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A web-based tool for streamlining environmental decision-making in building design

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Abstract. The construction industry is an important driver for economic growth, but it is also a major contributor to global energy use and greenhouse gas emissions. A plethora of sustainable design tools and rating schemes have been developed in an attempt to improve the environmental performance of buildings. Regardless of their increasing adoption by the construction industry, much of the existing focus is on improving the operational performance of buildings. However, a more holistic life cycle approach that also considers material production is critical. Despite this, limited information and tools are available that consider the full life cycle at the point where decisions can have the greatest impact – at the early stages of design. This paper presents a web-based tool to assist environmental decision-making by providing information on the life cycle energy loadings of building envelope assemblies at the early stages of design. Real-time embodied energy calculations are combined with cloud-based building energy simulation within a graphical user interface that enables exploration of different alternatives through interactive visualisations. This paper describes the tool, an output of over 10 years of research, and how it can be used to inform building envelope assembly selection to reduce life cycle energy.

1. Introduction

Buildings represent one of the greatest opportunities for reducing fossil-fuel energy demand and global greenhouse gas emissions [1]. The types and quantities of materials used within a building have a significant influence on its life cycle energy. This is particularly the case for building envelope materials, which control the thermal performance of the building as well as contributing to a considerable proportion of a building's embodied energy. The selection of building envelope materials is often done during the early stages of design, and as such it is here where design decisions can often have the greatest influence on the life cycle energy performance of a building. However, the ability of building designers to significantly improve the energy performance of their designs is limited by a lack of reliable and comprehensive energy performance information related to building materials and assemblies [2].

While most effort has traditionally focussed on reducing the operational energy associated with buildings, a more holistic approach to low-energy building design is required to ensure that any energy reduction strategies provide a net benefit over a building's life. An increasing number of studies demonstrate the significance of embodied energy [e.g. 3]. The initial embodied energy alone can be equivalent to the total energy required for the operation of a building over its life [4]. The life cycle energy performance of a building design can be determined through the application of a streamlined life cycle assessment (LCA). However, currently available LCA tools can be costly and/or time consuming to implement, are limited in their coverage of the broad life cycle effects of materials, or lack comprehensiveness in the data that is used. This limits the ability for designers to make a quick and reliable assessment of potential building assembly alternatives.

Previous studies have focused on either modelling the operational energy requirements of assemblies (e.g. [5, 6]) or on their associated embodied energy (e.g. [7-9]). Studies that have come closest to providing data that can be employed by designers in the selection of building materials or assemblies to optimise building life cycle energy performance include that by [10, 11], however, the energy requirements associated with the replacement, operation and maintenance of materials are excluded.

A limited number of tools to assist in building assembly selection currently exist (e.g. the ATHENA EcoCalculator for Assemblies [12]) that consider a broad range of life cycle stages, from raw material extraction through to eventual demolition and disposal. These are typically based on pre-compiled performance data, which can be problematic. For example, operational energy requirements of buildings vary based on the individual characteristics of a building (size, location, materials etc.). This may be one reason why existing tools and databases that provide pre-compiled environmental data for building assemblies (such as [12]) do not consider the energy demands associated with the operational stage of a building. This incomplete perspective can result in misleading information that can then lead to sub-optimal design solutions. Studies where both embodied and operational energy have been considered include that of [13, 14]; however, the use of incomplete, potentially erroneous data is apparent, specifically in terms of the use of disparate embodied energy data sources. For example, most existing tools use a process analysis approach for quantifying embodied energy. Previous research by [15] has shown that with this approach, up to 87 per cent of the energy demands can be excluded. A more comprehensive approach for the quantification of embodied energy is thus critical given the potential significance of embodied energy in the life cycle of buildings.

A simple-to-use, affordable and accessible tool which can be implemented during the very early design stages, coupled with comprehensive life cycle energy performance data is not currently available, particularly for the Australian context. It is thought that the development of such a tool could significantly improve the environmental performance of the building sector by facilitating more informed choices during the early design stages of a building.

1.1. Previous research

The work presenting in this paper builds upon and is the culmination of over 10 years of research as outlined in [2, 16-18]. This research involved an interdisciplinary team of architects, engineers, software developers and researchers across multiple institutions. The intention was to provide building designers with an easy-to-use approach for selecting building assemblies that lead to lower life cycle energy demand, based on comprehensive and location-specific life cycle performance data.

The prior research carried out by the authors [2] initialised the development of a method for ranking building assemblies based on their life cycle energy performance. This was the first crucial step in compiling a database of the life cycle energy requirements associated with a large range of building assemblies, for use in various climate zones across Australia. A ranking of assemblies within each element group was seen to be the most useful output from this study considering the difficulties in drawing generic conclusions from the operational energy figures obtained.

The ranking protocol was verified through a sensitivity analysis of variations to the floor area, shape and orientation of a base model. This was done to test the reliability and applicability of the ranking approach across a broad range of circumstances [16]. It was found that these variations did not influence the ranked order of the assemblies in relation to the life cycle energy demand associated with their use. Thus, the ranking of assemblies proved to be an appropriate approach for streamlining the selection of building assemblies during the building design process.

1.2. Aim

The aim of this paper is to describe the principles and implementation of the web-based decision-support tool intended to assist early-stage selection of low life cycle energy building envelope assemblies.

2. Development of a web-based tool for low-energy building decision-making

This section describes the methods used to quantify the life cycle energy performance of different building envelope assemblies and in the implementation of the web-based decision-support tool.

2.1. Quantifying thermal-based operational energy of building assemblies
The tool assesses the thermal-based operational energy (i.e. for heating and cooling). The operational energy simulation engine uses EnergyPlus v8, a validated whole-building energy modelling engine developed by the US Department of Energy (DOE). The EnergyPlus simulation parameters are specified in an input text file (idf) that is read by the engine before computing the results as a series of output files in multiple formats including csv files. In parallel, the engine requires weather data in the form of epw files. This structure enables direct interfacing with the engine by manipulating the input and output files, and running the simulations using the Python sub process module (see Section 2.4.2). The tool relies on this approach to simulate assemblies dynamically in two parallel ways. Firstly, a standalone Python script was written to batch run energy simulations for a list of inbuilt assemblies using all Australian weather files. A total of 3,080 annual cooling and heating load results (40 standard assemblies and 77 epw files) are stored in a fixed dataset that is available to a user. Secondly, as the tool enables a user to generate new assemblies and modify existing ones, the back-end relies on a fully-operational version of EnergyPlus installed on a virtual machine (VM) to compute operational energy loads on demand.

The previous research [16] identified that the use of a standardised building geometry is sufficiently reliable for ranking the thermal-based operational energy performance of building assemblies. Hence, the simulations are conducted on a 15.81 × 15.81 × 2.4m zone geometry with no windows, where all envelope elements are set to adiabatic with exception of the one being simulated. The simulations exclude internal loads and are displayed as GJ/m^2 of assembly. Setpoint and setback temperatures are set to 20°C for heating and 24°C for cooling, and an airtightness factor of 1 ach is assumed.

2.2. Quantifying initial embodied energy of building assemblies
The tool quantifies the embodied energy associated with the production of the materials contained within each assembly (as per A1-3 in EN 15978 [19]). A list of constituent materials with their quantities is created for a 1m^2 area of each assembly. Each material quantity is multiplied by its relevant hybrid embodied energy coefficient, obtained from the EPiC Database [20]. The use of hybrid coefficients ensures complete coverage of the production system boundary for each material and is a key strength of this tool compared to other similar tools that rely on the more incomplete process analysis approach.

2.3. Quantifying recurrent embodied energy of building assemblies
The embodied energy associated with material replacement during the life of the assembly is quantified within the tool (as per B5 within EN 15978 [19]). The material quantities contained within an assembly are multiplied by the number of replacements expected within a user-defined building life. The number of replacements is based on expected service life values for each material, obtained from a range of sources, including [21, 22]. The total material quantities associated with replacement within the life of the assembly are then multiplied by the relevant EPiC Database [20] embodied energy coefficients.

2.4. Software development
This section describes the main programming languages, libraries, front-end, back-end, and data storage used in the development of the tool (known as the Low Energy Building Assembly Selector).

2.4.1. Front-end. The tool uses Javascript (JS) as the main front-end programming language and Bootstrap as the interface development framework. JS enables components to be controlled dynamically by defining their characteristics before being loaded on the browser, or through direct manipulation of the website's Document Object Model (DOM) once loaded in the browser. Bootstrap is an open-source development framework that combines JS, HTML and CSS code to structure web interfaces. Among other features, Bootstrap provides predefined styles and interface components, a grid system that enables adaptation to multiple devices, and JS extensions. JQuery, a general-purpose library used to simplify client-side JS development, was also used to implement functionality such as manipulation of asynchronous content and dynamic loading of new content. In parallel, the tool uses the C3.js for interactive data visualisation procedures. C3.js is a reusable chart library that implements functionality

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of the Data-Driven Document (D3.js) JS library and simplifies its use by 'wrapping' selected code while providing an API to access, customise and update chart properties.

2.4.2. Back-end. Python 2.7 was used to develop the server-side components of the tool, including its core application functionality, energy simulations, web server, data storage and high-level manipulation procedures. Python is an open-source, interpreted, object-oriented, programming language that enables rapid development of production software. It supports compartmentalisation through modules and packages that may be combined to add functionality to the code. In this case, besides standard ones, the tool was developed using three main modules, i.e., Flask, NumPy and Eppy. Flask is an extendable micro web framework that enables straightforward development by 'wrapping' the Wekzeug web server gateway interface (WGSI) utility library for Python. Flask uses Jinja2 as a default template engine to generate HTML files using variables and expressions that are replaced by text when the template is rendered on the web. The tool uses Jinja2 in combination with Flask-bootstrap to enable access to the predefined templates of the Bootstrap framework for JS. NumPy is a scientific computing module for Python that provides functionality to manipulate large multi-dimensional arrays and matrices. The tool uses this library to support embodied energy calculations and complex data manipulation procedures. In parallel, the functionality needed to conduct operational energy calculations is supported by Eppy, a Python module that enables manipulation of input and output files generated by the EnergyPlus simulation engine. The code runs on a VM that is hosted by the Nectar Research Cloud project [23].

2.4.3. Data storage. The data is stored as a series of csv files that are manipulated dynamically by the back-end code. This data is stored as five independent files, namely the materials, assemblies, operational energy, projects, and weather datasets. The 'materials' dataset includes information of the different materials used to create assemblies including the name of the material, an identification code, its embodied energy coefficient, its minimum and maximum service life, default quantity and thickness, and its thermal conductivity, density and specific heat used for operational energy calculations. The 'assemblies' dataset stores ordered sets of these materials including the name, a description, and a list of assembly layers that includes their identification codes and initial embodied energy according to their quantity as defined by the thickness and/or density of the layer. The 'operational energy' dataset stores annual heating and cooling demand in GJ/m^2. While the operational energy of the default assemblies was pre-calculated (see Section 2.1), the operational energy of a new assembly generated by the tool is stored dynamically. The 'projects' dataset stores information about all projects created within the tool, including its type, name, address, climatic conditions, corresponding weather file, expected design life of the project, and other meta data. Lastly, the 'weather' dataset stores a list of the available epw weather files, their location and a generic name to be used for manual assignment when projects are created.

3. Decision-support system

This section presents the implementation of the decision-support system as a web-based tool and a workflow demonstration of its capabilities for selecting assemblies to reduce building life cycle energy.

3.1. Workflow demonstration

For illustration purposes, this overview of the functionality of the decision-support system focuses on creating a new project for a residential building to be located in Alice Springs, Australia (Section 3.1.1), exploring the life cycle energy performance of predefined standard assemblies (Section 3.1.2), and generating a new wall envelope assembly (Section 3.1.3), before visualising its performance. Similar functionality is available for different building types, locations, and building elements.

3.1.1. Creating projects. The tool landing page directs users to open or create a project (Figure 1). The user is then taken to the project dashboard where they can select the new or existing project to be opened. Project information includes the name and type of the project, the client name, as well as information that is needed to perform the life cycle energy calculations such as the location of the building, its proximity to the coastline, and expected building design life.

Figure 1. Assembly selector landing page (left), and project dashboard (right).

3.1.2. Exploring assemblies. After selecting a project, the user is redirected to an analysis page where they can explore various default assemblies and visualise their life cycle energy performance (Figure 2). These assemblies are grouped under three main building elements, i.e., floor, wall, and roof assemblies. The default assemblies are listed on the left side of the screen, and these can be sorted alphabetically, or by their initial or recurrent embodied, life cycle, or operational energy requirements. In order to explore the energy requirements of these assemblies, the user can drag and drop them into the 'Select Assembly' area (Figure 2a). This provides an overview of the total energy requirements of the selected assembly in GJ/m^2, lists the different material layers, and provides an overview of the contribution of initial and recurrent embodied and operational energy requirements in a pie chart. This information can be disaggregated by material allowing identification of the materials that are the highest contributors to initial (Figure 2c) or recurrent (Figure 2d) embodied energy demand. Assemblies can also be compared - here, a timber-framed brick veneer wall is compared to a timber-framed reverse brick veneer wall.

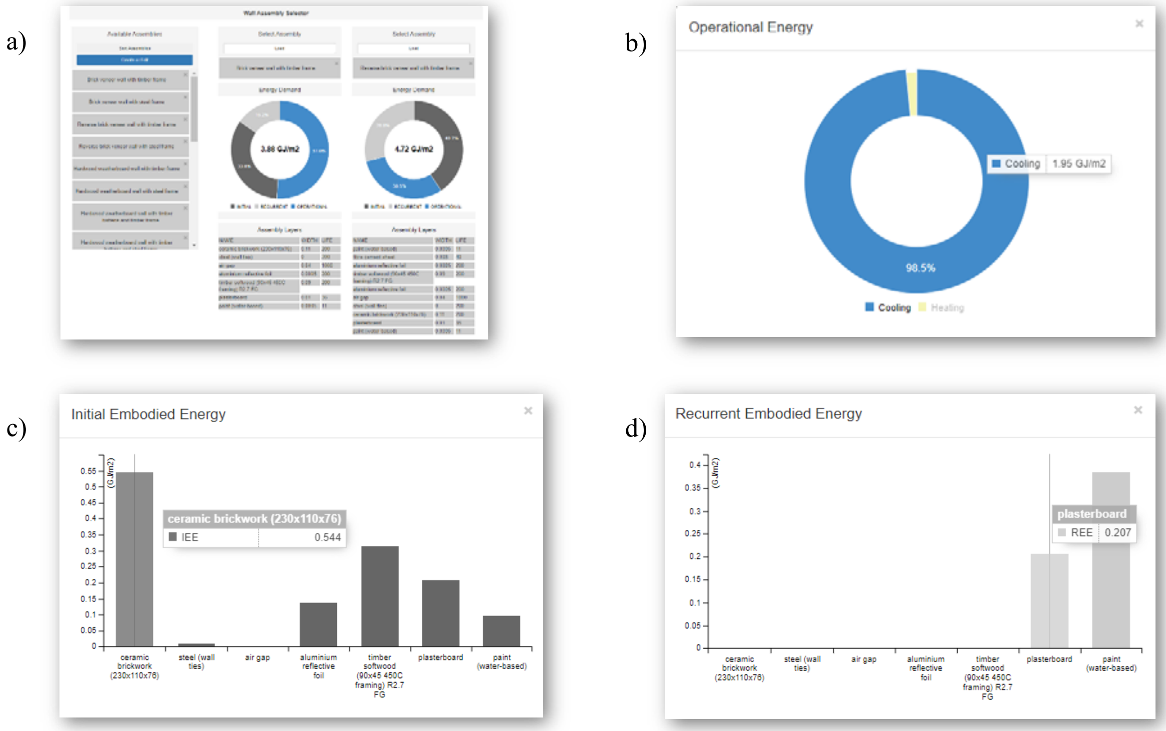

Figure 2. Assembly selector analysis page displaying functionality to compare assemblies (a), and disaggregate operational (b), initial embodied (c) and recurrent embodied (d) energy.

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In parallel, the 'Compare Assemblies' area displays the total energy requirements of all the available assemblies in the order predefined in the assemblies list while highlighting the selected assemblies (Figure 3). The 'Life Cycle Energy Projections' displays the energy requirements associated with the assemblies being compared over the design life of the building.

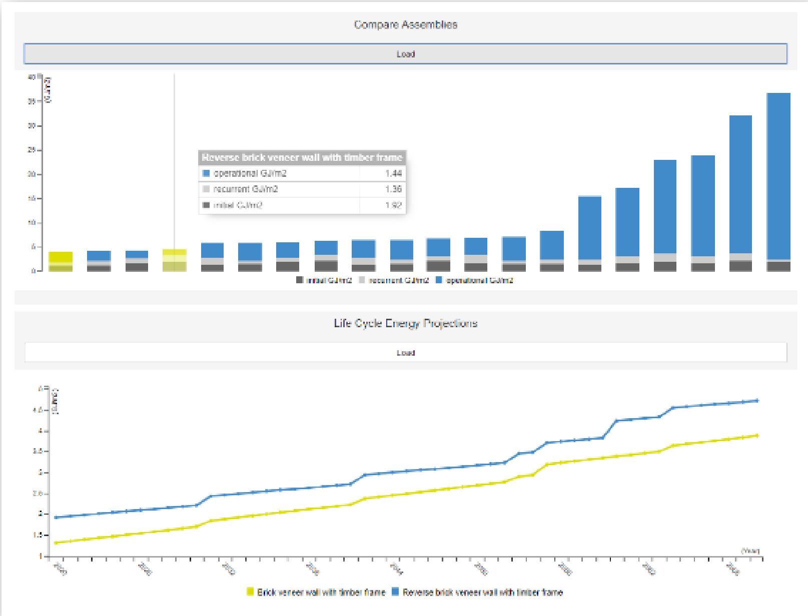

Figure 3. Assembly selector analysis page displaying comparison of all available assemblies in GJ/m^2 (top) and life cycle energy projections over the building design life (bottom).

3.1.3. Customising assemblies. To analyse the performance of custom assemblies, the tool enables new assemblies to be created or existing ones to be edited. To create a new assembly, the user defines its name and a description, before sequentially adding layers, selecting materials for those layers, and their thickness. To edit an existing assembly (Figure 4), the user selects one of the existing assemblies, modifies its name and description, and then changes, adds or removes layers. In both cases, by clicking 'Analyse Assembly', the tool then analyses the energy performance of the assembly by running EnergyPlus cloud simulations before displaying the results in the list of available assemblies. In this case, the example focuses on modifying the timber-framed reverse brick veneer wall assembly, eliminating paint in order to reduce its initial and recurrent embodied energy requirements.

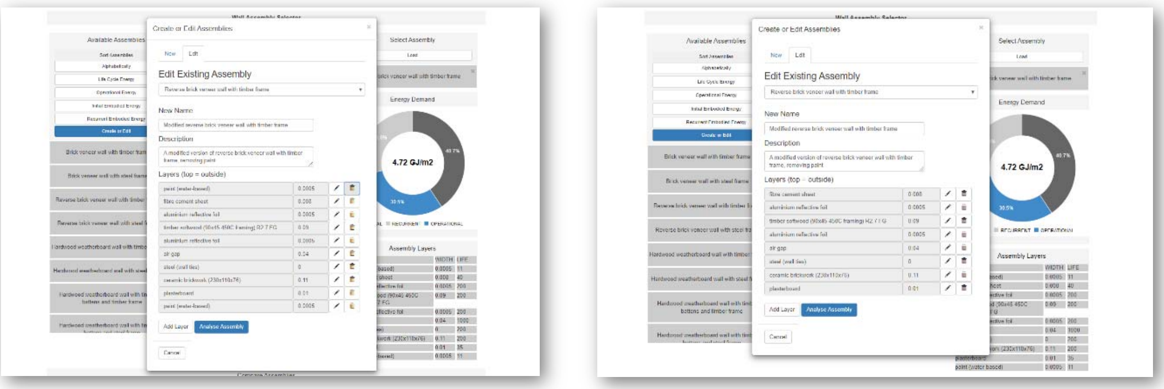

Figure 4. Assembly selector analysis page displaying assembly editing functionality before (left) and after (right) modifications.

As shown in Figure 5, the total energy requirements of the modified version of the timber-framed reverse brick veneer wall assembly is reduced by 20.6% from 4.72 to 3.75 GJ/m^2.

Figure 5. Assembly selector analysis page displaying results of edited assembly compared to the original assembly (left), other assemblies (top right) and life cycle energy projection (bottom right).

4. Conclusion

This paper presents a web-based tool to assist building designers make more informed early-stage design decisions aimed at reducing the life cycle energy associated with buildings. The tool focuses on providing critical information to select and specify envelope assemblies addressing the complete life cycle energy requirements of different solutions. Providing this information on a holistic life cycle perspective (rather than the piecemeal approach currently used) will ensure that decisions are being made based on the most comprehensive information possible, ensuring that environmental outcomes are not being compromised by missing or incomplete information. It is thus likely that the use of this approach during the early stages of design will be much more effective at reducing energy demand.

This will help in our strive towards meeting the sustainable development goals, particularly in relation to ensuring more responsible consumption and production (SDG12). Early-stage design decisions focussed on reducing life cycle energy demand of buildings is crucial for the efficient use of natural resources and in minimising the environmental effects of new construction and renovations. It will also help to reduce the adverse environmental effects at the larger city scale (SDG11). Further research will address the use of the tool in practice, including its integration with existing design processes and testing its use in various contexts, as well as how it could be adapted for use in other countries.

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References

[1] IPCC 2014 *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]* Cambridge University Press Cambridge, United Kingdom and New York, NY, USA 851

[2] Crawford R H, Czerniakowski I and Fuller R J 2010 A comprehensive framework for assessing the life cycle energy of building construction assemblies *Architectural Science Review* **53**(3) 288-96
[3] Gustavsson L and Joelsson A 2010 Life cycle primary energy analysis of residential buildings *Energy and Buildings* **42**(2) 210-220
[4] Treloar G J, Love P E D and Holt G D 2001 Using national input-output data for embodied energy analysis of individual residential buildings *Construction Management and Economics* **19** 49-61
[5] Bouchlaghem N 2000 Optimising the design of building envelopes for thermal performance *Automation in Construction* **10**(1) 101
[6] Al-Sanea S A 2002 Thermal performance of building roof elements *Building and Environment* **37**(7) 665
[7] Lawson W R 1996 *Building Materials, Energy and the Environment: Towards Ecologically Sustainable Development* The Royal Australian Institute of Architects Red Hill 135p
[8] Venkatarama Reddy B V and Jagadish K S 2003 Embodied Energy of Common and Alternative Building Materials and Technologies *Energy and Buildings* **35**(2) 129
[9] BRE 2008 *The Green Guide to Specification* Building Research Establishment UK
[10] Yao R and Steemers K 2005 A method of formulating energy load profile for domestic buildings in the UK *Energy and Buildings* **37**(6) 663-71
[11] Utama A and Gheewala S H 2008 Life cycle energy of single landed houses in Indonesia *Energy and Buildings* **40**(10) 1911-16
[12] ATHENA 2012 *ATHENA® EcoCalculator for Assemblies* Athena Sustainable Materials Institute Canada
[13] Pierquet P and Bowyer J L 1998 Thermal performance and embodied energy of cold climate wall systems *Forest Products Journal* **48**(6) 14p
[14] Chen T Y, Burnett J and Chau C K 2001 Analysis of embodied energy use in the residential building of Hong Kong *Energy* **26**(4) 323-340
[15] Crawford R H 2008 Validation of a hybrid life cycle inventory analysis method *Journal of Environmental Management* **88**(3) 496-506
[16] Crawford R H, Czerniakowski I and Fuller R J 2011 A comprehensive model for streamlining low-energy building design *Energy and Buildings* **43**(7) 1748-56
[17] Crawford R H, Czerniakowski I and Fuller R J 2011 Optimising the life cycle energy performance of residential buildings *From principles to practice in Architectural Science: Proceedings of the 45th Annual Conference of the Australian and New Zealand Architectural Science Association ANZAScA* Sydney
[18] Crawford R H, Czerniakowski I and Fuller R J 2014 An early-stage life cycle model for low-energy buildings *World Sustainable Building 2014 Conference* Barcelona Green Building Council Spain
[19] European Standards Organisation 2011 *EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* Czech Republic
[20] Crawford R H, Stephan A and Prideaux F 2019 *Environmental Performance in Construction (EPiC) Database* Melbourne The University of Melbourne
[21] Ding G K C 2004 *The Development of a Multi-criteria Approach for the Measurement of Sustainable Performance for Built Projects and Facilities* University of Technology, Sydney
[22] NAHB and Bank of America *Study of life expectancy of home components*, in *National Association of Home Builders/Bank of America Home Equity*, J. Jackson 2007, National Asssociation of Home Builders: Washington DC.
[23] Australian Government 2020 *The National eResearch Collaboration Tools and Resources project (Nectar)*