</td>
<td>Depth, velocity, waves, debris, Water contact</td>
<td>Materials and construction of building frame, windows, doors, foundation</td>
<td>Synthetic</td>
<td>Actual orientation of building is not decisive in use of these curves. Assumptions and approximation of building components in development of curves. Water contact damage was based on previously developed curves.</td>
</tr>
<tr>
<td>Geoscience Australia curves (Maqsood et al., 2014)</td>
<td>R</td>
<td>Financial</td>
<td>Depth</td>
<td>Number of stories, wall material, floor material, basement and presence of garage</td>
<td>Synthetic</td>
<td>Relative curves express damage as a ratio of &quot;repair to replacement cost&quot;. 19 different damage curves for different classes of residential and commercial buildings in Australia.</td>
</tr>
<tr>
<td>ANUFLOOD (Greenaway and Smith, 1983)</td>
<td>R</td>
<td>Economic</td>
<td>Depth</td>
<td>Building type</td>
<td>Synthetic</td>
<td>Most widely used set of stage-damage curves in Australia developed in 1980's for gently moving waters (velocity &lt; 1 m/s). In case of presence of velocities exceeding the above threshold, Queensland Government (2002) suggest to use dV criteria of NSW Government (2001)</td>
</tr>
<tr>
<td>Pistrika and Jonkman (2010)</td>
<td>R, C</td>
<td>Economic</td>
<td>Depth, velocity</td>
<td>Building type</td>
<td>Empirical</td>
<td>Adjustments to Clausen (1989) were made to improve the predictions against the damage data for the flooding of hurricane Katrina.</td>
</tr>
<tr>
<td>NHRC Curves (Leigh, 2006)</td>
<td>R</td>
<td>Financial, insurance</td>
<td>Depth</td>
<td>Building type</td>
<td>Empirical</td>
<td>The curves were developed based on FHRC damage database in UK data which was compared with Australian damage data.</td>
</tr>
</tbody>
</table>

100 Only direct tangible damages to buildings (other categories like roads and etc. are not discussed here)
101 R= riverine, C = coastal, DF = dam failure, FF = flash flood, TS = tsunami, DB = dike breach, P = pluvial flood, GW = groundwater flooding, Tidal = T.
<table>
<thead>
<tr>
<th>Model</th>
<th>Frequency</th>
<th>Financial Depth</th>
<th>Economic Depth</th>
<th>Synthetic or Empirical</th>
<th>Relative or Absolute</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Coloured Manual (Penning-Rowsell et al., 2003; FHRC, 2013)</td>
<td>R, C&lt;sup&gt;102&lt;/sup&gt;</td>
<td>Economic Depth, duration</td>
<td>Building type, age, social status of occupants</td>
<td>Synthetic</td>
<td>Absolute</td>
<td>120 absolute curves, synthetically derived FHRC damage database using experts' and loss assessors' opinions (Messner et al., 2007). Long and short duration (duration &lt; 12 and duration &gt; 12) are also considered. A percentage of damage increase from saltwater is also explained. Major shortcoming here is that the output of this model has never been validated (Meyer and Messner, 2005).</td>
</tr>
<tr>
<td>HAZUS-MH (Scawthorn et al., 2006; FEMA, 2011)</td>
<td>R</td>
<td>Economic Depth</td>
<td>Location, first floor elevation, building type, flood warning, Presence of basement.</td>
<td>Empirical</td>
<td>Relative</td>
<td>Warning only affects the content damage. Damage assessment at census block level</td>
</tr>
<tr>
<td>Sagala (2006)</td>
<td>R</td>
<td>Financial Depth</td>
<td>Building construction type, number of floors.</td>
<td>Empirical</td>
<td>Relative</td>
<td>Survey of buildings in philippines after two events and analysis and translation of these damaged data to empirical curves for 6 structural types and their contents. Separate curves were created for building and content damages.</td>
</tr>
<tr>
<td>MERK (Reese, 2003)</td>
<td>R</td>
<td>Economic Depth</td>
<td>Building structure types, age, and usage.</td>
<td>Empirical</td>
<td>Relative</td>
<td>Curves were obtained empirically from German HOWAS damage database. Value of building is based on normal construction cost (Messner and Meyer, 2005).</td>
</tr>
<tr>
<td>FLEMOps (Thieken et al., 2008b) in MEDIS project.</td>
<td>R</td>
<td>Economic Depth</td>
<td>Building type and quality.</td>
<td>Empirical</td>
<td>Relative</td>
<td>Developed stage-damage curves for five building types (three building types and 2 classes of quality) and according to the analysis of post-flood survey of 2002 floods in Germany. Content were also considered. Model is applicable to Micro and Meso (by aggregating the data) scales.</td>
</tr>
<tr>
<td>FLEMOps+ (Thieken et al., 2008b; Kreibich and Thieken, 2008) in MEDIS project.</td>
<td>R, GW</td>
<td>Economic Depth, contamination</td>
<td>Building type, quality and precaution of private</td>
<td>Empirical</td>
<td>Relative</td>
<td>Extension for FLEMOps to consider contamination and precautionary measures by residents. Scaling factor for 9 combination of contamination (high, medium and low) and precaution measures (no, medium, very good) can be applied to adjust the loss estimations.</td>
</tr>
</tbody>
</table>

<sup>102</sup> Only for non-residential buildings
Kreibich and Thieken (2008) discuss that these developed curves in addition to those stage-damage curves in FLEMOps+ extend the applicability of the model to groundwater flooding due to consideration for contamination and duration.

GIS was used to map the damage to buildings and other elements at risk. However, the mapping was based on aggregation at higher levels.

They tested the application of both absolute and relative curves of other countries for the building (residential and commercial) in urban context for Bangladesh. Damage to both structure and content are estimated. Islam (1997) discussed the benefits of relative curves over absolute ones.

17 damage functions (2 residential, 15 public and commercial) Expected Annual Damage (EAD) was calculated for each building.

The method calculates the damage based on land use (meso) input data and then according to the building uses in the land use, matches the level of damage to each building. (Hammond et al., 2013)

20 damage functions derived empirically from German HOWAS database. Adjusted curves by further insurance data.

Buildings are considered as points as property centroids. Statistical relationships were used to obtain floor level. Buildings were not represented properly.

A computer model highly integrated with HEC-RAS hydrodynamic simulation model, providing a structure-by-structure analysis of damage. Value of structure and its content are also stored in the GIS database used.
<table>
<thead>
<tr>
<th>Method</th>
<th>ID</th>
<th>Type</th>
<th>Units</th>
<th>Characteristics</th>
<th>Damage Estimation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOWAD-PREVENT (Neubert et al., 2009; Neubert et al., 2014)</td>
<td>P, GW</td>
<td>Economic</td>
<td>Depth, contamination</td>
<td>Building type, Precautionary measures</td>
<td>Synthetic Absolute</td>
<td>FDA using synthetic stage-damage curves on representative buildings in each class. Taking into account the floodwater and moisture impacts. The mean water level per building is used. Account for building content. No validation was performed. In 2014, a GIS-based tool for this FDA model was developed.</td>
</tr>
<tr>
<td>Golz et al. (2015)</td>
<td>P, GW</td>
<td>Economic</td>
<td>Depth, contamination</td>
<td>Building type, precautionary measures, flood resilient technologies</td>
<td>Synthetic Absolute</td>
<td>Golz et al. (2015) extended HOWAD-PREVENT to consider the Flood Resilience Technologies (FReT) such as flood proofing or other mitigation measures in the analysis of building damage.</td>
</tr>
<tr>
<td>Satrapa et al. (2006) and Cihak et al. (2005)</td>
<td>R</td>
<td>Economic</td>
<td>Depth</td>
<td>Construction material, number of floors, height of each floor, first floor height above ground, cellar information and the building age</td>
<td>Combination Relative</td>
<td>200 different types of buildings are differentiated. The derivation of the curves is on synthetic basis with assumptions of structure components for a typical building within each class. They are refined based on the experience from previous floods (Meyer and Messner, 2005).</td>
</tr>
<tr>
<td>Model</td>
<td>Methodology</td>
<td>Financial Depth</td>
<td>Building Type</td>
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<tr>
<td>ICPR (2001)</td>
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<td>Economic</td>
<td>Building type</td>
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<tr>
<td>Penning-Rowsell and Chatterton (1977)</td>
<td>R</td>
<td>Financial</td>
<td>Building type</td>
<td>Synthetic</td>
<td>Absolute</td>
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</table>

In these methods, building-specific curves for each building are created using expert assessors.

This method uses stage-damage curves and depreciated values for estimation of damage to building. However, the model is not validated.

At property level using HAZUS and NHRC curves. Depreciated replacement value of building was used. No validation for the assessed damage was made. Building footprints were digitised from satellite image.

GIS-based assessment of damage to structure and content using stage-damage curves and polynomial functions.

Curves in this study considered the effects of flood on masonry, floor, doors, windows and installations associated with each structure.

Most comprehensive study of residential houses in UK. 168 damage curves for building fabric damage (structure and utilities) and content damage curves for slow-rise flood.

Parker et al. (1987) provided value update for the curves according to the ownership rates and inflation.

Structural and building content loss stage-damage curves were established for wooden and non-wooden buildings in Thailand. The methodology used here was similar to Penning-Rowsell and Chatterton (1977). However, the curves are based on direct translation of collected damage data to curves.
The damage curves are developed for both residential and non-residential buildings.

<table>
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<th>Study</th>
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<th>Assumption</th>
<th>Method</th>
<th>Damage Function</th>
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<tbody>
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<td>R</td>
<td>Economic or Financial</td>
<td>Depth</td>
<td>Not discussed</td>
<td>Absolute</td>
<td>Three linear, square root, and point based power damage functions are used in this tool that can be chosen by the user for damage estimation.</td>
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<tr>
<td>Blanco-Vogt and Schanze (2013)</td>
<td>R</td>
<td>Physical</td>
<td>Depth</td>
<td>Synthetic</td>
<td>Relative</td>
<td>The building types are extracted from satellite images and according to previous works and expert judgment, physical vulnerability of representative building for each type is derived as a damage function. The typology of building according to the base resistance parameters is very broad and buildings may have a large variety.</td>
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<tr>
<td>Black and Evans (1999)</td>
<td>R</td>
<td>Economic</td>
<td>Depth, season</td>
<td>Empirical</td>
<td>Tabular absolute</td>
<td>Reliable data in the aftermath of the flood was only available for depth and seas of the flood.</td>
</tr>
<tr>
<td>Nascimento et al. (2006)</td>
<td>R</td>
<td>Financial or Economic</td>
<td>Depth</td>
<td>Empirical</td>
<td>Absolute</td>
<td>Following the 2000 brazil floods, using questionnaire and post-flood survey, a number of absolute curves were developed for two social classes.</td>
</tr>
</tbody>
</table>
## Appendix 4: Damage curves for structural damage assessment

<table>
<thead>
<tr>
<th>Work</th>
<th>Flood type</th>
<th>Assessment type</th>
<th>Influencing parameters</th>
<th>Model construction</th>
<th>Curve type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black (1975)</td>
<td>DF</td>
<td>Physical</td>
<td>Depth, velocity</td>
<td>Building type</td>
<td>Synthetic</td>
<td>Collapse curve</td>
</tr>
<tr>
<td>Dale et al. (2004)</td>
<td>DF</td>
<td>Physical</td>
<td>Depth, velocity</td>
<td>Building type and construction materials</td>
<td>Synthetic</td>
<td>Collapse curve</td>
</tr>
<tr>
<td>Clausen (1989) and Clausen and Clark (1990)</td>
<td>DF</td>
<td>Physical</td>
<td>Depth, velocity</td>
<td>Construction type of building</td>
<td>Empirical</td>
<td>Criteria for damage type</td>
</tr>
<tr>
<td>Sangrey et al. (1975)</td>
<td>DF</td>
<td>Physical</td>
<td>Depth, velocity</td>
<td>Building type, weight,</td>
<td>Synthetic</td>
<td>Collapse curve</td>
</tr>
<tr>
<td>USACE (1985)</td>
<td>DF, FF</td>
<td>Physical</td>
<td>Depth, velocity</td>
<td>Building type (age, foundation type, first floor elevation,</td>
<td>Synthetic</td>
<td>Collapse curve</td>
</tr>
<tr>
<td>RESCDAM by Finnish Environment Institute model (FEI, 2001)</td>
<td>DF, FF</td>
<td>Physical</td>
<td>Depth, velocity</td>
<td>Building type</td>
<td>Synthetic</td>
<td>Structural damage criteria</td>
</tr>
<tr>
<td>Roos (2003)</td>
<td>R, C</td>
<td>Physical</td>
<td>Depth, velocity, waves, debris</td>
<td>Building types, wall type, foundation type</td>
<td>Synthetic</td>
<td>Collapse curve</td>
</tr>
</tbody>
</table>
Kelman (2002) developed a number of vulnerability profiles for qualitative indication of level of damage to buildings in coastal areas in UK. He used analytical model and structural mechanics to estimate the damage. The building damage estimation against the lateral hydrostatic and hydrodynamic actions. Kelman (2002) was the first to calculate the rate of rise inside the house according to the infiltration sources in building.

Schwarz and Maiwald (2008) The classification of damage grades was based on judgement of the authors. On the other hand, velocities were recalculated for damage database. Therefore there are uncertainties associated to these parameters.

Smith et al. (2014) (Water Research Lab) The provided curves provide dangerous depth-velocity combinations that can be unsafe for people, vehicles, buildings and indicate where buildings should not be constructed or those areas where buildings require special engineering and design attention.

Blanco-Vogt and Schanz (2013) The building types are extracted from satellite images and according to previous works and expert judgment, physical vulnerability of representative building for each type is derived as a damage function. The typology of building according to the base resistance parameters is very broad and buildings may have a large variety.

<table>
<thead>
<tr>
<th>Studie</th>
<th>Method</th>
<th>Damage Parameters</th>
<th>Building Types</th>
<th>Damage Estimation</th>
<th>Damage Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelman (2002)</td>
<td>C</td>
<td>Physical (convertible to financial)</td>
<td>Depth, velocity</td>
<td>Building types</td>
<td>Synthetic Profiles</td>
</tr>
<tr>
<td>Schwarz and Maiwald (2008)</td>
<td>R</td>
<td>Physical Depth, velocity (qualitative)</td>
<td>Building type, floor levels, openings, etc.</td>
<td>Empirical</td>
<td>Damage curve</td>
</tr>
<tr>
<td>Blanco-Vogt and Schanz (2013)</td>
<td>R</td>
<td>Physical Depth Building type according to outline, height, elongatedness, compactness, adjacency and roof slope.</td>
<td>Synthetic</td>
<td>Relative</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 5: Summary of prominent data standards and specifications utilised in AEC/FM domain

The summary of prominent data standards and specifications utilised in AEC/FM domain (adopted and extended from Karimi and Akinci, 2010b)

<table>
<thead>
<tr>
<th>Standard/Data specification</th>
<th>Development group and project starting year</th>
<th>Targeted project phases</th>
<th>Usage</th>
<th>Included aspects</th>
<th>File Format</th>
<th>Extensibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Graphics Exchange Specification (IGES)</td>
<td>Boeing and General Electric - 1979</td>
<td>Design</td>
<td>Exchange of 2D/3D CAD data among various CAD applications</td>
<td>2D/3D geometries, topological relations, non-geometrical data</td>
<td>Based on ASCII</td>
<td>By development team</td>
</tr>
<tr>
<td>Drawing Exchange Format (DXF)</td>
<td>Autodesk - 1982</td>
<td>Design</td>
<td>Exchange of CAD data among various CAD applications</td>
<td>2D geometry (no topology or semantics)</td>
<td>Based on ASCII</td>
<td>By development team</td>
</tr>
<tr>
<td>STEP</td>
<td>ISO Technical committee 184/SC4 - 1984</td>
<td>Design, fabrication, erection (construction)</td>
<td>Exchange of 2D/3D CAD “product” data throughout their lifecycle</td>
<td>2D/3D geometries, topological relations, non-geometric data</td>
<td>STEP Part 21</td>
<td>By development team</td>
</tr>
<tr>
<td>CIS/2</td>
<td>University of Leeds and AISC - 1995 As STEP application protocol 230</td>
<td>Design, analysis, fabrication</td>
<td>Exchange of structural steel design, analysis, and fabrication information</td>
<td>Geometry, location, orientation, parts, assemblies, bolts, holes, welds, sequences, materials, surface treatments, connections and properties</td>
<td>STEP Part 21</td>
<td>Consensus among the software implementers and AISC</td>
</tr>
<tr>
<td>gbXML</td>
<td>Green Building Studio - 2000</td>
<td>Design</td>
<td>Exchange building CAD model to building simulation models</td>
<td>Geometry, spatial, geography (building coordinates)</td>
<td>XML</td>
<td>XML extension mechanisms</td>
</tr>
<tr>
<td>bcXML</td>
<td>eConstruct group - 2000</td>
<td>Design, construction, supply chain, operations and maintenance</td>
<td>Exchange of construction products, resources, work, methods, and regulations</td>
<td>Products, properties, taxonomy of terms and language rules</td>
<td>XML</td>
<td>XML extension mechanisms</td>
</tr>
<tr>
<td>Open Building Information Xchange (OBIX)</td>
<td>OASIS - 2003</td>
<td>Facilities / Operation and maintenance</td>
<td>Exchanged of sensor information between building automation systems</td>
<td>Sensor information (value, range and status)</td>
<td>XML and web services</td>
<td>XML extension mechanisms</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>--------------</td>
<td>----------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------------------</td>
<td>---------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Automated Equipment Information eXchange (AEX)</td>
<td>FIATECH - 2004</td>
<td>Design, supply chain, facilities/Operations and maintenance</td>
<td>Exchange engineered equipment information</td>
<td>Product information of equipment, properties (e.g. material), document associated with equipment</td>
<td>XML</td>
<td>XML extension mechanisms</td>
</tr>
<tr>
<td>ageXML</td>
<td>NBIMS committee - 2006</td>
<td>Design, construction, supply chain, operations and maintenance</td>
<td>Exchange of construction-related business-to-business documents</td>
<td>Documents</td>
<td>XML</td>
<td>XML extension mechanisms</td>
</tr>
<tr>
<td>BIM for Precast Concrete (BPC)</td>
<td>FIATECH - 2006</td>
<td>Design, manufacturing, installation</td>
<td>Exchange of information for design, manufacturing and installation of precast concrete members</td>
<td>Precast concrete members, parts, geometry, location and connection information</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Industry Foundation Classes (IFC)</td>
<td>BuildingSmart (formerly known as IAI) - 1996</td>
<td>All phases</td>
<td>Exchange of project information (product, process and contrl)</td>
<td>Products and associated elements, geometry, properties, geography, topology, relationships, costs, schedule, people, organisation, site, documents, etc.</td>
<td>STEP Part 21 (also available in XML format, the IfcXML)</td>
<td>Formal extension mechanisms</td>
</tr>
<tr>
<td>Building Collaboration Format (BCF) (BuildingSMART, 2009)</td>
<td>Tekla and Solibri -2009</td>
<td>Design</td>
<td>Exchange topics, such as, issues, scenes, etc. between different BIM software</td>
<td>Coordinates, view points, and other relevant information about action items during the design review (e.g. clash detection information)</td>
<td>XML</td>
<td>XML extension mechanisms</td>
</tr>
<tr>
<td>BIM Extended Markup Language (BIMXML) (bimxml.org, 2012)</td>
<td>Onuma - 2011</td>
<td>All phases</td>
<td>Exchange of project information</td>
<td>Simplified building elements (alternative to full scale IFC model)</td>
<td>XML</td>
<td>Xml Extension mechanisms</td>
</tr>
</tbody>
</table>
Appendix 6: Structured interview questions

Interviewee's details

Name:
........................................................................................................................................

Name of your organisation and division/unit:
........................................................................................................................................

What category best describes your organisation/unit?

- Local government (e.g. Council)
- Risk management
- General professional
- Government
- Referral Authority
- Architecture and engineering design
- Academia or Research and Development (R & D)
- Others

If "others", please specify: .................................................................

How do you describe your expertise?


Years of experience in the relevant roles to flood risk management:
  - Less than 1 year
  - 1 to 3 years
  - 4 to 10 years
  - More than 10 years
Verification and Validation of the framework

1. To how extent do you agree with the relevance and the validity of the formulated problem in practice?

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

2. To what extent do you agree with the followings?

(a) The design and flow of the framework is logical.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

(b) Relationships between the framework components and their inputs and outputs are designed properly.

| 1 | 2 | 3 | 4 | 5 |

(c) 3D BIM model as part of the integrated data layer with GIS is advantageous and an effective input for the framework.

| 1 | 2 | 3 | 4 | 5 |

3. Have the key flood parameters been properly used as the input of the model?

Yes / No.

Please provide your feedback.
4. According to the presented methods for assessment of damage to individual building components, in your expert opinion, are they appropriately designed in terms of their assumptions and process?

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumptions</th>
<th>Method</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Sliding doors</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Ceilings (including insulation)</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Utilities (Electrical)</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Flooring</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Soffit</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Skirting</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Cornices</td>
<td>Yes / No</td>
<td>Yes / No</td>
<td></td>
</tr>
</tbody>
</table>
### External walls

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumptions</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lining</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
<tr>
<td>Frame</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
<tr>
<td>Insulation</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
<tr>
<td>Cladding</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
</tbody>
</table>

### Internal walls

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumptions</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lining</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
<tr>
<td>Frame</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
<tr>
<td>Insulation</td>
<td>Yes / No</td>
<td>Yes / No</td>
</tr>
</tbody>
</table>

**5. Have the key building components been properly considered for the house type under investigation in this research?**

Yes / No.

If your answer is No, please specify what other important components can be considered to complete the model?
6. Have the damage criteria (or threshold) for the above components been set properly?  
Yes / No.

Any further feedback is welcomed.

7. To what extent do you agree with the following statements?

(a) The damage evaluation process properly considers the interrelationships between the building elements (e.g. the damage to window from damage to wall)

Strongly disagree

Strongly agree

If any additional comments, please provide.

(b) The damage predictions in the case study match the expected impacts from a flood situation.

Strongly disagree

Strongly agree

If any additional comments, please provide.

(c) The estimated water depth inside the house and cavities are relevant for the investigated flood in the case study

Strongly disagree

Strongly agree
8. To what extent do you agree with the following statements?

<table>
<thead>
<tr>
<th>The outputs (including the damage sheet and 3D visualisation) properly communicate the damage predictions.</th>
<th>Strongly disagree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

9. What is your overall assessment of the framework?
In addition to the answers to the above questions, your further feedbacks are welcomed.
**Appendix 7: Door Water Infiltration Equations**

This appendix presents the derived equations from door infiltration equations (Equation 6.8 to Equation 6.10) in Section 6.3.1 for calculation of water infiltration through bottom, top and side non-fixed panel cracks in different situations of water depths inside (h') and outside (h) of the building (b = door panel/frame bottom elevation, s = door panel/frame top elevation, W = width of panel/frame).

<table>
<thead>
<tr>
<th>Case</th>
<th>Panel cracks</th>
<th>Frame cracks&lt;sup&gt;103&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>h &gt; b h &lt;= s h' &lt;= b</td>
<td>Q (bottom crack) = $C W \left( \Delta P_{y=0} - \rho_w g h \right)^n$</td>
<td>Q (top crack) = 0</td>
</tr>
<tr>
<td>Q (top crack) = 0</td>
<td>Q (side cracks) = $\frac{c}{[\rho g(n+1)]} \times \left( \left( \Delta P_{y=0} - \rho_w g h \right)^{n+1} - \left( \Delta P_{y=0} - \rho_w g h' \right)^{n+1} \right)$</td>
<td>Q (side cracks) = $\frac{C W}{[\rho g(n+1)]} \times \left( \left( P_{outside, y=0} - \rho_w g h \right)^{n+1} - \left( P_{outside, y=0} - \rho_w g h' \right)^{n+1} \right)$</td>
</tr>
<tr>
<td>Q (side cracks) = $\frac{c}{[\rho g(n+1)]} \times \left( \left( \Delta P_{y=0} - \rho_w g h \right)^{n+1} - \left( \Delta P_{y=0} - \rho_w g h' \right)^{n+1} \right)$</td>
<td>Q (side cracks) = $\frac{C W}{[\rho g(n+1)]} \times \left( \left( P_{outside, y=0} - \rho_w g h \right)^{n+1} - \left( P_{outside, y=0} - \rho_w g h' \right)^{n+1} \right)$</td>
<td></td>
</tr>
<tr>
<td>h &gt; b h' &gt; b h' &lt; h</td>
<td>Q (bottom crack) = $-C W \left( \Delta P_{inside-outside} \right)^n$</td>
<td>Q (top crack) = 0</td>
</tr>
<tr>
<td>Q (top crack) = 0</td>
<td>Q (side cracks) = $\frac{c}{[\rho g(n+1)]} \times \left( \left( P_{inside} - \rho_w g h \right)^{n+1} - \left( P_{inside} - \rho_w g h' \right)^{n+1} \right)$</td>
<td>Q (side cracks) = $\frac{C W}{[\rho g(n+1)]} \times \left( \left( P_{outside} - \rho_w g h \right)^{n+1} - \left( P_{outside} - \rho_w g h' \right)^{n+1} \right)$</td>
</tr>
<tr>
<td>Q (side cracks) = $-\left[ C \left( h' - b \right) \left( \Delta P_{inside-outside} \right)^n \right] - \frac{c}{[\rho g(n+1)]} \times \left[ \left( P_{inside} - \rho_w g h \right)^{n+1} - \left( P_{inside} - \rho_w g h' \right)^{n+1} \right]$</td>
<td>Q (side cracks) = $\frac{C W}{[\rho g(n+1)]} \times \left( \left( P_{outside} - \rho_w g h \right)^{n+1} - \left( P_{outside} - \rho_w g h' \right)^{n+1} \right)$</td>
<td></td>
</tr>
</tbody>
</table>

<sup>103</sup> Note that C and (n) for frame is different and Table 6.4 should be used for this purpose. In addition, for the door frames, no bottom crack is considered.
\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
$h > b$ & Q (bottom crack) = $-C W (\Delta P_{\text{inside-outside}})^n$ & Q (top crack) = $-C W [\rho_w g (h' - s)]^n$ \\
$h <= s$ & Q (top crack) = $-C W [\rho_w g (h' - s)]^n$ & Q (side cracks) = $-C (h' - b) (\Delta P_{\text{inside-outside}})^n$ \\
$h' > b, h' > h$ & Q (side cracks) = $-C (h' - b) (\Delta P_{\text{inside-outside}})^n$ & $-C [\rho_w g] [\Delta P_{\text{inside-outside}}]^n$ \\
$h' > s$ & $[P_{\text{inside}} - \rho_w g h]^{n+1} - (P_{\text{inside}} - \rho_w g s)^{n+1}]$ & $[P_{\text{inside}} - \rho_w g h]^{n+1} - (P_{\text{inside}} - \rho_w g s)^{n+1}]$ \\
\hline
$h > s$ & Q (bottom crack) = $C W (P_{\text{outside}} y = 0 - \rho_w gh')^n$ & Q (top crack) = $C W (P_{\text{outside}} y = 0 - \rho_w gs)^n$ \\
$h' <= b$ & Q (top crack) = $C W (P_{\text{outside}} y = 0 - \rho_w gs)^n$ & Q (side cracks) = $C (h' - b) (\Delta P_{\text{outside-inside}})^n$ \\
& Q (side cracks) = $C (h' - b) (\Delta P_{\text{outside-inside}})^n + C \frac{c}{[\mu g (n+1)]} \times$ & $\frac{c}{[\mu g (n+1)]} \times [P_{\text{outside}} y = 0 - \rho_w g h']^{n+1} - (P_{\text{outside}} y = 0 - \rho_w g s)^{n+1}]$ \\
& $[(P_{\text{outside}} y = 0 - \rho_w gh')^{n+1} - (P_{\text{outside}} y = 0 - \rho_w gs)^{n+1}]$ & \\
\hline
$h > s$ & Q (bottom crack) = $C W (\Delta P_{\text{outside-inside}})^n$ & Q (top crack) = $C W (\Delta P_{\text{outside-inside}})^n$ \\
$h' > s, h' = h$ & Q (top crack) = $C W (\Delta P_{\text{outside-inside}})^n$ & Q (side cracks) = $C (s - b) (\Delta P_{\text{outside-inside}})^n$ \\
\hline
$h > s$ & Q (bottom crack) = $-C W (\Delta P_{\text{inside-outside}})^n$ & Q (top crack) = $-C W (\Delta P_{\text{inside-outside}})^n$ \\
$h' > s, h' < h$ & Q (top crack) = $-C W (\Delta P_{\text{inside-outside}})^n$ & Q (side cracks) = $-C (s - b) (\Delta P_{\text{outside-inside}})^n$ \\
\hline
$h <= b$ & Q (bottom crack) = 0 & Q (top crack) = 0 \\
$h' <= b$ & Q (side cracks) = 0 & \\
\hline
\end{tabular}
\end{table}
<table>
<thead>
<tr>
<th>Condition</th>
<th>Bottom Crack</th>
<th>Top Crack</th>
<th>Side Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \leq b$</td>
<td>$Q (\text{bottom crack}) = - C W (P_{\text{inside}} - \rho_w g b)^n$</td>
<td>$Q (\text{top crack}) = 0$</td>
<td>$Q (\text{side cracks}) = - \frac{c}{\rho g (n+1)} \times [(P_{\text{inside}} - \rho_w g b)^{n+1} - (P_{\text{inside}} - \rho_w g h')^{n+1}]$</td>
</tr>
<tr>
<td>$h' &gt; b$ $h' \leq s$</td>
<td>$Q (\text{side cracks}) = - \frac{c}{\rho g (n+1)} \times [(P_{\text{inside}} - \rho_w g b)^{n+1} - (P_{\text{inside}} - \rho_w g h')^{n+1}]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h' &gt; s$</td>
<td>$Q (\text{side cracks}) = - \frac{c}{\rho g (n+1)} \times [(P_{\text{inside}} - \rho_w g b)^{n+1} - (P_{\text{inside}} - \rho_w g s)^{n+1}]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 8: Failed doors water infiltration equations

In this appendix, the equations for calculation of the FIR (Q) from failed door is provided using the hydraulic structure theories, i.e. the box (or barrel) culverts. Three situations (three other cases can be added which are exactly the reverse of these) are illustrated according to the depth differential between the inside and outside without assuming the velocity of the water. Although velocity can generate extra pressure increasing the water infiltration, yet velocities are generally considered insignificant for slow-moving riverine flood and therefore the use of these equations can be justified.

<table>
<thead>
<tr>
<th>The free surface short box culvert model and cases 1 or 2 in page 448 of Chanson (2004) depending on tale water depth:</th>
<th>From Chanson (2004, pp 451)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition: ( \frac{H_1 - Z_{\text{inlet}}}{D} \leq 1.2 )</td>
<td>( \frac{Q}{B} = C_D \frac{2}{3} \sqrt{\frac{2}{3} g (H_1 - Z_{\text{inlet}})^{1.5}} )</td>
</tr>
<tr>
<td>( B ) = barrel width (door width)</td>
<td>( D ) = barrel height (door height)</td>
</tr>
<tr>
<td>( C_D ) = 1 for rounded vertical inlet edges and 0.9 for square-edged inlet</td>
<td>( H_1 ) = water depth at entry (from ground)</td>
</tr>
<tr>
<td>( Z_{\text{inlet}} ) = bottom height of the door</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>However, in the above case if ( \frac{H_1 - Z_{\text{inlet}}}{D} &gt; 1.2 )</th>
<th>From Chanson (2004, pp 449) is used.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{Q}{B} = \sqrt{2g(H_1 - Z_{\text{inlet}} - CD)} )</td>
<td>Submerged entrance box Culvert (free surface barrel flow) model inlet control case 5 in page 449 of Chanson (2004) is used.</td>
</tr>
<tr>
<td>( B ) = barrel width (door width)</td>
<td>( D ) = barrel height (door height)</td>
</tr>
<tr>
<td>( C_D ) = 1 for rounded vertical inlet edges and 0.9 for square-edged inlet</td>
<td>( H_1 ) = water depth at entry (from ground)</td>
</tr>
<tr>
<td>( Z_{\text{inlet}} ) = bottom height of the door</td>
<td></td>
</tr>
</tbody>
</table>

381
Where the depth of water inside and outside are greater than door height, yet the pressure difference still can cause failure in the door and water infiltration.

In this situation, case 6 is used with the formula (iii in table 21.4) in pp 451 of Chanson (2004) for submerged entrance and drowned barrel box culverts.

\[
\frac{Q}{D} = B \sqrt{\frac{2g \Delta H}{k'}}
\]

\(k'(\text{head loss coefficient})\) can be calculated using the Darcy equation:

\[
\Delta H = \text{inlet loss} - \text{friction less} - \text{outlet loss}
\]

\[
\text{Inlet loss} = k_i \frac{v^2}{2g}
\]

\[
\text{Outlet loss} = k_o \frac{v^2}{2g}
\]

\[
k' = k_{\text{inlet}} + k_{\text{outlet}} + k_{\text{friction}}
\]

\(k_{\text{inlet}} = 0.5, \ k_{\text{outlet}} = 1 \ for \ box \ culverts; \ k_{\text{friction}} = 0 \ due \ to \ short \ culvert\)
Appendix 9: Failed windows water infiltration equations

This appendix provides the infiltration (Q) through the failed windows (panels).

The rectangular sharp-crested weir (thin-plate weir) (adopted from Bos, 1978 pp 157)

The formula for this case can use Sharp Crested rectangular Weir theory (see above figure).

The main reference to be used here for calculation of free flow discharge is the "Bos (1978)".

\[ Q = 2.9524 \times C_e B \times h_e^{1.5} \]

\( C_e \) = an 'effective free flow' discharge coefficient (is a function of \( h_e/p \) and \( b/B \)). The values of \( C_e \) and \( K_b \) are provided in (Bos, 1978, pp 159-160)

\( b_e \) = the 'effective width' of the construction in m;

\( b_e = b + k_b \)

\( h_e \) = the 'effective head' in meters
The free surface short box culvert model and cases 1 or 2 in page 448 of Chanson (2004) depending on tale water depth

This is similar to the first case of doors.

\[
\frac{Q}{B} = C_D \frac{2}{3} \sqrt{\frac{2}{3}} g(H_1 - z_{inlet})^{1.5}
\]

With condition: \(\frac{H_1 - z_{inlet}}{B} > 1.2\)

B = barrel width (window panel width)
D = barrel height (window panel height)
\(C_D = 1\) for rounded vertical inlet edges and 0.9 for square-edged inlet
\(H_1\) = water depth at entry (from ground)
\(z_{inlet}\) = bottom height of the window panel

The formula for orifice flow can be used for infiltration in case the window breaks (Imnoeng.com/Tank/TankTime.htm)

In this case, we use the general equation for the discharge of water from an orifice.

\[
Q = C_c A \sqrt{2 g \Delta h}
\]

\(Q\) = discharge from the orifice
\(C_c\) = coefficient of contraction (which in case of sharp-edged orifice is 0.61)
A = area of the orifice (m\(^2\))
G = gravitational acceleration
\(\Delta h\) = depth differential between head on horizontal center line of the centroid of the orifice (m) outside and inside (see the source link for more).

Submerged entrance box Culvert model inlet control case 5 or 6 in page 449 of Chanson (2004) depending on tale water depth above the critical depth; and flow depth in the barrel

\[
\frac{Q}{B} = C D \sqrt{2 g(H_1 - z_{inlet} - CD)}
\]

Submerged entrance and free surface barrel flow. With condition:

\[
\frac{H_1 - z_{inlet}}{D} > 1.2
\]
| B = barrel width (window panel width) |
| D = barrel height (window panel height) |
| $C_D = 1$ for rounded vertical inlet edges and $0.9$ for square-edged inlet |
| $H_1$ = water depth at entry (from ground) |
| $Z_{ina}$ = bottom height of the window panel |

If window breaks:
Submerged entrance box Culvert model inlet control case 5 or 6 in page 449 of Chanson (2004) depending on tale water depth above the critical depth; and flow depth in the barrel.

\[
\frac{Q}{D} = B \sqrt{\frac{2g}{k'}} \frac{\Delta H}{k'}
\]

$K'$ (head loss coefficient) can be calculated using the Darcy equation;

\[
\Delta H = \text{inlet loss} - \text{friction loss} - \text{outlet loss}
\]

\[
\text{Inlet loss} = k_i \frac{v^2}{2g}
\]

\[
\text{Outlet loss} = k_o \frac{v^2}{2g}
\]

$\Delta H$ and $k'$ can be calculated similarly to the Appendix 3
Appendix 10: Water infiltration equations through air bricks and vents to and from cavity space

In here, the $h''$ represents the water depth inside the cavity space.

<table>
<thead>
<tr>
<th>Case</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h, h'' \leq 0$</td>
<td>$Q = 0$</td>
</tr>
<tr>
<td>$h \leq s, h'' \leq h$</td>
<td>$Q = C \cdot W \cdot h'' \cdot \Delta P^n + \int_{h''}^{h} [\rho_w g (h - y)]^n , dy$</td>
</tr>
<tr>
<td>$h \leq s$</td>
<td>$Q = -C \cdot W \cdot h'' \cdot \Delta P^n - \int_{h''}^{h} [\rho_w g (h'' - y)]^n , dy$</td>
</tr>
<tr>
<td>$h &gt; s, h'' \leq s$</td>
<td>$Q = C \cdot W \cdot h'' \cdot \Delta P^n - \int_{h''}^{s} [\rho_w g (s - y)]^n , dy$</td>
</tr>
<tr>
<td>$h &gt; s_{\text{wall}}$</td>
<td>$Q = C \cdot W \cdot s_{\text{wall}} \cdot \Delta P^n$</td>
</tr>
<tr>
<td>$h &gt; s_{\text{wall}}, h'' \leq h$</td>
<td>$Q = -C \cdot W \cdot s_{\text{wall}} \cdot \Delta P^n$</td>
</tr>
<tr>
<td>$h &gt; s_{\text{wall}}, h'' &gt; h$</td>
<td>$Q = C \cdot W \cdot h'' \cdot \Delta P^n + \int_{h''}^{h} [\rho_w g (h'' - y)]^n , dy$</td>
</tr>
<tr>
<td>$h_{\text{adj}}, h''_{\text{adj}} \leq 0$</td>
<td>$Q = 0$</td>
</tr>
<tr>
<td>$h_{\text{adj}} \leq s, h''<em>{\text{adj}} \leq h</em>{\text{adj}}$</td>
<td>$Q = C \cdot W \cdot h''<em>{\text{adj}} \cdot \Delta P</em>{\text{adj}}^n + \int_{h''<em>{\text{adj}}}^{h</em>{\text{adj}}} [\rho_w g (h_{\text{adj}} - y)]^n , dy$</td>
</tr>
<tr>
<td>$h_{\text{adj}} &gt; s, h''_{\text{adj}} \leq s$</td>
<td>$Q = -C \cdot W \cdot h''<em>{\text{adj}} \cdot \Delta P</em>{\text{adj}}^n - \int_{h''<em>{\text{adj}}}^{s} [\rho_w g (h</em>{\text{adj}} - y)]^n , dy$</td>
</tr>
<tr>
<td>$h_{\text{adj}} &gt; s_{\text{wall}}$</td>
<td>$Q = C \cdot W \cdot h''<em>{\text{adj}} \cdot \Delta P</em>{\text{adj}}^n + \int_{h''_{\text{adj}}}^{s} [\rho_w g (s - y)]^n , dy$</td>
</tr>
</tbody>
</table>

In a similar way, the infiltration for Section 3 of the wall is calculated as follows. However, the $h$ and $h''$ should adjusted for the wall panel. Accordingly, $h_{\text{adj}} = h - b_{\text{wall panel}}$ and $h''_{\text{adj}} = h'' - b_{\text{wall panel}}$. 
<table>
<thead>
<tr>
<th>$h_{adj} \leq 0$</th>
<th>$h^{''}_{adj} &gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = -CW \int_{0}^{S} [\rho_w g (h^{''}_{adj} - y)]^n dy$</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 11: Water infiltration equations for vents and air bricks

The required calculations for water infiltration through air bricks and vents to and from the cavity space.

<table>
<thead>
<tr>
<th>Case</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h, h'' \leq 0$</td>
<td>$Q = 0$</td>
</tr>
<tr>
<td>$h \leq s, h'' \leq b, h &gt; b$</td>
<td>$Q = 2^{1/2} C_{\text{drag}} W \int_{0}^{h} \left[ \frac{(\Delta P_{y=0} - \rho_w g y)}{\rho_w} \right]^{1/2} dy$</td>
</tr>
<tr>
<td>$h &gt; b, h'' \leq s, h \leq h'' \leq s$</td>
<td>$Q = - C_{\text{drag}} \times (h - b) W \left( \frac{2\Delta P}{\rho_w} \right)^{1/2}$ $- 2^{1/2} C_{\text{drag}} W \int_{h}^{h''} \left[ \frac{(\Delta P_{y=0} - \rho_w g y)}{\rho_w} \right]^{1/2} dy$</td>
</tr>
<tr>
<td>$h \leq s, h'' &gt; b, h'' &gt; s$</td>
<td>$Q = - C_{\text{drag}} \times (h - b) W \left( \frac{2\Delta P}{\rho_w} \right)^{1/2}$ $- 2^{1/2} C_{\text{drag}} W \int_{h}^{s} \left[ \frac{(\Delta P_{y=0} - \rho_w g y)}{\rho_w} \right]^{1/2} dy$</td>
</tr>
<tr>
<td>$h &gt; s_{\text{wall}}, h'' \leq b$</td>
<td>$Q = 2^{1/2} C_{\text{drag}} W \int_{0}^{s} \left[ \frac{(\Delta P_{y=0} - \rho_w g y)}{\rho_w} \right]^{1/2} dy$</td>
</tr>
<tr>
<td>Condition</td>
<td>Equation</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>( h &gt; s_{\text{wall}} ) \n( b &lt; h'' \leq s )</td>
<td>[ Q = C_{\text{drag}} \times \left( h'' - b \right) W \left( \frac{2\Delta P}{\rho_w} \right)^{1/2} ] (</td>
</tr>
<tr>
<td>( h &gt; s ) \n( s &lt; h'' \leq h )</td>
<td>[ Q = C_{\text{drag}} \times (s - b) W \left( \frac{2\Delta P}{\rho_w} \right)^{1/2} ] (</td>
</tr>
<tr>
<td>( h &gt; s ) \n( s &lt; h &lt; h'' )</td>
<td>[ Q = -C_{\text{drag}} \times (s - b) W \left( \frac{2\Delta P}{\rho_w} \right)^{1/2} ] (</td>
</tr>
<tr>
<td>( h &lt; b ) \n( b &lt; h'' \leq s )</td>
<td>[ Q = -2^{1/2} C_{\text{drag}} | W \int_{h''}^{s} \left[ \frac{\Delta P_{y=0} - \rho_w g y}{\rho_w} \right]^{1/2} ) \dy</td>
</tr>
<tr>
<td>( h \leq b ) \n( h'' \geq s )</td>
<td>[ Q = -2^{1/2} C_{\text{drag}} | W \int_{h''}^{s} \left[ \frac{\Delta P_{y=0} - \rho_w g y}{\rho_w} \right]^{1/2} ) \dy</td>
</tr>
</tbody>
</table>
Appendix 12: Wall-floor interface water infiltration equations

The calculations for water infiltration through the wall perimeter interface with floors.

<table>
<thead>
<tr>
<th>Case</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h'' = 0$</td>
<td>$Q = 0$</td>
</tr>
<tr>
<td>$h'' \leq b_{floor}$</td>
<td></td>
</tr>
<tr>
<td>$h'', h' &gt; b_{floor}$</td>
<td>$Q = CW \times [\rho_w g(h'' - b_{floor}) - \rho_w g h']^n$</td>
</tr>
<tr>
<td>$h'' \geq h'$</td>
<td></td>
</tr>
<tr>
<td>$h'', h' &gt; b_{floor}$</td>
<td>$Q = -CW \times [\rho_w g h' - \rho_w g(h'' - b_{floor})]^n$</td>
</tr>
<tr>
<td>$h'' &lt; h'$</td>
<td></td>
</tr>
<tr>
<td>$h', h' &lt; b_{floor}$</td>
<td>$Q = CW \times [\rho_w g h']^n$</td>
</tr>
<tr>
<td>$h' \geq 0$</td>
<td></td>
</tr>
<tr>
<td>$h' &lt; b_{floor}$</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 13: XML schema for the design profile of GML to facilitate micro-level FDA on building

Schema UrbanFloodBase.xsd

<table>
<thead>
<tr>
<th>Elements</th>
<th>Complex types</th>
<th>Simple types</th>
</tr>
</thead>
<tbody>
<tr>
<td>_UrbanObject</td>
<td>AbstractUrbanObjectType</td>
<td>SpatialStructureTypeEnum</td>
</tr>
<tr>
<td>Classification</td>
<td>ClassificationDefinitionObject</td>
<td></td>
</tr>
<tr>
<td>Definition</td>
<td>ClassificationObjectType</td>
<td></td>
</tr>
<tr>
<td>DamageLookupTable</td>
<td>DamageLookupTableType</td>
<td></td>
</tr>
<tr>
<td>Element</td>
<td>ElementInfoType</td>
<td></td>
</tr>
<tr>
<td>Necessities</td>
<td>SpatialStructureObjectMemberType</td>
<td></td>
</tr>
<tr>
<td>SpatialStructure</td>
<td>SpatialStructureObjectType</td>
<td></td>
</tr>
<tr>
<td>UrbanFloodModel</td>
<td>UrbanFloodModelType</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UrbanObjectMemberType</td>
<td></td>
</tr>
</tbody>
</table>

```xml
    xmlns:gmlBase="http://www.opengis.net/gml/3.2"
    xmlns:gml="http://www.opengis.net/gml/3.2"
    xmlns="http://localhost/schemas/1.0"
    xmlns:mtl="http://localhost/schemas/Material/1.0"
    xmlns:val="http://localhost/schemas/Valuation/1.0"
    targetNamespace="http://localhost/schemas/1.0"
    elementFormDefault="qualified"
    attributeFormDefault="unqualified" version="1.0">

    <xs:import namespace="http://www.opengis.net/gml/3.2"
        schemaLocation="http://schemas.opengis.net/gml/3.2.1/gmlBase.xsd"/>

    <xs:import namespace="http://www.opengis.net/gml/3.2"
        schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

    <xs:import namespace="http://localhost/schemas/Material/1.0"
        schemaLocation="MaterialDomain.xsd"/>

    <xs:import namespace="http://localhost/schemas/Valuation/1.0"
        schemaLocation="Valuation.xsd"/>

    element _UrbanObject
    <xs:element name="_UrbanObject" type="AbstractUrbanObjectType" abstract="true"
        substitutionGroup="gml:AbstractFeature"/>

    element Classification
    <xs:element name="Classification" type="ClassificationObjectType"
        substitutionGroup="gml:AbstractGML"/>
```
<table>
<thead>
<tr>
<th>Element Name</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ClassificationDefinition</strong></td>
<td><code>&lt;xs:element name=&quot;ClassificationDefinition&quot; substitutionGroup=&quot;gml:AbstractGML&quot;&gt;</code></td>
</tr>
<tr>
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<td><code>&lt;xs:element name=&quot;DamageLookupTable&quot; type=&quot;DamageLookupTableType&quot;/&gt;</code></td>
</tr>
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<td><strong>Element</strong></td>
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<td><code>&lt;xs:documentation&gt;Kg/m³&lt;/xs:documentation&gt;</code></td>
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<td></td>
<td><code>&lt;xs:element name=&quot;SpatialStructure&quot; type=&quot;SpatialStructureObjectType&quot;/&gt;</code></td>
</tr>
<tr>
<td><strong>UrbanFloodModel</strong></td>
<td><code>&lt;xs:element name=&quot;UrbanFloodModel&quot; type=&quot;UrbanFloodModelType&quot; substitutionGroup=&quot;gml:AbstractFeatureCollection&quot;/&gt;</code></td>
</tr>
</tbody>
</table>
### complexType AbstractUrbanObjectType

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    <xs:documentation>Type describing the abstract superclass of urban objects.</xs:documentation>
  </xs:annotation>
  <xs:complexContent>
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            <xs:sequence>
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            </xs:sequence>
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        </xs:element>
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      </xs:sequence>
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  </xs:complexContent>
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### complexType ClassificationDefinitionObject

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        <xs:element name="Edition" type="xs:string" minOccurs="0"/>
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    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

### complexType ClassificationObject

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      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
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```
complexType DamageLookupTableType

source
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  </xs:sequence>
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complexType ElementInfoType

source
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  <xs:attribute name="TimeStepWaterContactFinished" type="xs:int" default="0"/>
  <xs:attribute name="DamageState" type="xs:int" default="0"/>
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complexType SpatialStructureObjectMemberType

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  </xs:annotation>
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  </xs:complexContent>
</xs:complexType>

complexType SpatialStructureObjectType

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      <xs:element name="Type" type="xs:int" minOccurs="0" maxOccurs="unbounded"/>
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    </xs:sequence>
  </xs:complexContent>
</xs:complexType>
complexType UrbanFloodModelType

source

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          <xs:choice>
            <xs:element ref="val:_CostObject"/>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element name="SpatialStructureObjectMember" maxOccurs="unbounded">
        <xs:complexType>
        </xs:complexType>
      </xs:element>
      <xs:element name="MaterialObjectMember" type="mt:MaterialObjectMemberType" minOccurs="0" maxOccurs="unbounded">
        <xs:complexType>
        </xs:complexType>
      </xs:element>
      <xs:element name="ClassificationDefinitionMember" minOccurs="0" maxOccurs="unbounded">
        <xs:complexType>
        </xs:complexType>
      </xs:element>
      <xs:element name="UrbanObjectMember" type="UrbanObjectMemberType" maxOccurs="unbounded">
        <xs:complexType>
        </xs:complexType>
      </xs:element>
      <xs:element name="DamageLookupTable" type="DamageLookupTableType"/>
    </xs:sequence>
  </xs:extension>
</xs:complexContent>

<xs:attribute name="Owner" type="xs:string" use="required"/>
<xs:attribute name="DateCreated" type="xs:date" use="required"/>
<xs:attribute name="FloodType" type="xs:string" use="optional"/>
<xs:attribute name="FloodExceedanceProbability" type="xs:double" use="optional"/>
</xs:extension>
</xs:complexType>

**complexType** UrbanObjectMemberType

<table>
<thead>
<tr>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;xs:complexType name=&quot;UrbanObjectMemberType&quot;&gt;</td>
</tr>
<tr>
<td><a href="">xs:sequence</a></td>
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<tr>
<td>&lt;xs:element ref=&quot;_UrbanObject&quot;/&gt;</td>
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<tr>
<td>&lt;/xs:sequence&gt;</td>
</tr>
<tr>
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**simpleType** SpatialStructureTypeEnum

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<tr>
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</tr>
<tr>
<td>&lt;xs:enumeration value=&quot;0&quot; id=&quot;City&quot;/&gt;</td>
</tr>
<tr>
<td>&lt;xs:enumeration value=&quot;1&quot; id=&quot;Site&quot;/&gt;</td>
</tr>
<tr>
<td>&lt;xs:enumeration value=&quot;2&quot; id=&quot;Building&quot;/&gt;</td>
</tr>
<tr>
<td>&lt;xs:enumeration value=&quot;3&quot; id=&quot;BuildingStory&quot;/&gt;</td>
</tr>
<tr>
<td>&lt;xs:enumeration value=&quot;4&quot; id=&quot;Space&quot;/&gt;</td>
</tr>
<tr>
<td>&lt;/xs:restriction&gt;</td>
</tr>
<tr>
<td>&lt;/xs:simpleType&gt;</td>
</tr>
</tbody>
</table>
Schema Terrain.xsd

Elements
- _TerrainObject
- MassPointTerrain
- Terrain
- TinTerrain

Complex types
- AbstractTerrainObjectType
- MassPointTerrainType
- TerrainComponentsType
- TerrainType
- TinObject
- TinTerrainType

Simple types
- TerrainLoDEnum

```xml
xmlns:core="http://localhost/schemas/1.0"
xmlns="http://localhost/schemas/Terrain/1.0"
targetNamespace="http://localhost/schemas/Terrain/1.0"
elementFormDefault="qualified"
attributeFormDefault="unqualified"
version="1.0">
  <xs:import namespace="http://localhost/schemas/1.0" schemaLocation="UrbanFloodBase.xsd"/>
  <xs:import namespace="http://www.opengis.net/gml/3.2"
schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

  <element name="_TerrainObject" source="xs:element name="_TerrainObject" type="AbstractTerrainObjectType" abstract="true"
substitutionGroup="core:_UrbanObject"/>

  <element name="MassPointTerrain" source="xs:element name="MassPointTerrain" type="MassPointTerrainType"
substitutionGroup="_TerrainObject"/>

  <element name="Terrain" source="xs:element name="Terrain" type="TerrainType" abstract="true"
substitutionGroup="core:_UrbanObject"/>

  <element name="TinTerrain" source="xs:element name="TinTerrain" type="TinTerrainType" substitutionGroup="_TerrainObject"/>

  <complexType name="AbstractTerrainObjectType" source="xs:complexType name="AbstractTerrainObjectType" abstract="true">
    <xs:annotation>
      <xs:documentation>Type describing the abstract superclass for physical property objects such as buildings, land, tunnels, utility networks, etc.</xs:documentation>
    </xs:annotation>
  </xs:complexType>
</xs:schema>
```
```xml
<xs:complexType name="MassPointTerrainType">
  <xs:sequence>
    <xs:element ref="gml:MultiPoint"/>
  </xs:sequence>
</xs:complexType>

complexType MassPointTerrainType

complexType TerrainComponentsType

complexType TerrainType

complexType TinObject
```
<table>
<thead>
<tr>
<th>complexType</th>
<th>TinTerrainType</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
<td><code>&lt;xs:complexContent&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:extension base=&quot;AbstractTerrainObjectType&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;tin&quot; type=&quot;TinObject&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:extension&gt;</code></td>
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<tr>
<td></td>
<td><code>&lt;xs:restriction base=&quot;xs:int&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;0&quot; id=&quot;LoD0&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;1&quot; id=&quot;LoD1&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;2&quot; id=&quot;LoD2&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;3&quot; id=&quot;LoD3&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;4&quot; id=&quot;LoD4&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;5&quot; id=&quot;BIM&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;6&quot; id=&quot;Mixed&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;7&quot; id=&quot;NotDefined&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;/xs:restriction&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;/xs:simpleType&gt;</code></td>
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</table>
### Elements

<table>
<thead>
<tr>
<th>Elements</th>
<th>Complex types</th>
</tr>
</thead>
<tbody>
<tr>
<td>_FloodObject</td>
<td>_AbstractFloodObjectType</td>
</tr>
<tr>
<td>FloodBody</td>
<td>AbstractFloodBoundarySurfaceType</td>
</tr>
<tr>
<td>FloodBoundarySurface</td>
<td>BoundedByFloodSurfaceType</td>
</tr>
<tr>
<td>FloodClosureSurface</td>
<td>FloodBodyType</td>
</tr>
<tr>
<td>FloodGroundSurface</td>
<td>FloodClosureSurfaceType</td>
</tr>
<tr>
<td>FloodMetadataObject</td>
<td>FloodGroundSurfaceType</td>
</tr>
<tr>
<td>FloodSurface</td>
<td>FloodMetadataObjectType</td>
</tr>
<tr>
<td>FloodTimeSeriesElement</td>
<td>FloodSurfaceType</td>
</tr>
<tr>
<td>FloodTimeSeriesElementArray</td>
<td>FloodTimeSeriesElementArrayType</td>
</tr>
<tr>
<td></td>
<td>FloodTimeSeriesElementType</td>
</tr>
</tbody>
</table>

```xml
  targetNamespace="http://localhost/schemas/Flood/1.0"
  elementFormDefault="qualified" attributeFormDefault="unqualified" version="1.0">

  <xs:import namespace="http://localhost/schemas/1.0" schemaLocation="UrbanFloodBase.xsd"/>

  <xs:import namespace="http://www.opengis.net/gml/3.2" schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

  <xs:element name="_FloodObject" type="_AbstractFloodObjectType" abstract="true" substitutionGroup="core:_UrbanObject"/>

  <xs:element name="FloodBody" type="FloodBodyType" substitutionGroup="_FloodObject"/>

  <xs:element name="FloodBoundarySurface" type="AbstractFloodBoundarySurfaceType" substitutionGroup="gml:AbstractFeature"/>

  <xs:element name="FloodClosureSurface" type="FloodClosureSurfaceType" substitutionGroup="FloodBoundarySurface"/>

  <xs:element name="FloodGroundSurface" type="FloodGroundSurfaceType" substitutionGroup="FloodBoundarySurface"/>

  <xs:element name="FloodMetadataObject" type="FloodMetadataObjectType"/>

  <xs:element name="FloodSurface" type="FloodSurfaceType" substitutionGroup="FloodBoundarySurface"/>
```

402
### element **FloodTimeSeriesElement**
```xml
<xs:element name="FloodTimeSeriesElement" type="FloodTimeSeriesElementType">
   <xs:annotation>
      <xs:documentation>To create the compositeValue of the GML and restrict it to the timeStepNo, WaterLevel, Depth, Velocity items ONLY!</xs:documentation>
   </xs:annotation>
</xs:element>
```

### element **FloodTimeSeriesElementArray**
```xml
<xs:element name="FloodTimeSeriesElementArray" type="FloodTimeSeriesElementArrayType" substitutionGroup="gml:AbstractValue"/>
```

### complexType **_AbstractFloodObjectType**
```xml
<xs:complexType name="_AbstractFloodObjectType" abstract="true">
   <xs:complexContent>
      <xs:extension base="core:AbstractUrbanObjectType">
         <xs:sequence>
            <xs:element ref="FloodMetadataObject" minOccurs="0"/>
         </xs:sequence>
      </xs:extension>
   </xs:complexContent>
</xs:complexType>
```

### complexType **AbstractFloodBoundarySurfaceType**
```xml
<xs:complexType name="AbstractFloodBoundarySurfaceType" abstract="true">
   <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
         <xs:sequence>
            <xs:element name="surface">
               <xs:complexType>
                  <xs:sequence>
                     <xs:element ref="gml:MultiSurface" minOccurs="0"/>
                  </xs:sequence>
               </xs:complexType>
            </xs:element>
         </xs:sequence>
      </xs:extension>
   </xs:complexContent>
</xs:complexType>
```

### complexType **BoundedByFloodSurfaceType**
```xml
<xs:complexType name="BoundedByFloodSurfaceType">
   <xs:sequence/>
</xs:complexType>
```
complexType FloodBodyType

source

<xs:complexType name="FloodBodyType">
  <xs:complexContent>
    <xs:extension base="_AbstractFloodObjectType">
      <xs:sequence>
        <xs:element name="MaxExtent" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Polygon"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedByPointCoverage" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:MultiPointCoverage"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedBySurface" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="FloodBoundarySurface" maxOccurs="unbounded"/>
            </xs:sequence>
            <xs:attribute name="TimeStepNumber" type="xs:int" use="required"/>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedByTemporalSurface" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element name="TimeSeriesSurfaces">
                <xs:complexType>
                  <xs:sequence>
                    <xs:element name="TimeStep" maxOccurs="unbounded">
                      <xs:complexType>
                        <xs:sequence>
                          <xs:element ref="FloodBoundarySurface" maxOccurs="unbounded"/>
                        </xs:sequence>
                      </xs:complexType>
                    </xs:element>
                  </xs:sequence>
                </xs:complexType>
              </xs:element>
              <xs:attribute name="TimeStepNumber" type="xs:int" use="required"/>
            </xs:complexType>
          </xs:element>
        </xs:element>
        <xs:element name="RepresentedBySolid" minOccurs="0" maxOccurs="1">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid"/>
            </xs:sequence>
            <xs:attribute name="TimeStepNumber" type="xs:int"/>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedByTemporalSolid" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid"/>
            </xs:sequence>
            <xs:attribute name="TimeStepNumber" type="xs:int"/>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
complexType **FloodClosureSurfaceType**

```xml
complexType
<xs:sequence>
  <xs:element name="TimeSeriesSolids" />
  <xs:complexType>
    <xs:sequence>
      <xs:element name="TimeStep" maxOccurs="unbounded" />
      <xs:complexType>
        <xs:sequence>
          <xs:element name="Representation" />
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid" />
            </xs:sequence>
            <xs:element>
              <xs:sequence>
                <xs:complexType>
                  <xs:sequence>
                    <xs:element>
                      <xs:sequence>
                        <xs:extension>
                          <xs:complexContent>
                            <xs:extension base="AbstractFloodBoundarySurfaceType"/>
                          </xs:complexContent>
                        </xs:extension>
                      </xs:complexType>
                    </xs:element>
                  </xs:sequence>
                </xs:complexType>
              </xs:sequence>
            </xs:complexType>
          </xs:complexType>
        </xs:sequence>
      </xs:complexType>
    </xs:sequence>
    <xs:attribute name="TimeStepNumber" type="xs:int" use="required"/>
  </xs:complexType>
</xs:sequence>
</xs:complexType>
```

**source**

```xml
<xs:complexType name="FloodClosureSurfaceType">
  <xs:complexContent>
    <xs:extension base="AbstractFloodBoundarySurfaceType"/>
  </xs:complexContent>
</xs:complexType>
```

complexType **FloodGroundSurfaceType**

```xml
complexType
<xs:sequence>
  <xs:element name="TimeSeriesSolids" />
  <xs:complexType>
    <xs:sequence>
      <xs:element name="TimeStep" maxOccurs="unbounded" />
      <xs:complexType>
        <xs:sequence>
          <xs:element name="Representation" />
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid" />
            </xs:sequence>
            <xs:element>
              <xs:sequence>
                <xs:extension>
                  <xs:complexContent>
                    <xs:extension base="AbstractFloodBoundarySurfaceType"/>
                  </xs:complexContent>
                </xs:extension>
              </xs:sequence>
            </xs:complexType>
          </xs:complexType>
        </xs:sequence>
      </xs:complexType>
    </xs:sequence>
    <xs:attribute name="TimeStepNumber" type="xs:int" use="required"/>
  </xs:complexType>
</xs:sequence>
</xs:complexType>
```

**source**

```xml
<xs:complexType name="FloodGroundSurfaceType">
  <xs:complexContent>
    <xs:extension base="AbstractFloodBoundarySurfaceType"/>
  </xs:complexContent>
</xs:complexType>
```

complexType **FloodMetadataObjectType**

```xml
complexType
<xs:sequence>
  <xs:element name="TimeSeriesSolids" />
  <xs:complexType>
    <xs:sequence>
      <xs:element name="TimeStep" maxOccurs="unbounded" />
      <xs:complexType>
        <xs:sequence>
          <xs:element name="Representation" />
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid" />
            </xs:sequence>
            <xs:element>
              <xs:sequence>
                <xs:extension>
                  <xs:complexContent>
                    <xs:extension base="gml:AbstractMetaDataType"/>
                  </xs:complexContent>
                </xs:extension>
              </xs:sequence>
            </xs:complexType>
          </xs:complexType>
        </xs:sequence>
      </xs:complexType>
    </xs:sequence>
    <xs:attribute name="TimeStepNumber" type="xs:int" use="required"/>
  </xs:complexType>
</xs:sequence>
</xs:complexType>
```

**source**

```xml
<xs:complexType name="FloodMetadataObjectType" mixed="true">
  <xs:complexContent>
    <xs:extension base="gml:AbstractMetaDataType">
    </xs:complexContent>
  </xs:complexType>
```
<xs:complexType name="FloodSurfaceType">
  <xs:complexContent>
    <xs:extension base="AbstractFloodBoundarySurfaceType">
      <xs:sequence>
        <xs:element name="FloodDepth" type="xs:double" minOccurs="0" maxOccurs="1"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

<xs:complexType name="FloodTimeSeriesElementArrayType">
  <xs:complexContent>
    <xs:extension base="FloodTimeSeriesElementType">
      <xs:attribute name="PointReferenceID" type="xs:string" use="optional"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

<xs:complexType name="FloodTimeSeriesElementType">
  <xs:complexContent>
    <xs:extension base="FloodTimeSeriesElementType">
      <xs:attribute name="TimeStepNumber" type="xs:int" use="required"/>
      <xs:attribute name="WaterSurfaceLevel" type="xs:double" use="optional"/>
      <xs:attribute name="Velocity_U" type="xs:double" use="required"/>
      <xs:attribute name="Velocity_V" type="xs:double" use="required"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
Schema Valuation.xsd

Elements
  _CostObject
  AssemblyCostObject
  BuildingValue

Complex types
  AbstractCostObjectType
  AssemblyCostObjectType
  BuildingValueType

<x:schema xmlns:xs="http://www.w3.org/2001/XMLSchema" xmlns:gml="http://www.opengis.net/gml/3.2"
  xmlns="http://localhost/schemas/Valuation/1.0"
  targetNamespace="http://localhost/schemas/Valuation/1.0"
  elementFormDefault="qualified" attributeFormDefault="unqualified" version="1.0">
  <xs:import namespace="http://www.opengis.net/gml/3.2"
    schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

  <element name="_CostObject" type="AbstractCostObjectType" abstract="true"
    substitutionGroup="gml:AbstractGML"/>

  <element name="AssemblyCostObject" type="AssemblyCostObjectType"
    substitutionGroup="_CostObject"/>

  <element name="BuildingValue" type="BuildingValueType"
    substitutionGroup="_CostObject"/>

complexType AbstractCostObjectType

  <xs:complexType name="AbstractCostObjectType">
    <xs:complexContent>
      <xs:extension base="gml:AbstractGMLType">
        <xs:sequence>
          <xs:element name="Description" type="xs:string" minOccurs="0"/>
        </xs:sequence>
        <xs:attribute name="Ref" type="xs:IDREF" use="optional"/>
        <xs:attribute name="Name" type="xs:string" use="optional"/>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>

complexType AssemblyCostObjectType

  <xs:complexType name="AssemblyCostObjectType">
    <xs:complexContent base="AbstractCostObjectType">
      <xs:attribute name="UnitCost" type="xs:double" use="optional"/>
      <xs:attribute name="IssuingInstitution" type="xs:string" use="optional"/>
      <xs:attribute name="IssueDate" type="xs:date" use="optional"/>
      <xs:attribute name="Manufacturer" type="xs:string" use="optional"/>
      <xs:attribute name="ProductionDate" type="xs:date" use="optional"/>
    </xs:complexContent>
  </xs:complexType>
<xs:attribute name="ExternalReference" type="xs:string" use="optional"/>
<xs:attribute name="UnitOfMeasurement" type="xs:string" use="optional"/>
<xs:attribute name="CurrencyType" type="xs:string" use="optional"/>
</xs:extension>
</xs:complexContent>
</xs:complexType>

complexType BuildingValueType

source
<xs:complexType name="BuildingValueType">
  <xs:complexContent>
    <xs:extension base="AbstractCostObjectType">
      <xs:attribute name="Value" type="xs:double" use="optional"/>
      <xs:attribute name="CurrencyType" type="xs:string" use="optional"/>
      <xs:attribute name="IssuingInstitution" type="xs:string" use="optional"/>
      <xs:attribute name="IssueDate" type="xs:date" use="optional"/>
      <xs:attribute name="ExternalReference" type="xs:string" use="optional"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
## Schema MaterialDomain.xsd

### Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Complex types</th>
<th>Simple types</th>
</tr>
</thead>
<tbody>
<tr>
<td>_MaterialObject</td>
<td>AbstractMaterialObject Type</td>
<td>MaterialLayer Enum</td>
</tr>
<tr>
<td>Material</td>
<td>MaterialConstituent Set Type</td>
<td>Material Type Enum</td>
</tr>
<tr>
<td>MaterialConstituent</td>
<td>Material Constituent Type</td>
<td>Material Water Resistance Class</td>
</tr>
<tr>
<td>MaterialConstituent Set</td>
<td>Material Layers Set Type</td>
<td></td>
</tr>
<tr>
<td>MaterialLayer</td>
<td>Material Layer Type</td>
<td></td>
</tr>
<tr>
<td>MaterialLayersSet</td>
<td>Material Object Member Type</td>
<td></td>
</tr>
<tr>
<td>TimberFramingElementMaterial</td>
<td>Material Type</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TimberFramingElementMaterial Type</td>
</tr>
</tbody>
</table>

```xml
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema" xmlns="http://localhost/schemas/Material/1.0"
xmlns:gml="http://www.opengis.net/gml/3.2" xmlns:val="http://localhost/schemas/Valuation/1.0"
targetNamespace="http://localhost/schemas/Material/1.0" elementFormDefault="qualified"
attributeFormDefault="unqualified" version="1.0">

  <xs:import namespace="http://www.opengis.net/gml/3.2"
schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>
  <xs:import namespace="http://localhost/schemas/Valuation/1.0"
schemaLocation="Valuation.xsd"/>

  <xs:element name="_MaterialObject" type="AbstractMaterialObject Type" abstract="true"
substitutionGroup="gml:AbstractGML"/>

  <xs:element name="Material" type="MaterialType" substitutionGroup="_MaterialObject"/>

  <xs:element name="MaterialConstituent" type="MaterialConstituentType"
substitutionGroup="_MaterialObject"/>

  <xs:element name="MaterialConstituent Set" type="MaterialConstituent Set Type"
substitutionGroup="_MaterialObject"/>

  <xs:element name="MaterialLayer" type="MaterialLayer Type" substitutionGroup="_MaterialObject"/>

  <xs:element name="MaterialLayersSet" type="MaterialLayersSet Type"
substitutionGroup="_MaterialObject"/>

</xs:schema>
```
element TimberFramingElementMaterial

source
<xs:element name="TimberFramingElementMaterial" type="TimberFramingElementMaterialType" substitutionGroup="Material"/>

complexType AbstractMaterialObjectType

source
<xs:complexType name="AbstractMaterialObjectType" abstract="true">
  <xs:annotation>
    <xs:documentation>Type describing the abstract superclass of urban objects.</xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="gml:AbstractGMLType">
      <xs:sequence>
        <xs:element name="Description" type="xs:string" minOccurs="0"/>
      </xs:sequence>
      <xs:attribute name="Ref" type="xs:IDREF" use="optional"/>
      <xs:attribute name="Name" type="xs:string" use="optional"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType MaterialConstituentSetType

source
<xs:complexType name="MaterialConstituentSetType">
  <xs:annotation>
    <xs:documentation>Type describing the elements, attributes, and associations of buildings.</xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="AbstractMaterialObjectType">
      <xs:sequence>
        <xs:element name="MaterialConstituentObject" minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element name="MaterialConstituent" type="MaterialConstituentType"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
**complexType MaterialConstituentType**

```
<xs:complexType name="MaterialConstituentType">
  <xs:annotation>
    <xs:documentation> Type describing the elements, attributes, and associations of buildings. </xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="AbstractMaterialObjectType">
      <xs:sequence>
        <xs:element name="MaterialObject" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="Material"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="ConstructionCost" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="val:AssemblyCostObject"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

**complexType MaterialLayersSetType**

```
<xs:complexType name="MaterialLayersSetType">
  <xs:annotation>
    <xs:documentation> Type describing the elements, attributes, and associations of buildings. </xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="AbstractMaterialObjectType">
      <xs:sequence>
        <xs:element name="MaterialLayerObject" minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element name="MaterialLayer" type="MaterialLayerType"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```
complexType **MaterialLayerType**

```xml
complexType MaterialLayerType

source
<xs:complexType name="MaterialLayerType">
  <xs:annotation>
    <xs:documentation> Type describing the elements, attributes, and associations of buildings. </xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="AbstractMaterialObjectType">
      <xs:sequence>
        <xs:element name="MaterialObject" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="_MaterialObject" minOccurs="0"/>
            </xs:sequence>
            <xs:complexType>
              <xs:sequence>
                <xs:attribute name="Thickness" type="xs:double" use="optional"/>
                <xs:attribute name="IsVentilated" type="xs:boolean" use="optional"/>
                <xs:attribute name="ConstructionCostRef" type="xs:IDREF" use="optional"/>
              </xs:sequence>
              <xs:complexType>
                <xs:sequence>
                  <xs:element ref="val:AssemblyCostObject"/>
                </xs:sequence>
                <xs:complexType>
                  <xs:sequence>
                    <xs:attribute name="Thickness" type="xs:double" use="optional"/>
                    <xs:attribute name="IsVentilated" type="xs:boolean" use="optional"/>
                    <xs:attribute name="ConstructionCostRef" type="xs:IDREF" use="optional"/>
                  </xs:sequence>
                  <xs:complexType>
                    <xs:sequence>
                      <xs:element ref="_MaterialObject" minOccurs="0"/>
                    </xs:sequence>
                    <xs:complexType>
                      <xs:sequence>
                        <xs:complexType>
                          <xs:sequence>
                            <xs:attribute name="Thickness" type="xs:double" use="optional"/>
                            <xs:attribute name="IsVentilated" type="xs:boolean" use="optional"/>
                            <xs:attribute name="ConstructionCostRef" type="xs:IDREF" use="optional"/>
                          </xs:sequence>
                          <xs:complexType>
                            <xs:sequence>
                              <xs:element>
                                <xs:complexType>
                                  <xs:sequence>
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                                      <xs:complexType>
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                                          ...
                                        </xs:sequence>
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                                                  ...
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                                                            <xs:element>
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                                                                  ...
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                                                                                    <xs:element>
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                </xs:complexType>
              </xs:complexType>
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          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

complexType **MaterialObjectMemberType**

```xml
complexType MaterialObjectMemberType

source
<xs:complexType name="MaterialObjectMemberType">
  <xs:sequence>
    <xs:element ref="_MaterialObject" minOccurs="0"/>
  </xs:sequence>
</xs:complexType>
```

complexType **MaterialType**

```xml
complexType MaterialType

source
<xs:complexType name="MaterialType">
  <xs:annotation>
    <xs:documentation> Type describing the elements, attributes, and associations of buildings. </xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="AbstractMaterialObjectType">
      <xs:sequence>
        <xs:element name="MaterialObject">
          <xs:complexType>
            <xs:sequence>
              <xs:element>
                <xs:complexType>
                  <xs:sequence>
                    <xs:element>
                      <xs:complexType>
                        <xs:sequence>
                          ...
                        </xs:sequence>
                        <xs:complexType>
                          <xs:sequence>
                            <xs:element>
                              <xs:complexType>
                                <xs:sequence>
                                  ...
                                </xs:sequence>
                                <xs:complexType>
                                  <xs:sequence>
                                    <xs:element>
                                      <xs:complexType>
                                        <xs:sequence>
                                          ...
                                        </xs:sequence>
                                        <xs:complexType>
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                                                <xs:sequence>
                                                  ...
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                                                      <xs:complexType>
                                                        <xs:sequence>
                                                          ...
                                                        </xs:sequence>
                                                        <xs:complexType>
                                                          <xs:sequence>
                                                            <xs:element>
                                                              <xs:complexType>
                                                                <xs:sequence>
                                                                  ...
                                                                </xs:sequence>
                                                                <xs:complexType>
                                                                  <xs:sequence>
                                                                    <xs:element>
                                                                      <xs:complexType>
                                                                        <xs:sequence>
                                                                          ...
                                                                        </xs:sequence>
                                                                        <xs:complexType>
                                                                          <xs:sequence>
                                                                            <xs:element>
                                                                              <xs:complexType>
                                                                                <xs:sequence>
                                                                                  ...
                                                                                </xs:sequence>
                                                                                <xs:complexType>
                                                                                  <xs:sequence>
                                                                                    <xs:element>
                                                                                      <xs:complexType>
                                                                                        <xs:sequence>
                                                                                      </xs:sequence>
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                                                                                      </xs:complexType>
                                                                                  </xs:complexType>
                                                                            </xs:complexType>
                                                                        </xs:complexType>
                                                                      </xs:complexType>
                                                                    </xs:complexType>
                                                                  </xs:complexType>
                                                                </xs:complexType>
                                                              </xs:complexType>
                                                            </xs:complexType>
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                                                    </xs:complexType>
                                                  </xs:complexType>
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                                          </xs:complexType>
                                        </xs:complexType>
                                      </xs:complexType>
                                    </xs:complexType>
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                            </xs:complexType>
                          </xs:complexType>
                        </xs:complexType>
                      </xs:complexType>
                    </xs:complexType>
                  </xs:complexType>
                </xs:complexType>
              </xs:complexType>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```
<xs:element name="Weight" type="xs:double" minOccurs="0"/>
<xs:element name="WeightUoM" type="xs:string" minOccurs="0"/>
</xs:sequence>
<xs:attribute name="MaterialLabel" type="xs:string" use="optional"/>
<xs:attribute name="MaterialClass" type="xs:int" use="optional"/>
<xs:attribute name="MaterialType" type="xs:int" use="optional"/>
<xs:attribute name="MinimumContactDuration" type="xs:double" use="optional"/>
<xs:attribute name="ContactDurationUoM" type="xs:string" use="optional"/>
</xs:extension>
</xs:complexContent>
</xs:complexType>

complexType TimberFramingElementMaterialType
<xs:complexType name="TimberFramingElementMaterialType">
<xs:annotation>
<xs:documentation>Type describing the elements, attributes, and associations of buildings.</xs:documentation>
</xs:annotation>
<xs:complexContent>
<xs:extension base="MaterialType">
<xs:attribute name="IsSeasoned" type="xs:boolean" use="optional"/>
<xs:attribute name="StressGrade" type="xs:string" use="optional"/>
</xs:extension>
</xs:complexContent>
</xs:complexType>

simpleType MaterialLayerEnum
<xs:simpleType name="MaterialLayerEnum">
<xs:restriction base="xs:int">
<xs:enumeration value="0" id="Lining"/>
<xs:enumeration value="1" id="Insulation"/>
<xs:enumeration value="2" id="Framing"/>
<xs:enumeration value="3" id="Cladding"/>
</xs:restriction>
</xs:simpleType>

simpleType MaterialTypeEnum
<xs:simpleType name="MaterialTypeEnum">
<xs:restriction base="xs:int">
<xs:enumeration value="0" id="Material"/>
<xs:enumeration value="1" id="Component"/>
<xs:enumeration value="2" id="System"/>
</xs:restriction>
</xs:simpleType>
<table>
<thead>
<tr>
<th>simpleType</th>
<th>MaterialWaterResistanceClass</th>
</tr>
</thead>
<tbody>
<tr>
<td>source</td>
<td><code>&lt;xs:simpleType name=&quot;MaterialWaterResistanceClass&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:restriction base=&quot;xs:int&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;0&quot; id=&quot;AcceptableForFloodWater&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;1&quot; id=&quot;AcceptableForClearWater&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;2&quot; id=&quot;UnacceptableForWaterContact&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:enumeration value=&quot;3&quot; id=&quot;NotApplicable&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;/xs:restriction&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;/xs:simpleType&gt;</code>,</td>
</tr>
</tbody>
</table>

<xs:import namespace="http://www.opengis.net/gml/3.2" schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

</xs:schema>
<xs:import namespace="http://localhost/schemas/Material/1.0" schemaLocation="MaterialDomain.xsd"/>
<xs:import namespace="http://localhost/schemas/Valuation/1.0" schemaLocation="Valuation.xsd"/>
<xs:import namespace="http://localhost/schemas/Utility/1.0" schemaLocation="Utility.xsd"/>
<xs:import namespace="http://localhost/schemas/Connection/1.0" schemaLocation="Connection.xsd"/>

element _BuildingElement

| source | <xs:element name="_BuildingElement" type="AbstractBuildingElementType" abstract="true"/> |

element _Opening

| source | <xs:element name="_Opening" type="AbstractOpeningType" abstract="true" substitutionGroup="_BuildingElement"/> |

element AirBrick

| source | <xs:element name="AirBrick" substitutionGroup="_Opening">
|        | <xs:complexType>
|        | <xs:complexContent>
|        | <xs:extension base="AbstractOpeningType">  
|        | <xs:sequence>
|        | <xs:element name="NominalUnitHeight" type="xs:double" minOccurs="0" maxOccurs="1"/>
|        | </xs:sequence>
|        | </xs:extension>
|        | </xs:complexContent>
|        | </xs:complexType>
|        | </xs:element> |

element Beam

| source | <xs:element name="Beam" type="BeamObjectType" substitutionGroup="_BuildingElement"/> |

element Brick

| source | <xs:element name="Brick" type="BrickObjectType"/> |

element Building

| source | <xs:element name="Building" substitutionGroup="core:_UrbanObject">
|        | <xs:complexType>
|        | <xs:complexContent>
|        | <xs:extension base="BuildingObjectType"/>
|        | </xs:complexContent>
|        | </xs:complexType>
<p>|        | &lt;/xs:element&gt; |</p>
<table>
<thead>
<tr>
<th>Element</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>BuildingElementPart</td>
<td><code>&lt;xs:element name=&quot;BuildingElementPart&quot; type=&quot;BuildingElementPartType&quot; substitutionGroup=&quot;_BuildingElement&quot;/&gt;</code></td>
</tr>
<tr>
<td>BuildingElementProxy</td>
<td><code>&lt;xs:element name=&quot;BuildingElementProxy&quot; type=&quot;BuildingElementProxyObjectType&quot; substitutionGroup=&quot;_BuildingElement&quot;/&gt;</code></td>
</tr>
</tbody>
</table>
| BuildingStorey | `<xs:element name="BuildingStorey" substitutionGroup="core:_UrbanObject">`  
  `<xs:complexType>`  
  `<xs:complexContent>`  
  `<xs:extension base="BuildingStoreyType"/>`  
  `<xs:complexType>`  
  `<xs:element>`  
| Ceiling       | `<xs:element name="Ceiling" type="CeilingType" substitutionGroup="Covering"/>` |
| CladdingElement | `<xs:element name="CladdingElement" type="CladdingElementObjectType" substitutionGroup="WallComponentElement"/>` |
| Column        | `<xs:element name="Column" type="ColumnObjectType" substitutionGroup="_BuildingElement"/>` |
| Cornice       | `<xs:element name="Cornice" type="CorniceType" substitutionGroup="Covering"/>` |
| Covering      | `<xs:element name="Covering" type="CoveringType" abstract="true" substitutionGroup="_BuildingElement"/>` |
element CoveringLayerElement
source <xs:element name="CoveringLayerElement" type="CoveringLayerElementType" substitutionGroup="BuildingElementPart"/>

element Door
source <xs:element name="Door" type="DoorObjectType" substitutionGroup="_Opening"/>

element DoorLining
source <xs:complexType>
  <xs:complexContent>
    <xs:extension base="DoorLiningType"/>
  </xs:complexContent>
</xs:complexType>

element DoorPanel
source <xs:element name="DoorPanel" type="DoorPanelType"/>

element Floor
source <xs:element name="Floor" type="FloorObjectType" substitutionGroup="Slab"/>

element Flooring
source <xs:element name="Flooring" type="FlooringType" substitutionGroup="Covering"/>

element FoundationSlab
source <xs:element name="FoundationSlab" type="FoundationSlabObjectType" substitutionGroup="Slab"/>

element FramingMember
source <xs:element name="FramingMember" type="FramingMemberObjectType" substitutionGroup="_BuildingElement"/>
### element GlassLayer

```xml
<xs:element name="GlassLayer">
  <xs:complexType>
    <xs:complexContent>
      <xs:extension base="GlassLayerObjectType">
        <xs:attribute name="Ref" type="xs:IDREF" use="optional"/>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
</xs:element>
```

### element GlassLayers

```xml
<xs:element name="GlassLayers">
  <xs:complexType>
    <xs:complexContent>
      <xs:extension base="GlassLayersObjectType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:element>
```

### element Railing

```xml
<xs:element name="Railing" type="RailingObjectType" substitutionGroup="_BuildingElement"/>
```

### element Roof

```xml
<xs:element name="Roof" type="RoofObjectType" substitutionGroup="_BuildingElement"/>
```

### element Site

```xml
<xs:element name="Site" type="SiteObjectType" substitutionGroup="core:_UrbanObject"/>
```

### element Skirting

```xml
<xs:element name="Skirting" substitutionGroup="Covering">
  <xs:complexType>
    <xs:complexContent>
      <xs:extension base="SkirtingType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:element>
```

### element Slab

```xml
<xs:element name="Slab" type="SlabObjectType" substitutionGroup="_BuildingElement"/>
```
element SlidingDoor
source <xs:element name="SlidingDoor" type="WindowObjectType" substitutionGroup="_Opening"/>

element Soffit
source <xs:element name="Soffit" type="SoffitType" substitutionGroup="Covering"/>

element Space
source <xs:element name="Space" type="SpaceObjectType"/>

element Stair
source <xs:element name="Stair" type="StairObjectType" substitutionGroup="_BuildingElement"/>

element StairFlight
source <xs:element name="StairFlight" type="StairFlightObjectType" substitutionGroup="_BuildingElement"/>

element VoidOpening
source <xs:element name="VoidOpening" type="VoidOpeningType" substitutionGroup="_Opening"/>

element Wall
source <xs:element name="Wall" type="WallObjectType" substitutionGroup="_BuildingElement"/>

element WallComponentElement
source <xs:element name="WallComponentElement" type="WallComponentElementType" substitutionGroup="BuildingElementPart"/>

element WallTie
source <xs:element name="WallTie" type="WallTieObjectType" substitutionGroup="_BuildingElement"/>

element Weephole
source <xs:element name="Weephole" substitutionGroup="VoidOpening">
  <xs:complexType>
    <xs:complexContent>
      <xs:extension base="VoidOpeningType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:element>
<table>
<thead>
<tr>
<th>element</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window</td>
<td><code>&lt;xs:element name=&quot;Window&quot; type=&quot;WindowObjectType&quot; substitutionGroup=&quot;_Opening&quot;/&gt;</code></td>
</tr>
<tr>
<td>WindowLining</td>
<td><code>&lt;xs:element name=&quot;WindowLining&quot; type=&quot;WindowLiningObjectType&quot; substitutionGroup=&quot;core:_UrbanObject&quot;/&gt;</code></td>
</tr>
<tr>
<td>WindowPanel</td>
<td><code>&lt;xs:element name=&quot;WindowPanel&quot; type=&quot;WindowPanelObjectType&quot; substitutionGroup=&quot;core:_UrbanObject&quot;/&gt;</code></td>
</tr>
<tr>
<td>complexType</td>
<td><code>&lt;xs:complexType name=&quot;AbstractBuildingElementType&quot; abstract=&quot;true&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:extension base=&quot;core:AbstractUrbanObjectType&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;ObjectType&quot; type=&quot;xs:string&quot; minOccurs=&quot;0&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;BaseHeight&quot; type=&quot;xs:double&quot; minOccurs=&quot;0&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;AssemblyCost&quot; minOccurs=&quot;0&quot; maxOccurs=&quot;1&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:complexType&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
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<td></td>
<td><code>&lt;xs:element ref=&quot;Val:AssemblyCostObject&quot; minOccurs=&quot;1&quot;/&gt;</code></td>
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<td></td>
<td>&lt;/xs:sequence&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:complexType&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:element&gt;</td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;ConsistsOfOpening&quot; nillable=&quot;true&quot; minOccurs=&quot;0&quot; maxOccurs=&quot;unbounded&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:complexType&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element ref=&quot;_Opening&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:sequence&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:complexType&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:element&gt;</td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;ConsistsOfPart&quot; nillable=&quot;true&quot; minOccurs=&quot;0&quot; maxOccurs=&quot;unbounded&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:complexType&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element ref=&quot;_BuildingElement&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:sequence&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:complexType&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:element&gt;</td>
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<td><code>&lt;xs:element name=&quot;CoveredBy&quot; nillable=&quot;true&quot; minOccurs=&quot;0&quot; maxOccurs=&quot;unbounded&quot;&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:complexType&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element ref=&quot;Covering&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:sequence&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:complexType&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:element&gt;</td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element name=&quot;RepresentedBySolid&quot; minOccurs=&quot;0&quot;&gt;</code></td>
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<td></td>
<td><code>&lt;xs:complexType&gt;</code></td>
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<tr>
<td></td>
<td><code>&lt;xs:sequence&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>&lt;xs:element ref=&quot;gml:Solid&quot;/&gt;</code></td>
</tr>
<tr>
<td></td>
<td>&lt;/xs:sequence&gt;</td>
</tr>
</tbody>
</table>
complexType

source

complexType

BeamObjectType

source

complexType

AbstractOpeningType

source

complexType

AbstractBuildingElementType

source

complexType

Listing 1-25. UoMType, UoMContent, BuildingElementType, and OpeningType elements.
```xml
<xs:element name="Material" minOccurs="0">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="mtl:Material"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="MaterialLayers" minOccurs="0">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="mtl:MaterialLayersSet"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="Roll" type="xs:double" minOccurs="0"/>
<xs:element name="Slope" type="xs:double" minOccurs="0"/>
</xs:sequence>
</xs:extension>
</xs:complexContent>
</xs:complexType>

complexType BrickObjectType

source <xs:complexType name="BrickObjectType">
  <xs:sequence>
    <xs:element name="Width" type="xs:double" default="0.110" minOccurs="0"/>
    <xs:element name="Height" type="xs:double" default="0.076" minOccurs="0"/>
    <xs:element name="Length" type="xs:double" default="0.230" minOccurs="0"/>
  </xs:sequence>
  <xs:attribute name="Id" type="xs:string" use="optional"/>
  <xs:attribute name="Ref" type="xs:IDREF" use="optional"/>
  <xs:attribute name="Name" type="xs:string" use="optional"/>
  <xs:attribute name="Description" type="xs:string" use="optional"/>
</xs:complexType>

complexType BuildingElementPartType

source <xs:complexType name="BuildingElementPartType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="UserdefinedType" minOccurs="0"/>
        <xs:element name="ElementUsage" nillable="true" minOccurs="0"/>
        <xs:complexType>
          <xs:sequence>
            <xs:element name="usage" type="xs:int" minOccurs="0" maxOccurs="unbounded"/>
          </xs:sequence>
        </xs:complexType>
      </xs:sequence>
      <xs:element name="UserdefinedUsage" type="xs:string" minOccurs="0"/>
      <xs:element name="Material" minOccurs="0"/>
      <xs:complexType>
        <xs:sequence>
          <xs:element ref="mtl:Material"/>
        </xs:sequence>
      </xs:complexType>
      <xs:element name="MaterialLayers" minOccurs="0"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```
complexType BuildingElementProxyObjectType

source
<xs:complexType name="BuildingElementProxyObjectType" abstract="false">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="IsExternal" type="xs:boolean" minOccurs="0"/>
        <xs:element name="IsLoadBearing" type="xs:boolean" minOccurs="0"/>
        <xs:element name="Material" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="mtl:Material"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="MaterialLayers" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="mtl:MaterialLayersSet"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="Length" type="xs:double" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType BuildingObjectType

source
<xs:complexType name="BuildingObjectType">
  <xs:annotation>
    <xs:documentation>The type describes the superclass of all the utility objects in the model!</xs:documentation>
  </xs:annotation>
  <xs:complexContent base="core:AbstractUrbanObjectType">
    <xs:sequence>
      <xs:element name="ContainedInSite" minOccurs="0">
        <xs:complexType>
          <xs:sequence>
            <xs:element ref="Site"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
      <xs:element name="Value" minOccurs="0">
        <xs:complexType>
          <xs:sequence>
            <xs:element ref="Val:BuildingValue"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
    </xs:sequence>
  </xs:complexContent>
</xs:complexType>
<xs:complexType>
  <xs:element name="ConsistsOfStorey" minOccurs="0" maxOccurs="1">
    <xs:complexType>
      <xs:sequence>
        <xs:element ref="BuildingStorey" minOccurs="1" maxOccurs="unbounded"/>
      </xs:sequence>
    </xs:complexType>
  </xs:element>
  <xs:element name="Footprint" minOccurs="0" maxOccurs="1">
    <xs:complexType>
      <xs:sequence>
        <xs:element ref="gml:Polygon"/>
      </xs:sequence>
    </xs:complexType>
  </xs:element>
  <xs:element name="ConsistsOf" minOccurs="0">
    <xs:complexType>
      <xs:choice minOccurs="0" maxOccurs="unbounded">
        <xs:element ref="_BuildingElement" minOccurs="0" maxOccurs="unbounded"/>
        <xs:element ref="utl:UtilityObject" minOccurs="0" maxOccurs="unbounded"/>
        <xs:element ref="utl:UtilitySystem" minOccurs="0" maxOccurs="unbounded"/>
        <xs:element ref="conn:Connection" minOccurs="0" maxOccurs="unbounded"/>
      </xs:choice>
    </xs:complexType>
  </xs:element>
  <xs:attribute name="SiteId" type="xs:IDREF" use="optional"/>
  <xs:attribute name="Address" type="xs:string" use="optional"/>
  <xs:attribute name="Height" type="xs:double" use="optional"/>
  <xs:attribute name="NetTotalArea" type="xs:double" use="optional"/>
</xs:complexType>

complexType BuildingStoreyType
source
<xs:complexType name="BuildingStoreyType">
  <xs:complexContent>
    <xs:extension base="core:AbstractUrbanObjectType">
      <xs:sequence>
        <xs:element name="RepresentedByMultiSurface" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:MultiSurface"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedBySolid" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedByElement" minOccurs="0" maxOccurs="unbounded"/>
        <xs:element name="ElevationOfRefHeight" type="xs:double" use="optional"/>
        <xs:element name="ElevationOfTerrain" type="xs:double" use="optional"/>
        <xs:element name="Height" type="xs:double" use="optional"/>
        <xs:element name="BaseHeight" type="xs:double" use="optional"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexType>
</xs:complexType>
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<td><code>&lt;xs:element name=&quot;MaterialLayers&quot; minOccurs=&quot;0&quot;&gt;</code></td>
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<td></td>
</tr>
<tr>
<td><code>&lt;xs:element name=&quot;Height&quot; type=&quot;xs:double&quot; minOccurs=&quot;0&quot;/&gt;</code></td>
<td></td>
</tr>
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<td><code>&lt;xs:element name=&quot;Thickness&quot; type=&quot;xs:double&quot; default=&quot;0&quot; minOccurs=&quot;0&quot;/&gt;</code></td>
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<td></td>
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<td><code>&lt;xs:sequence&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:extension&gt;</code></td>
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<tr>
<td><code>&lt;xs:complexType&gt;</code></td>
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</tr>
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<tr>
<td><code>&lt;xs:sequence&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:element name=&quot;UserdefinedType&quot; type=&quot;xs:string&quot; minOccurs=&quot;0&quot;/&gt;</code></td>
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<tr>
<td><code>&lt;xs:element name=&quot;NetArea&quot; type=&quot;xs:double&quot; minOccurs=&quot;0&quot;/&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:element name=&quot;MaterialLayers&quot; minOccurs=&quot;0&quot;&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:complexType&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:element ref=&quot;mtl:MaterialLayersSet&quot;/&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:sequence&gt;</code></td>
<td></td>
</tr>
<tr>
<td><code>&lt;xs:element name=&quot;Material&quot; minOccurs=&quot;0&quot;&gt;</code></td>
<td></td>
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<td></td>
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<tr>
<td><code>&lt;xs:sequence&gt;</code></td>
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</table>
complexType DoorLiningType

complexType

source
<xs:complexType name="DoorLiningType">
    <xs:complexContent>
        <xs:extension base="core:AbstractUrbanObjectType">
            <xs:sequence>
                <xs:element name="DoorId" type="xs:IDREF" minOccurs="0"/>
                <xs:element name="LiningDepth" type="xs:double" minOccurs="0"/>
                <xs:element name="LiningThickness" type="xs:double" minOccurs="0"/>
                <xs:element name="LiningOffset" type="xs:double" minOccurs="0"/>
                <xs:element name="CasingDepth" type="xs:double" minOccurs="0"/>
                <xs:element name="CasingThickness" type="xs:double" minOccurs="0"/>
                <xs:element name="Material" minOccurs="0">
                    <xs:complexType>
                        <xs:sequence>
                            <xs:element ref="mtl:_MaterialObject"/>
                        </xs:sequence>
                    </xs:complexType>
                </xs:element>
                <xs:element name="RepresentedByMultiSurface" minOccurs="0">
                    <xs:complexType>
                        <xs:sequence>
                            <xs:element ref="gml:MultiSurface"/>                        
                        </xs:sequence>
                    </xs:complexType>
                </xs:element>
                <xs:element name="RepresentedBySolid" minOccurs="0">
                    <xs:complexType>
                        <xs:sequence>
                            <xs:element ref="gml:Solid"/>                        
                        </xs:sequence>
                    </xs:complexType>
                </xs:element>
                <xs:element name="ReplacementCost" minOccurs="0">
                    <xs:complexType>
                        <xs:sequence>
                            <xs:element ref="Val:AssemblyCostObject"/>                        
                        </xs:sequence>
                    </xs:complexType>
                </xs:element>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
complexType DoorObjectType

source<xs:complexType name="DoorObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractOpeningType">
      <xs:sequence>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="IsWeatherStripped" type="xs:boolean" minOccurs="0"/>
        <xs:element name="IsFramingCaulked" type="xs:boolean" minOccurs="0"/>
        <xs:element name="IsExternal" type="xs:boolean" minOccurs="0"/>
        <xs:element name="OperationType" type="xs:int" minOccurs="0"/>
        <xs:element ref="mtl:_MaterialObject"/>
        <xs:element name="DoorConstructionMaterialSet" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="mtl:MaterialConstituentSet"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="Panel" nillable="true" minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="DoorPanel"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="Lining" nillable="true" minOccurs="0" maxOccurs="1"/>
      </xs:sequence>
    </xs:extension>
    </xs:complexContent>
  </xs:complexType>
</xs:complexType>

complexType DoorPanelType

source<xs:complexType name="DoorPanelType">
  <xs:complexContent>
    <xs:extension base="core:AbstractUrbanObjectType">
      <xs:sequence>
        <xs:element name="DoorId" type="xs:iIDREF" minOccurs="0"/>
        <xs:element name="Width" type="xs:double" minOccurs="0"/>
        <xs:element name="Height" type="xs:double" minOccurs="0"/>
        <xs:element name="PanelPosition" type="xs:int" minOccurs="0"/>
        <xs:element name="OpeningMethod" type="xs:int" minOccurs="0" maxOccurs="1"/>
        <xs:element name="UserdefinedOperationType" type="xs:string" minOccurs="0" maxOccurs="1"/>
        <xs:element ref="mtl:_MaterialObject"/>  
      </xs:sequence>
    </xs:extension>
  </xs:complexType>
</xs:complexType>
<xs:element name="BaseHeight" type="xs:double" minOccurs="0"/>
<xs:element name="ReplacementCost" minOccurs="0"/>
<xs:complexType>
  <xs:sequence>
    <xs:element ref="Val:AssemblyCostObject"/>
  </xs:sequence>
</xs:complexType>
<xs:element name="ReplacementCost" minOccurs="0">
<xs:complexType>
  <xs:sequence>
    <xs:element ref="Val:AssemblyCostObject"/>
  </xs:sequence>
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</xs:element>
</xs:sequence>
<xs:extension>
  <xs:sequence>
    <xs:element>
      <xs:complexType>
        <xs:complexContent>
          <xs:extension base="FlooringType"/>
        </xs:complexContent>
      </xs:complexType>
    </xs:element>
  </xs:sequence>
</xs:extension>
<xs:complexType FlooringType>
  source <xs:complexType name="FlooringType">
    <xs:complexContent>
      <xs:extension base="CoveringType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:complexType>
<xs:complexType FloorObjectType>
  source <xs:complexType name="FloorObjectType">
    <xs:complexContent>
      <xs:extension base="SlabObjectType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:complexType>
<xs:complexType FoundationSlabObjectType>
  source <xs:complexType name="FoundationSlabObjectType">
    <xs:complexContent>
      <xs:extension base="SlabObjectType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:complexType>
<xs:complexType FramingMemberObjectType>
  source <xs:complexType name="FramingMemberObjectType" abstract="true">
    <xs:complexContent>
      <xs:extension base="AbstractBuildingElementType"/>
    </xs:complexContent>
  </xs:complexType>
</xs:complexType>
```xml
<xs:element name="Slope" type="xs:double" minOccurs="0"/>
<xs:element name="IsExternal" type="xs:boolean" minOccurs="0"/>
<xs:element name="IsLoadBearing" type="xs:boolean" minOccurs="0"/>
<xs:element name="Material" minOccurs="0">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="mtl:Material"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
</xs:complexContent>
</xs:complexType>

complexType GlassLayerObjectType
source
<xs:complexType name="GlassLayerObjectType">
  <xs:complexContent>
    <xs:extension base="gml:AbstractGMLType">
      <xs:sequence>
        <xs:element name="Label" type="xs:string"/>
        <xs:element name="Description" type="xs:string" minOccurs="0"/>
        <xs:element name="Color" type="xs:string" minOccurs="0"/>
        <xs:element name="Thickness" type="xs:double"/>
        <xs:element name="IsTempered" type="xs:boolean"/>
        <xs:element name="IsLaminated" type="xs:boolean"/>
        <xs:element name="IsCoated" type="xs:boolean"/>
        <xs:element name="IsWired" type="xs:boolean"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType GlassLayersObjectType
source
<xs:complexType name="GlassLayersObjectType">
  <xs:complexContent>
    <xs:extension base="gml:AbstractGMLType">
      <xs:sequence>
        <xs:element name="Name" type="xs:string"/>
        <xs:element name="Description" type="xs:string" minOccurs="0"/>
        <xs:element name="FillGlass" type="xs:string" minOccurs="0"/>
        <xs:element name="Layer">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="GlassLayer" maxOccurs="unbounded"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```
### complexType RailingObjectType

```xml
<xs:complexType name="RailingObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="Material" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="mtl:Material"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="IsExternal" type="xs:boolean" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

### complexType RoofObjectType

```xml
<xs:complexType name="RoofObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="NetArea" type="xs:double" minOccurs="0"/>
        <xs:element name="Material" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="mtl:Material"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="MaterialLayers" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="mtl:MaterialLayersSet"/>  
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

### complexType SiteObjectType

```xml
<xs:complexType name="SiteObjectType">
  <xs:annotation>
    <xs:documentation>This object describes the SITE object as a substitute for the UrbanObject element within the model!</xs:documentation>
  </xs:annotation>
  <xs:complexContent base="core:AbstractUrbanObjectType">
    <xs:sequence>
      <xs:element name="Footprint" minOccurs="0" maxOccurs="1” />
    </xs:sequence>
  </xs:complexContent>
</xs:complexType>
```
```xml
<xs:complexType>
  <xs:element name="ContainsBuilding" minOccurs="0" maxOccurs="unbounded">
    <xs:complexType>
      <xs:sequence>
        <xs:element ref="Building"/>
      </xs:sequence>
    </xs:complexType>
  </xs:element>
  <xs:element name="Address" type="xs:string" use="optional"/>
</xs:complexType>

complexType SkirtingType
source
<xs:complexType name="SkirtingType">
  <xs:complexContent>
    <xs:extension base="CoveringType">
      <xs:sequence>
        <xs:element name="Length" type="xs:double" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType SlabObjectType
source
<xs:complexType name="SlabObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="IsExternal" type="xs:boolean" minOccurs="0"/>
        <xs:element name="Material" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

433
**complexType SoffitType**

```xml
<xs:complexType name="SoffitType">
  <xs:complexContent>
    <xs:extension base="CoveringType"/>
  </xs:complexContent>
</xs:complexType>
```

**complexType SpaceObjectType**

```xml
<xs:complexType name="SpaceObjectType">
  <xs:complexContent>
    <xs:extension base="core:AbstractUrbanObjectType">
      <xs:sequence>
        <xs:element name="Type" type="xs:int" minOccurs="0"/>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="ElevationWithFlooring" type="xs:double" minOccurs="0"/>
        <xs:element name="NetArea" type="xs:double" minOccurs="0"/>
        <xs:element name="Height" type="xs:double" minOccurs="0"/>
        <xs:element name="BoundedBy" minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="_BuildingElement"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="CoveredBy" minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="Covering"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedByMultiSurface" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:MultiSurface"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="RepresentedBySolid" minOccurs="0">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:Solid"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:complexType>
  </xs:extension>
</xs:complexContent>
</xs:complexType>
```

**complexType StairFlightObjectType**

```xml
<xs:complexType name="StairFlightObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="Material" minOccurs="0"/>
      </xs:sequence>
    </xs:complexType>
  </xs:extension>
</xs:complexContent>
</xs:complexType>
```
complexType StairObjectType

source <xs:complexType name="StairObjectType">
   <xs:complexContent>
      <xs:extension base="AbstractBuildingElementType">
         <xs:sequence>
            <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
            <xs:element name="Material" minOccurs="0"/>
            <xs:sequence>
               <xs:element ref="mtl:Material"/>
            </xs:sequence>
            <xs:complexType>
               <xs:element name="ConsistsOfRailing" minOccurs="0" maxOccurs="unbounded"/>
            </xs:complexType>
            <xs:element name="ConsistsOfStairFlight" minOccurs="0" maxOccurs="unbounded"/>
            <xs:complexType>
               <xs:element name="Landing" minOccurs="0" maxOccurs="unbounded"/>
            </xs:complexType>
         </xs:sequence>
      </xs:extension>
   </xs:complexContent>
</xs:complexType>

complexType VoidOpeningType

source <xs:complexType name="VoidOpeningType">
   <xs:complexContent>
      <xs:extension base="AbstractOpeningType">
         <xs:sequence>
            <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
            <xs:element name="RepresentedByPoint" minOccurs="0"/>
            <xs:sequence>
               <xs:element ref="gml:Point"/>
            </xs:sequence>
         </xs:complexType>
      </xs:extension>
   </xs:complexContent>
</xs:complexType>
### complexType WallComponentElementType

```xml
<xs:complexType name="WallComponentElementType">
  <xs:complexContent>
    <xs:extension base="BuildingElementPartType">
      <xs:sequence>
        <xs:element name="Width" type="xs:double" minOccurs="0" maxOccurs="1"/>
        <xs:element name="Height" type="xs:double" minOccurs="0" maxOccurs="1"/>
        <xs:element name="Thickness" type="xs:double" default="0" minOccurs="0"/>
        <xs:element name="NetArea" type="xs:double" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

### complexType WallObjectType

```xml
<xs:complexType name="WallObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="UserdefinedType" type="xs:string" minOccurs="0"/>
        <xs:element name="Width" type="xs:double" minOccurs="0"/>
        <xs:element name="Height" type="xs:double" minOccurs="0"/>
        <xs:element name="Thickness" type="xs:double" minOccurs="0"/>
        <xs:element name="IsExternal" type="xs:boolean" minOccurs="0"/>
        <xs:element ref="mtl:Material" minOccurs="0"/>
        <xs:element ref="mtl:MaterialLayersSet" minOccurs="0"/>
        <xs:element name="RepresentedByCurve" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```

### complexType WallTieObjectType

```xml
<xs:complexType name="WallTieObjectType">
  <xs:complexContent>
    <xs:extension base="AbstractBuildingElementType">
      <xs:sequence>
        <xs:element name="CompressionCapacity" type="xs:double" minOccurs="0"/>
        <xs:element name="TensionCapacity" type="xs:double" minOccurs="0"/>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>
```
<xs:element name="RepresentedByCurve" minOccurs="0">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:AbstractCurve"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:complexType name="WindowLiningObjectType">
  <xs:complexContent>
    <xs:extension base="core:AbstractUrbanObjectType"/>
    <xs:sequence>
      <xs:element name="WindowId" type="xs:IDREF" minOccurs="0"/>
      <xs:element name="LiningThickness" type="xs:double" minOccurs="0"/>
      <xs:element name="LiningDepth" type="xs:double" minOccurs="0"/>
      <xs:element name="LiningToPanelOffsetX" type="xs:double" minOccurs="0"/>
      <xs:element name="LiningToPanelOffsetY" type="xs:double" minOccurs="0"/>
      <xs:element name="MullionThickness" type="xs:double" minOccurs="0"/>
      <xs:element name="TransomThickness" type="xs:double" minOccurs="0"/>
      <xs:element name="FirstMullionOffset" type="xs:double" minOccurs="0"/>
      <xs:element name="SecondMullionOffset" type="xs:double" minOccurs="0"/>
      <xs:element name="FirstTransomOffset" type="xs:double" minOccurs="0"/>
      <xs:element name="SecondTransomOffset" type="xs:double" minOccurs="0"/>
      <xs:element name="Material" minOccurs="0">"m:Material"</xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="RepresentedByMultiSurface" minOccurs="0">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:MultiSurface"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="RepresentedBySolid" minOccurs="0">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:Solid"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
simpleType CeilingDamageStateEnum

```xml
<xs:simpleType name="CeilingDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="cds_NoDamage"/>
    <xs:enumeration value="1" id="c_WetOnly"/>
    <xs:enumeration value="2" id="c_MaterialDamage"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType CeilingInsulationDamageStateEnum

```xml
<xs:simpleType name="CeilingInsulationDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="cids_NoDamage"/>
    <xs:enumeration value="1" id="cids_WetOnly"/>
    <xs:enumeration value="2" id="cids_MaterialDamageOrCollapse"/>
  </xs:restriction>
</xs:simpleType>
```

class claddingType

```xml
<xs:simpleType name="claddingType">
  <xs:restriction base="xs:int">
    <xs:enumeration value="1" id="Brick"/>
    <xs:enumeration value="2" id="timberOrWeatherboard"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType ColumnTypeEnum

```xml
<xs:simpleType name="ColumnTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="COLUMN"/>
    <xs:enumeration value="1" id="PILASTER"/>
    <xs:enumeration value="2" id="USERDEFINED_Column"/>
    <xs:enumeration value="3" id="Column_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType CoveringLayerElementUsageEnum

```xml
<xs:simpleType name="CoveringLayerElementUsageEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="cleu_Finishing"/>
    <xs:enumeration value="1" id="cleu_Lining"/>
    <xs:enumeration value="2" id="cleu_Insulation"/>
    <xs:enumeration value="3" id="cleu_Structure"/>
    <xs:enumeration value="4" id="cleu_USERDEFINED"/>
    <xs:enumeration value="5" id="cleu_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```
simpleType CoveringTypeEnum

aniel start

<xs:simpleType name="CoveringTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="CEILING"/>
    <xs:enumeration value="1" id="FLOORING"/>
    <xs:enumeration value="2" id="CLADDING"/>
    <xs:enumeration value="3" id="ROOFING"/>
    <xs:enumeration value="4" id="MOLDING"/>s
    <xs:enumeration value="5" id="SKIRTINGBOARD"/>
    <xs:enumeration value="6" id="INSULATION"/>
    <xs:enumeration value="7" id="MEMBRANE"/>
    <xs:enumeration value="8" id="SLEEVING"/>
    <xs:enumeration value="9" id="WRAPPING"/>
    <xs:enumeration value="10" id="USERDEFINED_CoveringType"/>
    <xs:enumeration value="11" id="NOTDEFINED_CoveringType"/>
  </xs:restriction>
</xs:simpleType>

simpleType DoorComponentsForMaterialDefinitionEnum

<xs:simpleType name="DoorComponentsForMaterialDefinitionEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="Glazing"/>
    <xs:enumeration value="1" id="dcfmd_Framing"/>
    <xs:enumeration value="2" id="Panel"/>
    <xs:enumeration value="3" id="dcfmd_Lining"/>
  </xs:restriction>
</xs:simpleType>

simpleType DoorOperationTypeEnum

<xs:simpleType name="DoorOperationTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="SINGLE_SWING_LEFT"/>
    <xs:enumeration value="1" id="SINGLE_SWING_RIGHT"/>
    <xs:enumeration value="2" id="DOUBLE_DOOR_SINGLE_SWING"/>
    <xs:enumeration value="3" id="DOUBLE_DOOR_SINGLE_SWING_OPPOSITE_LEFT"/>
    <xs:enumeration value="4" id="DOUBLE_DOOR_SINGLE_SWING_OPPOSITE_RIGHT"/>
    <xs:enumeration value="5" id="DOUBLE_SWING_LEFT"/>
    <xs:enumeration value="6" id="DOUBLE_SWING_RIGHT"/>
    <xs:enumeration value="7" id="DOUBLE_DOOR_DOUBLE_SWING"/>
    <xs:enumeration value="8" id="SLIDING_TO_LEFT"/>
    <xs:enumeration value="9" id="SLIDING_TO_RIGHT"/>
    <xs:enumeration value="10" id="DOUBLE_DOOR_SLIDING"/>
    <xs:enumeration value="11" id="FOLDING_TO_LEFT"/>
    <xs:enumeration value="12" id="FOLDING_TO_RIGHT"/>
    <xs:enumeration value="13" id="DOUBLE_DOOR_FOLDING"/>
    <xs:enumeration value="14" id="REVOLVING"/>
    <xs:enumeration value="15" id="ROLLINGUP"/>
    <xs:enumeration value="16" id="DoorOperationType_USERDEFINED"/>
    <xs:enumeration value="17" id="DoorOperationType_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
### `DoorPanelOperationTypeEnum`

```xml
<xs:simpleType name="DoorPanelOperationTypeEnum">
    <xs:restriction base="xs:int">
        <xs:enumeration value="0" id="SWINGING"/>
        <xs:enumeration value="1" id="DOUBLE_ACTING"/>
        <xs:enumeration value="2" id="SLIDING"/>
        <xs:enumeration value="3" id="FOLDING"/>  
        <xs:enumeration value="4" id="REVOLVING_DoorPanel"/>
        <xs:enumeration value="5" id="ROLLINGUP_DoorPanel"/>
        <xs:enumeration value="6" id="DoorPanel_FIXEDPANEL"/>
        <xs:enumeration value="7" id="DoorPanel_USERDEFINED"/>
    </xs:restriction>
</xs:simpleType>
```

### `DoorPanelPositionEnum`

```xml
<xs:simpleType name="DoorPanelPositionEnum">
    <xs:restriction base="xs:int">
        <xs:enumeration value="0" id="LEFT"/>
        <xs:enumeration value="1" id="MIDDLE"/>
        <xs:enumeration value="2" id="RIGHT"/>
        <xs:enumeration value="3" id="DoorPanelPosition_NOTDEFINED"/>
    </xs:restriction>
</xs:simpleType>
```

### `DoorTypeEnum`

```xml
<xs:simpleType name="DoorTypeEnum">
    <xs:restriction base="xs:int">
        <xs:enumeration value="0" id="DOOR"/>
        <xs:enumeration value="1" id="GATE"/>
        <xs:enumeration value="2" id="TRAPDOOR"/>
        <xs:enumeration value="3" id="USERDEFINED_doorType"/>
    </xs:restriction>
</xs:simpleType>
```

### `ExternalWallDamageStateEnum`

```xml
<xs:simpleType name="ExternalWallDamageStateEnum">
    <xs:restriction base="xs:int">
        <xs:enumeration value="0" id="eWDS_NoDamage"/>
        <xs:enumeration value="1" id="eWDS_DamageToLiningOnly"/>
        <xs:enumeration value="2" id="eWDS_DamageToInsulationOnly"/>
        <xs:enumeration value="3" id="eWDS_DamageToCladdingOnly"/>
        <xs:enumeration value="4" id="eWDS_DamageToLiningAndInsulation"/>
        <xs:enumeration value="5" id="eWDS_DamageToLiningAndCladding"/>
        <xs:enumeration value="6" id="eWDS_DamageToFramingOrCollapse"/>
    </xs:restriction>
</xs:simpleType>
```

### `FlooringDamageStateEnum`

```xml
<xs:simpleType name="FlooringDamageStateEnum">
    <xs:restriction base="xs:int">
        <xs:enumeration value="0" id="NoDamage"/>
        <xs:enumeration value="1" id="WetOnly"/>
        <xs:enumeration value="2" id="MaterialDamage"/>
    </xs:restriction>
</xs:simpleType>
```
simpleType FramingMemberTypeEnum

```xml
<xs:simpleType name="FramingMemberTypeEnum">
<xs:restriction base="xs:int">
  <xs:enumeration value="0" id="BRACE"/>
  <xs:enumeration value="1" id="CHORD"/>
  <xs:enumeration value="2" id="COLLAR"/>
  <xs:enumeration value="3" id="MEMBER"/>
  <xs:enumeration value="4" id="MULLION"/>
  <xs:enumeration value="5" id="PLATE"/>
  <xs:enumeration value="6" id="POST"/>
  <xs:enumeration value="7" id="RAFTER"/>
  <xs:enumeration value="8" id="STRINGER"/>
  <xs:enumeration value="9" id="STRUT"/>
  <xs:enumeration value="10" id="STUD"/>
  <xs:enumeration value="12" id="USERDEFINED_framingMember"/>
  <xs:enumeration value="13" id="framingMember_NOTDEFINED"/>
</xs:restriction>
</xs:simpleType>
```

simpleType InternalExternalDoorsDamageStateEnum

```xml
<xs:simpleType name="InternalExternalDoorsDamageStateEnum">
<xs:restriction base="xs:int">
  <xs:enumeration value="0" id="iedds_NoDamage"/>
  <xs:enumeration value="1" id="iedds_DoorPanelsDamageWithReusableHardware"/>
  <xs:enumeration value="2" id="iedds_FrameDamage"/>
  <xs:enumeration value="3" id="iedds_DoorPanelAndFrameDamageWithReusableHardware"/>
  <xs:enumeration value="4" id="iedds_DoorPanelDamage"/>
  <xs:enumeration value="5" id="iedds_TotalDamage"/>
</xs:restriction>
</xs:simpleType>
```

SimpleType InternalWallDamageStateEnum

```xml
<xs:simpleType name="InternalWallDamageStateEnum">
<xs:restriction base="xs:int">
  <xs:enumeration value="0" id="IWDS_NoDamage"/>
  <xs:enumeration value="1" id="IWDS_DamageToLiningOnly"/>
  <xs:enumeration value="2" id="IWDS_DamageToInsulationOnly"/>
  <xs:enumeration value="3" id="IWDS_DamageToLiningAndInsulation"/>
  <xs:enumeration value="4" id="IWDS_DamageToFramingOrCollapse"/>
</xs:restriction>
</xs:simpleType>
```

simpleType RailingTypeEnum

```xml
<xs:simpleType name="RailingTypeEnum">
<xs:restriction base="xs:int">
  <xs:enumeration value="0" id="HANDRAIL"/>
  <xs:enumeration value="1" id="GUARDRAIL"/>
  <xs:enumeration value="2" id="BALUSTRADE"/>
  <xs:enumeration value="3" id="USERDEFINED_railingType"/>
</xs:restriction>
</xs:simpleType>
```
simpleType RoofTypeEnum

source <xs:simpleType name="RoofTypeEnum">
   <xs:restriction base="xs:int">
      <xs:enumeration value="0" id="FLAT_ROOF"/>
      <xs:enumeration value="1" id="SHED_ROOF"/>
      <xs:enumeration value="2" id="GABLE_ROOF"/>
      <xs:enumeration value="3" id="HIP_ROOF"/>
      <xs:enumeration value="4" id="HIPPED_GABLE_ROOF"/>
      <xs:enumeration value="5" id="GAMBREL_ROOF"/>
      <xs:enumeration value="6" id="MANSARD_ROOF"/>
      <xs:enumeration value="7" id="BARREL_ROOF"/>
      <xs:enumeration value="8" id="RAINBOW_ROOF"/>
      <xs:enumeration value="9" id="HIPPED_GABLE_ROOF"/>
      <xs:enumeration value="10" id="PAVILION_ROOF"/>
      <xs:enumeration value="11" id="DOME_ROOF"/>
      <xs:enumeration value="12" id="FREEFORM"/>
      <xs:enumeration value="13" id="RoofType_USERDEFINED"/>
      <xs:enumeration value="14" id="RoofType_NOTDEFINED"/>
   </xs:restriction>
</xs:simpleType>

simpleType SlabDamageStateEnum

source <xs:simpleType name="SlabDamageStateEnum">
   <xs:restriction base="xs:int">
      <xs:enumeration value="0" id="sds_NoDamage"/>
      <xs:enumeration value="1" id="sds_Cracked"/>
      <xs:enumeration value="2" id="sds_Collapsed"/>
   </xs:restriction>
</xs:simpleType>

simpleType SlabTypeEnum

source <xs:simpleType name="SlabTypeEnum">
   <xs:restriction base="xs:int">
      <xs:enumeration value="0" id="FLOOR"/>
      <xs:enumeration value="1" id="ROOF"/>
      <xs:enumeration value="2" id="LANDING"/>
      <xs:enumeration value="3" id="BASESLAB"/>  
      <xs:enumeration value="4" id="USERDEFINED_slab"/>
      <xs:enumeration value="5" id="slab_NOTDEFINED"/>
   </xs:restriction>
</xs:simpleType>

simpleType SoffitDamageStateEnum

source <xs:simpleType name="SoffitDamageStateEnum">
   <xs:restriction base="xs:int">
      <xs:enumeration value="0" id="sofds_NoDamage"/>
      <xs:enumeration value="1" id="sofds_WetOnly"/>
      <xs:enumeration value="2" id="sofds_MaterialDamageOrCollapse"/>
   </xs:restriction>
</xs:simpleType>
simpleType `SpaceTypeEnum`

```xml
<xs:simpleType name="SpaceTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="Space"/>
    <xs:enumeration value="1" id="ParkingOrGarage"/>
    <xs:enumeration value="2" id="GFA"/>
    <xs:enumeration value="3" id="Internal"/>
    <xs:enumeration value="4" id="External"/>
    <xs:enumeration value="5" id="Userdefined_space"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType `StairFlightTypeEnum`

```xml
<xs:simpleType name="StairFlightTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="STRAIGHT"/>
    <xs:enumeration value="1" id="WINDER"/>
    <xs:enumeration value="2" id="SPIRAL"/>
    <xs:enumeration value="3" id="CURVED"/>
    <xs:enumeration value="4" id="FREEFORM_stairFlight"/>
    <xs:enumeration value="5" id="USERDEFINED_StairFlightType"/>
    <xs:enumeration value="6" id="StairFlightType_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType `StairTypeEnum`

```xml
<xs:simpleType name="StairTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="STRAIGHT_RUN_STAIR"/>
    <xs:enumeration value="1" id="TWO_STRAIGHT_RUN_STAIR"/>
    <xs:enumeration value="2" id="QUARTER_WINDING_STAIR"/>
    <xs:enumeration value="3" id="QUARTER_TURN_STAIR"/>
    <xs:enumeration value="4" id="HALF_WINDING_STAIR"/>
    <xs:enumeration value="5" id="HALF_TURN_STAIR"/>
    <xs:enumeration value="6" id="TWO_QUARTER_WINDING_STAIR"/>
    <xs:enumeration value="7" id="TWO_QUARTER_TURN_STAIR"/>
    <xs:enumeration value="8" id="THREE_QUARTER_WINDING_STAIR"/>
    <xs:enumeration value="9" id="THREE_QUARTER_TURN_STAIR"/>
    <xs:enumeration value="10" id="SPIRAL_STAIR"/>
    <xs:enumeration value="11" id="DOUBLE_RETURN_STAIR"/>
    <xs:enumeration value="12" id="CURVED_RUN_STAIR"/>
    <xs:enumeration value="13" id="TWO_CURVED_RUN_STAIR"/>
    <xs:enumeration value="12" id="USERDEFINED_stairType"/>
    <xs:enumeration value="13" id="stairType_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType `TieDamageStateEnum`

```xml
<xs:simpleType name="TieDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="InAct"/>
    <xs:enumeration value="1" id="Failed"/>
  </xs:restriction>
</xs:simpleType>
```
simpleType TType

```xml
<xs:simpleType name="TType">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="LightDuty"/>
    <xs:enumeration value="1" id="MediumDuty"/>
    <xs:enumeration value="2" id="HeavyDuty"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WallCladdingDamageState

```xml
<xs:simpleType name="WallCladdingDamageState">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="wcds_NoDamage"/>
    <xs:enumeration value="1" id="wcds_Cracked"/>
    <xs:enumeration value="2" id="wcds_Collapsed"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WallComponentElementUsage

```xml
<xs:simpleType name="WallComponentElementUsage">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="Cladding"/>
    <xs:enumeration value="1" id="AirGap"/>
    <xs:enumeration value="2" id="Insulation"/>
    <xs:enumeration value="3" id="Lining"/>
    <xs:enumeration value="4" id="Skirting"/>
    <xs:enumeration value="5" id="Cornice"/>
    <xs:enumeration value="6" id="Framing"/>
    <xs:enumeration value="7" id="Finishing"/>
    <xs:enumeration value="8" id="Others"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WallCorniceDamageStateEnum

```xml
<xs:simpleType name="WallCorniceDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="wcods_NoDamage"/>
    <xs:enumeration value="1" id="wcods_WetOnly"/>
    <xs:enumeration value="2" id="wcods_MaterialDamageOrCollapse"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WallInsulationDamageStateEnum

```xml
<xs:simpleType name="WallInsulationDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="wids_NoDamage"/>
    <xs:enumeration value="1" id="wids_WetOnly"/>
    <xs:enumeration value="2" id="wids_MaterialDamageOrCollapse"/>
  </xs:restriction>
</xs:simpleType>
```
simpleType WallSkirtingDamageStateEnum

```xml
<xs:simpleType name="WallSkirtingDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="wskds_NoDamage"/>
    <xs:enumeration value="1" id="wskds_WetOnly"/>
    <xs:enumeration value="2" id="wskds_MaterialDamageOrCollapse"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WindowOpeningStyleEnum

```xml
<xs:simpleType name="WindowOpeningStyleEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="Hinged"/>
    <xs:enumeration value="1" id="Sliding"/>
    <xs:enumeration value="2" id="Louvre"/>
    <xs:enumeration value="3" id="FixedPanel"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WindowPanelDamageState

```xml
<xs:simpleType name="WindowPanelDamageState">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="wpds_NoDamage"/>
    <xs:enumeration value="1" id="wpds_FrameOrLiningDamageOnly"/>
    <xs:enumeration value="2" id="wpds_GlazingFailure"/>
    <xs:enumeration value="3" id="wpds_TotalDamage"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType WindowPanelOperationEnum

```xml
<xs:simpleType name="WindowPanelOperationEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="SIDEHUNGRIGHTHAND"/>
    <xs:enumeration value="1" id="SIDEHUNGLEFTHAND"/>
    <xs:enumeration value="2" id="TILTANDTURNRIGHTHAND"/>
    <xs:enumeration value="3" id="TILTANDTURNLEFTHAND"/>
    <xs:enumeration value="4" id="TOPHUNG"/>
    <xs:enumeration value="5" id="BOTTOMHUNG"/>
    <xs:enumeration value="6" id="PIVOTHORIZONTAL"/>
    <xs:enumeration value="7" id="PIVOTVERTICAL"/>
    <xs:enumeration value="8" id="SLIDINGHORIZONTAL"/>
    <xs:enumeration value="9" id="SLIDINGVERTICAL"/>
    <xs:enumeration value="10" id="REMOVABLECASEMENT"/>
    <xs:enumeration value="11" id="FIXEDCASEMENT"/>
    <xs:enumeration value="12" id="OTHEROPERATION"/>
    <xs:enumeration value="13" id="wpo_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```
**Schema** Utility.xsd

<table>
<thead>
<tr>
<th>Elements</th>
<th>Complex types</th>
<th>Simple types</th>
</tr>
</thead>
<tbody>
<tr>
<td>_ControlElement</td>
<td>AbstractUtilityObjectType</td>
<td>ElectricDistributionBoardTypeEnum</td>
</tr>
<tr>
<td>_FlowController</td>
<td>AbstractControlElementType</td>
<td>FlowMeterTypeEnum</td>
</tr>
<tr>
<td>_FlowElement</td>
<td>AbstractFlowControllerType</td>
<td>FlowSegmentTypeEnum</td>
</tr>
<tr>
<td>_FlowTerminal</td>
<td>AbstractFlowElementType</td>
<td>LightFixtureMountingTypeEnum</td>
</tr>
<tr>
<td>_UtilityObject</td>
<td>AbstractFlowTerminalType</td>
<td>LightFixturePlacingTypeEnum</td>
</tr>
<tr>
<td>ElectricalDistributionBoard</td>
<td>AbstractUtilitySystemType</td>
<td>UtilityObjectDamageStateEnum</td>
</tr>
<tr>
<td>FlowMeter</td>
<td>composedOfType</td>
<td>UtilitySystemTypeEnum</td>
</tr>
<tr>
<td>FlowSegment</td>
<td>ElectricalDistributionBoardType</td>
<td>SwitchingDeviceType</td>
</tr>
<tr>
<td>LightFixture</td>
<td>FlowMeterType</td>
<td></td>
</tr>
<tr>
<td>Outlet</td>
<td>FlowSegmentType</td>
<td></td>
</tr>
<tr>
<td>SwitchingDevice</td>
<td>LightFixtureType</td>
<td></td>
</tr>
<tr>
<td>UtilitySystem</td>
<td>MultiCurveRepresentationType</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MultiSurfaceRepresentationType</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OutletType</td>
<td></td>
</tr>
<tr>
<td></td>
<td>replacementCostType</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SolidRepresentationType</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SwitchingDeviceType</td>
<td></td>
</tr>
</tbody>
</table>

```xml
  <xs:import namespace="http://localhost/schemas/1.0" schemaLocation="UrbanFloodBase.xsd"/>
  <xs:import namespace="http://localhost/schemas/Valuation/1.0" schemaLocation="Valuation.xsd"/>
  <xs:import namespace="http://www.opengis.net/gml/3.2" schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

  <xs:element name="_ControlElement" type="AbstractControlElementType" abstract="true" substitutionGroup="_UtilityObject"/>

  <xs:element name="_FlowController" type="AbstractFlowControllerType" abstract="true" substitutionGroup="_FlowElement"/>

  <xs:element name="_FlowElement" type="AbstractFlowElementType" abstract="true" substitutionGroup="_UtilityObject"/>

  <xs:element name="_FlowTerminal" type="AbstractFlowTerminalType" abstract="true" substitutionGroup="_FlowElement"/>

</xs:schema>
```
### Element: UtilityObject
```
source: <xs:element name="UtilityObject" type="AbstractUtilityObjectType" abstract="true"
    substitutionGroup="core:_UrbanObject"/>
```

### Element: ElectricalDistributionBoard
```
source: <xs:element name="ElectricalDistributionBoard" type="ElectricalDistributionBoardType"
    substitutionGroup="_FlowController"/>
```

### Element: FlowMeter
```
source: <xs:element name="FlowMeter" type="FlowMeterType" substitutionGroup="_FlowController"/>
```

### Element: FlowSegment
```
source: <xs:element name="FlowSegment" type="FlowSegmentType" abstract="false"
    substitutionGroup="_FlowElement"/>
```

### Element: LightFixture
```
source: <xs:element name="LightFixture" type="LightFixtureType" substitutionGroup="_FlowTerminal"/>
```

### Element: Outlet
```
source: <xs:element name="Outlet" type="OutletType" substitutionGroup="_FlowTerminal"/>
```

### Element: SwitchingDevice
```
source: <xs:element name="SwitchingDevice" type="SwitchingDeviceType"
    substitutionGroup="_FlowController"/>
```

### Element: UtilitySystem
```
source: <xs:element name="UtilitySystem" type="AbstractUtilitySystemType"
    substitutionGroup="core:_UrbanObject"/>
```

### Complex Type: AbstractUtilityObjectType
```
source: <xs:complexType name="AbstractUtilityObjectType" abstract="true">
    <xs:annotation>
        <xs:documentation>The type describes the superclass of all the utility objects in the
        model!</xs:documentation>
        <xs:annotation>
            <xs:complexContent>
                <xs:extension base="core:AbstractUrbanObjectType"
                    <xs:sequence>
```
<xs:element name="ObjectType" type="xs:string" minOccurs="0"/>
<xs:element ref="core:Classification" minOccurs="0" maxOccurs="unbounded"/>
<xs:element name="ReplacementCost" minOccurs="0"/>
<xs:complexType>
<xs:complexContent>
<xs:extension base="replacementCostType"/>
</xs:complexContent>
</xs:complexType>
<xs:element name="ConstructionMaterial" minOccurs="0"/>
<xs:element ref="mtl:_MaterialObject"/>
<xs:element name="RepresentedBySolid" type="SolidRepresentationType" minOccurs="0"/>
<xs:element name="RepresentedByMultiSurface" type="MultiSurfaceRepresentationType" minOccurs="0"/>
<xs:attribute name="Type" type="xs:int" use="optional"/>
<xs:attribute name="UserdefinedType" type="xs:string" use="optional"/>
<xs:attribute name="IsExternal" type="xs:boolean" use="optional"/>
<xs:attribute name="BaseHeight" type="xs:double" use="optional"/>
<xs:attribute name="DamageState" type="xs:int" use="optional"/>
</xs:extension>
</xs:complexType>

complexType AbstractControlElementType

source <xs:complexType name="AbstractControlElementType" abstract="true">
<xs:annotation>
<xs:documentation>The type describes the superclass of all the utility objects in the model!</xs:documentation>
</xs:annotation>
<xs:complexType>
<xs:extension base="_AbstractUtilityObjectType"/>
</xs:complexType>
</xs:complexType>

complexType AbstractFlowControllerType

source <xs:complexType name="AbstractFlowControllerType" abstract="true">
<xs:annotation>
<xs:documentation>The type describes the superclass of all the utility objects in the model!</xs:documentation>
</xs:annotation>
<xs:complexType>
<xs:extension base="AbstractFlowElementType"/>
</xs:complexType>
</xs:complexType>

complexType AbstractFlowElementType

source <xs:complexType name="AbstractFlowElementType" abstract="true">
<xs:annotation>
<xs:documentation>The type describes the superclass of all the utility objects in the model!</xs:documentation>
</xs:annotation>
<xs:complexType>
complexType AbstractFlowTerminalType

source
<xs:complexType name="AbstractFlowTerminalType" abstract="true">
  <xs:annotation>
    <xs:documentation>
      The type describes the superclass of all the utility objects in the model!
    </xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="_AbstractUtilityObjectType"/>
  </xs:complexContent>
</xs:complexType>

complexType AbstractUtilitySystemType

source
<xs:complexType name="AbstractUtilitySystemType">
  <xs:annotation>
    <xs:documentation>
      The type describes the superclass of all the utility objects in the model!
    </xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="core:AbstractUrbanObjectType">
      <xs:sequence>
        <xs:element name="composedOf" type="composedOfType" minOccurs="0" maxOccurs="unbounded"/>
      </xs:sequence>
      <xs:attribute name="UtilitySystemType" type="UtilitySystemTypeEnum" use="optional"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType composedOfType

source
<xs:complexType name="composedOfType">
  <xs:sequence>
    <xs:element ref="_UtilityObject"/>
  </xs:sequence>
</xs:complexType>

complexType ElectricalDistributionBoardType

source
<xs:complexType name="ElectricalDistributionBoardType">
  <xs:complexContent>
    <xs:extension base="AbstractFlowControllerType"/>
  </xs:complexContent>
</xs:complexType>
complexType FlowMeterType

source
<xs:complexType name="FlowMeterType">
  <xs:complexContent>
    <xs:extension base="AbstractFlowControllerType"/>
  </xs:complexContent>
</xs:complexType>

complexType FlowSegmentType

source
<xs:complexType name="FlowSegmentType" abstract="false">
  <xs:annotation>
    <xs:documentation>The type describes the superclass of all the utility objects in the model!</xs:documentation>
  </xs:annotation>
  <xs:complexContent>
    <xs:extension base="AbstractFlowElementType">
      <xs:sequence>
        <xs:element name="RepresentedByCurve" type="MultiCurveRepresentationType" minOccurs="0" maxOccurs="1"/>
      </xs:sequence>
      <xs:attribute name="OverallLength" type="xs:double" use="optional"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType LightFixtureType

source
<xs:complexType name="LightFixtureType">
  <xs:complexContent>
    <xs:extension base="AbstractFlowTerminalType">
      <xs:attribute name="LightFixtureMountingType" type="xs:int" use="optional"/>
      <xs:attribute name="LightFixturePlacingType" type="xs:int" use="optional"/>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

complexType MultiCurveRepresentationType

source
<xs:complexType name="MultiCurveRepresentationType">
  <xs:sequence>
    <xs:element ref="gml:MultiCurve"/>
  </xs:sequence>
</xs:complexType>

complexType MultiSurfaceRepresentationType

source
<xs:complexType name="MultiSurfaceRepresentationType">
  <xs:sequence>
    <xs:element ref="gml:MultiSurface"/>
  </xs:sequence>
</xs:complexType>
complexType **OutletType**

source

```xml
<xs:complexType name="OutletType">
  <xs:complexContent>
    <xs:extension base="AbstractFlowTerminalType"/>
  </xs:complexContent>
</xs:complexType>
```

complexType **replacementCostType**

source

```xml
<xs:complexType name="replacementCostType">
  <xs:choice>
    <xs:element ref="val:AssemblyCostObject"/>
  </xs:choice>
</xs:complexType>
```

complexType **SolidRepresentationType**

source

```xml
<xs:complexType name="SolidRepresentationType">
  <xs:sequence>
    <xs:element ref="gml:Solid"/>
  </xs:sequence>
</xs:complexType>
```

complexType **SwitchingDeviceType**

source

```xml
<xs:complexType name="SwitchingDeviceType">
  <xs:complexContent>
    <xs:extension base="AbstractFlowControllerType"/>
  </xs:complexContent>
</xs:complexType>
```

simpleType **ElectricDistributionBoardTypeEnum**

source

```xml
<xs:simpleType name="ElectricDistributionBoardTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="CONSUMERUNIT"/>
    <xs:enumeration value="1" id="DISTRIBUTIONBOARD"/>
    <xs:enumeration value="2" id="MOTORCONTROLCENTRE"/>
    <xs:enumeration value="3" id="SWITCHBOARD"/>
    <xs:enumeration value="4" id="USERDEFINED_edb"/>
    <xs:enumeration value="5" id="edb_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType **FlowMeterTypeEnum**

source

```xml
<xs:simpleType name="FlowMeterTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="ENERGYMETER"/>
    <xs:enumeration value="1" id="GASMETER"/>
    <xs:enumeration value="2" id="OILMETER"/>
    <xs:enumeration value="3" id="WATERMETER"/>
    <xs:enumeration value="4" id="USERDEFINED_meter"/>
    <xs:enumeration value="5" id="meter_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```
simpleType FlowSegmentTypeEnum

source
<xs:simpleType name="FlowSegmentTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="USERDEFINED_fst"/>
    <xs:enumeration value="1" id="fst_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>

simpleType LightFixtureTypeEnum

source
<xs:simpleType name="LightFixtureTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="POINTSOURCE"/>
    <xs:enumeration value="1" id="DIRECTIONSOURCE"/>
    <xs:enumeration value="2" id="SECURITYLIGHTING"/>
    <xs:enumeration value="3" id="USERDEFINED_lfmt"/>
    <xs:enumeration value="4" id="lfmt_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>

simpleType OutletTypeEnum

source
<xs:simpleType name="OutletTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="AUDIOVISUALOUTLET"/>
    <xs:enumeration value="1" id="COMMUNICATIONSOUTLET"/>
    <xs:enumeration value="2" id="POWEROUTLET"/>
    <xs:enumeration value="3" id="DATAOUTLET"/>
    <xs:enumeration value="4" id="TELEPHONEOUTLET"/>
    <xs:enumeration value="5" id="USERDEFINED_outlet"/>
    <xs:enumeration value="6" id="outlet_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>

simpleType SwitchingDeviceTypeEnum

source
<xs:simpleType name="SwitchingDeviceTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="CONTACTOR"/>
    <xs:enumeration value="1" id="DIMMERSWITCH"/>
    <xs:enumeration value="2" id="EMERGENCYSTOP"/>
    <xs:enumeration value="3" id="KEYPAD"/>
    <xs:enumeration value="4" id="MOMENTARYSWITCH"/>
    <xs:enumeration value="5" id="SELECTORSWITCH"/>
    <xs:enumeration value="6" id="STARTER"/>
    <xs:enumeration value="7" id="SWITCHDISCONNECTOR"/>
    <xs:enumeration value="8" id="TOGGLESWITCH"/>
    <xs:enumeration value="9" id="USERDEFINED_sd"/>
    <xs:enumeration value="10" id="sd_NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
simpleType UtilityObjectDamageStateEnum

```xml
<xs:simpleType name="UtilityObjectDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="NoDamage"/>
    <xs:enumeration value="1" id="Failure"/>
  </xs:restriction>
</xs:simpleType>
```

simpleType UtilitySystemTypeEnum

```xml
<xs:simpleType name="UtilitySystemTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="ELECTRICAL"/>
    <xs:enumeration value="1" id="HVAC"/>
    <xs:enumeration value="2" id="SANITARY"/>
    <xs:enumeration value="3" id="FUEL"/>
    <xs:enumeration value="4" id="USERDEFINED"/>
    <xs:enumeration value="5" id="NOTDEFINED"/>
  </xs:restriction>
</xs:simpleType>
```
### Schema Connection.xsd

#### Elements
- Connection
- ConnectionGeometryObjectType
- CurveConnectionGeometry
- MechanicalConnection
- PointConnectionGeometry
- SurfaceConnectionGeometry

#### Complex types
- AbstractConnectionGeometryType
- ConnectionType
- CurveConnectionGeometryType
- MechanicalConnectionType
- PointConnectionGeometryType
- SurfaceConnectionGeometryType

#### Simple types
- ConnectionDamageStateEnum
- ConnectionTypeEnum

```xml
  xmlns="http://localhost/schemas/Connection/1.0" xmlns:core="http://localhost/schemas/1.0"
  xmlns:bld="http://localhost/schemas/Building/1.0" targetNamespace="http://localhost/schemas/Connection/1.0"
  elementFormDefault="qualified" attributeFormDefault="unqualified" version="1.0">

  <xs:import namespace="http://www.opengis.net/gml/3.2"
              schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>

  <xs:import namespace="http://localhost/schemas/1.0" schemaLocation="UrbanFloodBase.xsd"/>

  <xs:import namespace="http://localhost/schemas/Building/1.0" schemaLocation="Building.xsd"/>

  <xs:element name="Connection" type="ConnectionType" substitutionGroup="core:_UrbanObject"/>

  <xs:element name="ConnectionGeometryObjectType" type="AbstractConnectionGeometryType" abstract="true" substitutionGroup="gml:AbstractFeature"/>

  <xs:element name="CurveConnectionGeometry" type="CurveConnectionGeometryType" substitutionGroup="ConnectionGeometryObjectType"/>

  <xs:element name="MechanicalConnection" type="MechanicalConnectionType" substitutionGroup="Connection"/>

  <xs:element name="PointConnectionGeometry">
    <xs:complexType>
      <xs:complexContent>
        <xs:extension base="PointConnectionGeometryType"/>
      </xs:complexContent>
    </xs:complexType>
  </xs:element>

</xs:schema>
```
element SurfaceConnectionGeometry
{
  source
    <xs:element name="SurfaceConnectionGeometry" type="SurfaceConnectionGeometryType" substitutionGroup="ConnectionGeometryObjectType"/>
}

complexType AbstractConnectionGeometryType
{
  source
    <xs:complexType name="AbstractConnectionGeometryType" abstract="true">
      <xs:complexContent>
        <xs:extension bases="gml:AbstractFeatureType">
          <xs:sequence>
            <xs:element name="Description" type="xs:string" minOccurs="0"/>
          </xs:sequence>
        </xs:extension>
      </xs:complexContent>
    </xs:complexType>
}

complexType ConnectionType
{
  source
    <xs:complexType name="ConnectionType">
      <xs:complexContent>
        <xs:extension bases="core:AbstractUrbanObjectType">
          <xs:sequence>
            <xs:element name="RelatingElement" type="bld:AbstractBuildingElementType" minOccurs="0" maxOccurs="1"/>
            <xs:element name="RelatedElement" type="bld:AbstractBuildingElementType" minOccurs="0" maxOccurs="1"/>
            <xs:element name="TensileCapacity" minOccurs="0" maxOccurs="1"/>
            <xs:element name="CompressionCapacity" minOccurs="0" maxOccurs="1"/>
            <xs:element name="ShearCapacity" minOccurs="0" maxOccurs="1"/>
            <xs:element name="BendingCapacity" minOccurs="0" maxOccurs="1"/>
          </xs:sequence>
        </xs:extension>
      </xs:complexContent>
    </xs:complexType>
}
complexType CurveConnectionGeometryType

source <xs:complexType name="CurveConnectionGeometryType">
<xs:complexContent>
<xs:extension base="AbstractConnectionGeometryType">
<xs:sequence>
<xs:element name="CurveOnRelatedElement" minOccurs="0" maxOccurs="1">
<xs:complexType>
<xs:sequence>
<xs:element ref="gml:AbstractCurve"/>
</xs:sequence>
</xs:complexType>
</xs:element>
<xs:element name="CurveOnRelatingElement" minOccurs="1" maxOccurs="1">
<xs:complexType>
<xs:sequence>
<xs:element ref="gml:AbstractCurve"/>
</xs:sequence>
</xs:complexType>
</xs:element>
</xs:sequence>
</xs:extension>
</xs:complexContent>
</xs:complexType>

complexType MechanicalConnectionType

source <xs:complexType name="MechanicalConnectionType">
<xs:complexContent>
<xs:extension base="ConnectionType">
<xs:sequence>
<xs:element name="ConnectionRealizingElement" minOccurs="0" maxOccurs="unbounded">
<xs:complexType>
<xs:sequence>
<xs:element ref="bld:_BuildingElement" minOccurs="1"/>
</xs:sequence>
</xs:complexType>
</xs:element>
<xs:element name="ConnectionGeometryType" minOccurs="0">
<xs:complexType>
<xs:sequence>
<xs:element ref="ConnectionGeometryObjectType"/>
</xs:sequence>
</xs:complexType>
</xs:element>
</xs:sequence>
</xs:extension>
</xs:complexContent>
</xs:complexType>

complexType PointConnectionGeometryType

source <xs:complexType name="PointConnectionGeometryType">
<xs:complexContent>
<xs:extension base="AbstractConnectionGeometryType">
<xs:sequence>
<xs:element name="PointOnRelatedElement" minOccurs="0" maxOccurs="1">
<xs:complexType>
<xs:sequence>
<xs:element ref="gml:Point"/>
</xs:sequence>
</xs:complexType>
</xs:element>
</xs:sequence>
</xs:extension>
</xs:complexContent>
</xs:complexType>
<xs:element name="PointOnRelatingElement" minOccurs="1" maxOccurs="1">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:Point"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="SurfaceOnRelatedElement" minOccurs="0" maxOccurs="1">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:AbstractSurface"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="SurfaceOnRelatingElement" minOccurs="1" maxOccurs="1">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:AbstractSurface"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="SurfaceOnRelatingElement" minOccurs="1" maxOccurs="1">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:AbstractSurface"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="SurfaceOnRelatedElement" minOccurs="0" maxOccurs="1">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="gml:AbstractSurface"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>

complexType SurfaceConnectionGeometryType

<xs:complexType name="AbstractConnectionGeometryType">
  <xs:complexContent>
    <xs:extension base="AbstractConnectionGeometryType">
      <xs:sequence>
        <xs:element name="SurfaceOnRelatedElement" minOccurs="0" maxOccurs="1">
          <xs:complexType>
            <xs:sequence>
              <xs:element ref="gml:AbstractSurface"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:extension>
  </xs:complexContent>
</xs:complexType>

simpleType ConnectionDamageStateEnum

<xs:simpleType name="ConnectionDamageStateEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="CDS_InAct"/>
    <xs:enumeration value="1" id="CDS_Failed"/>
  </xs:restriction>
</xs:simpleType>

simpleType ConnectionTypeEnum

<xs:simpleType name="ConnectionTypeEnum">
  <xs:restriction base="xs:int">
    <xs:enumeration value="0" id="CT_Userdefined"/>
    <xs:enumeration value="1" id="CT_Undefined"/>
  </xs:restriction>
</xs:simpleType>
Appendix 14: Process for extracting the point and surface-based flood information from MIKE output in the ArcGIS ModelBuilder
Appendix 15: Plans of the building in the case study
ENERGY EFFICIENCY

- R4.4 batt insulation to ceiling (excluding garage).
- R2.8 batts plus wall wrap to all external house walls.
- R2.8 batts to house/garage common wall.
- Building fabric thermal insulation to comply with BCA 3.12.1.1.
- Thermal insulation must form a continuous barrier with ceilings and walls contributing to the thermal barrier, insulation to abut or overlap adjoining insulation other than being interrupted by a structural member.
- Bulk insulation to be installed so that it maintains its thickness.
- Exhaust fans with self-closing damper.
- CSR inspection & certification including taped wall wrap to joins, all penetrations & polyester strip seal to all windows & doors as per BCA 3.12.3.
- Windows comply with AS 2047 for air infiltration as required by BCA 3.12.3.
- Refer to thermal performance assessors report for window frame and glazing specification.
- Duct work to comply with BCA 3.12.5.3 for heating and cooling.
- Weatherstrip draft protection device to bottom of external hinged doors with seals to heads and jambs (excludes garage rear access doors if shown on plan).
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