Based on T-spherical Fuzzy Environment: A Combination of FWZIC and FDOSM for Prioritising COVID-19 Vaccine Dose Recipients

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Abstract
The problem complexity of multi-criteria decision-making (MCDM) has been raised in the distribution of coronavirus disease 2019 (COVID-19) vaccines, which required solid and robust MCDM methods. Compared with other MCDM methods, the fuzzy-weighted zero-inconsistency (FWZIC) method and fuzzy decision by opinion score method (FDOSM) have demonstrated their solidity in solving different MCDM challenges. However, the fuzzy sets used in these methods have neglected the refusal concept and limited the restrictions on their constants. To end this, considering the advantage of the T-spherical fuzzy sets (T-SFSs) in handling the uncertainty in the data and obtaining information with more degree of freedom, this study has extended FWZIC and FDOSM methods into the T-SFSs environment (called T-SFWZIC and T-SFDOSM) to be used in the distribution of COVID-19 vaccines. The methodology was formulated on the basis of decision matrix adoption and development phases. The first phase described the adopted decision matrix used in the COVID-19 vaccine distribution. The second phase presented the sequential formulation steps of T-SFWZIC used for weighting the distribution criteria followed by T-SFDOSM utilised for prioritising the vaccine recipients. Results revealed the following: (1) T-SFWZIC effectively weighted the vaccine distribution criteria based on several parameters including T = 2, T = 4, T = 6, T = 8, and T = 10. Amongst all parameters, the age criterion received the highest weight, whereas the geographic locations severity criterion has the lowest weight. (2) According to the T parameters, a considerable variance has occurred on the vaccine recipient orders, indicating that the existence of T values affected the vaccine distribution. (3) In the individual context of T-SFDOSM, no unique prioritisation was observed based on the obtained opinions of each expert. (4) The group context of T-SFDOSM used in the prioritisation of vaccine recipients was considered the final distribution result as it unified the differences found in an individual context. The evaluation was performed based on systematic ranking assessment and sensitivity analysis. This evaluation showed that the prioritisation results based on each T parameter were subject to a systematic ranking that is supported by high correlation results over all discussed scenarios of changing criteria weights values.

Keywords: COVID-19, Vaccine, Multi-criteria Decision-making, T-spherical fuzzy sets, FWZIC, FDOSM.

1. Introduction

Countries worldwide faced the greatest challenge last year brought by the coronavirus disease 2019 (COVID-19) pandemic [1-8], and the need for a vaccine has become more important than ever [9]. Thus, many companies have succeeded in developing vaccines to stop the disease [10]. However, the limited available doses might not cover the current needs of all populations and could lead to anxiety amongst such populations [11]. Considering these limited vaccine doses, some fear that the allocation will not be fair at the global (between countries) and local (amongst different groups of society) levels where the evaluation of vaccine distribution has become a complex problem and the state of vaccine progress is unclear [12]. Therefore, governments must follow a priority mechanism for allocating COVID-19 vaccine doses amongst the population and avoid randomisation of vaccine distribution [13]. Equity and fairness considerations are high priorities in healthcare policy discussions and have become an important global responsibility [14]. To support the community with a mechanism for COVID-19 vaccine distribution across different kinds of populations, World Health Organisation (WHO) encourages a fair allocation mechanism. Moreover, reports stated that equitable and consistent allocation plans, informed by ethical values and public health needs, are essential to maximise public health benefits and ensure that scarce health products are available and accessible to those in need [15]. Hence, developing an effective and dynamic mechanism for vaccine distribution is crucial and regarded as the only progress method to ensure equity and fairness considerations.

Based on the literature review analysis, a strategic advisory group of experts on immunisation working with the WHO provided a standard framework for the allocation of the vaccine distribution amongst the populations [16]. This framework defines general attributes of prioritisation and is motivated by any potential work related to COVID-19 vaccine distribution. Another work [12] divided societal segments into two levels: firstly, priority is given to health care employees, people with high health risks, old people, and essential workers who provide services to people. Secondly, priority is given to secondary-line workers who support healthcare workers and people who face greater barriers to accessing care if they become seriously ill or those living or working in conditions that place them at risk of infection. Reference [17] utilised an informed approach to prioritise vaccines based on age and serological status. They concluded that to reduce cumulative infection, adults aged between 20 and 49 years should be prioritised, and to reduce the mortality rate, adults over the age of 60 years should be prioritised. Furthermore, four relevant studies used the approach of multi-criteria decision-making (MCDM) in the context of COVID-19 vaccine distribution. In this context, the MCDM evaluates alternatives by integrating individual criteria that are often conflicting into a comprehensive evaluation [18-37]. Decision-making techniques are gaining wide attention, of which the MCDM is the most vital [38-45]. The technique involves various procedures, including structuring, planning, and solving various problems using multiple criteria [46-53], and thus it is increasingly used to enhance the resolution quality [54-64].

Firstly, reference [65] analysed the effect of the COVID-19 pandemic on the availability of alternative supplier selection using the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Secondly, reference [66] explored the most significant factors affecting the demand for vaccines that are not included in national immunisation campaigns. This study presented the cause-and-effect relationships amongst the factors using the fuzzy Decision Making Trial and Evaluation Laboratory method to provide insights to policymakers for better vaccine demand forecast and increase vaccine uptake. Thirdly, reference [11] identified four main criteria and 15 sub-criteria; several groups of people were considered when prioritising vaccine distribution. This study utilised an MCDM approach to resolving the distribution issue, and the analytic hierarchy process method was used to assign the criteria weights (i.e. age index, health state, women state and job kind index). Moreover, TOPSIS was used to evaluate the COVID-19 vaccine alternatives to select a suitable vaccine in the early stage. This study is limited to different issues including the following: (i) prioritising certain groups in society and did not use a dataset to prove the distribution mechanism, and (ii) the inconsistency problem amongst the criteria weights should be solved to guarantee a fair distribution process. Based on this, reference [13] presented a fourth study to solve the aforementioned COVID-19 vaccine distribution limitations. This study proved that the COVID-19 vaccine distribution is a complex MCDM problem with three issues, namely, identification of different distribution criteria, importance criteria and data variation amongst them. Thus, a novel homogeneous Pythagorean fuzzy decision-making framework is developed. In such COVID-19 vaccine distribution framework, the Pythagorean fuzzy decision by opinion score method (PFDOSM) is used for prioritising vaccine recipients. Then, considering that the PFDOSM weighs the criteria implicitly only [67], PFDOSM is combined with Pythagorean fuzzy-weighted zero-inconsistency (FWZIC) for weighting each criterion explicitly. The FWZIC method is chosen because this method considers the most powerful weighting MCDM method for providing explicit weights for criteria with zero inconstancies. In such a framework, the establishment of a mechanism for allocating the limited doses of the COVID-19 vaccines is presented suitably and effectively. Moreover, the types of vaccine recipients and attributes/criteria that play a key role and can affect the distribution mechanism amongst those recipients are identified and discussed thoroughly.

To overcome uncertainty issues in the process of COVID-19 vaccine distribution and obtain more helpful information under imprecise and uncertain conditions, the Pythagorean Fuzzy Set (PFS) is used in FWZIC and FDOSM methods [13]. The reason is that, in this fuzzy set, the distinctness between the two types of fuzzy sets is that the former needs to satisfy the condition that the square sum of the membership and non-membership degrees is equal to or less than one, and the latter needs to satisfy the condition that the sum of the two degrees is equal to or less than one.

However, the structure of PFS fails to depict the human opinion when more than three options are available similar to voting systems (abstinence is included in information), where four conditions exist: yes, no, abstinence and refusal (see [68] for example). The concept of refusal in such a fuzzy set was not taken into account [69]. The aggregation operators proposed for PFS fail when abstinence is included in the data and when the sum or square sum of membership and non-membership functions exceeds one [70, 71]. In this fuzzy type, although the decision-makers have more options for giving values to an object, they did not allow them to select the values of three characteristic functions from their own choice [72, 73]. PFSs have not enough ability to deal with such kind of situation (the sum of membership and non-membership exceeds 1). According to the aforementioned limitations of PFS and other fuzzy sets, a new concept of T-spherical fuzzy sets (T-SFSs) has been developed. The T-SFSs structure is more wide and general with no restrictions on their constants, and this structure can handle the uncertainty in the data to capture the information with more degree of freedom [74]. In the T-SFSs, if the power on constraints is raised to T where T is any positive integer then we can assign any value of our choice to membership, non-membership and hesitancy degrees in the interval [0, 1]. In this case, the summation of membership, non-membership, and hesitancy degrees should not exceed 1. The choice of T is up to the decision makers involved. This choice of T makes T-SFSs of special attention making its space is observed for different values of T. In addition, the T-SFSs structure can completely express people's decision-making consciousness and describe the decision information precisely by a parameter that can flexibly adjust the scope of information expression [75].

Reference [75] developed a novel MCDM approach based on the T-SFSs-generalised Maclaurin symmetric mean operator and the T-SFSs-weighted GMSM operator for selecting a toothpaste product. The selection of the solar cells is presented in [70] based on a series of averaging interactive aggregation operators by assigning associate probabilities for T-SFSs. The development of new operational laws for T-SFSs is presented and applied to solve the MCDM problem of pollution in five major cities in China [76]. Reference [77] defined different operations of T-SFSs in addition to spherical fuzzy for solving the medical decision-making problem. Then, Reference [78] introduced different improved algebraic operations for T-SFSs based on Einstein t-norms and t-conorms. Reference [71] utilised Hamacher aggregation operators based on T-SFSs for the analysis of the performance of search and rescue robots. Moreover, reference [79] introduced T-SFSs correlation coefficients owning to the non-applicability of correlations of other fuzzy sets in certain conditions, such as clustering and MCDM problems. Reference [80] solved the measurement problem of the distance between T-SFSs accurately by proposing a new divergence measure considering the advantages of the Jensen-Shannon divergence. Reference [81] produced a decision assembly framework using interval-valued T-SFSs considering the alternatives of human judgments, such as favour, abstinence, disfavour and refusal degree. Reference [82] proposed some operation laws of and interaction aggregation operators of T-SFSs in addition to developing a new extension of TODIM based on T-SFSs. An extension of the technique of the generalised MULTIMOORA method is developed based on T-SFSs [83]. Lastly, the reference [84] introduced the idea of T-spherical type-2 hesitant fuzzy sets (T-ST2HFS) and correlation coefficients and weighted correlation coefficients for congregating the companies wanting to invest with a large amount of money.

According to the above discussions, T-SFS is exceedingly utilised in different areas for widely solving many MCDM problems, and this method is more capable of processing and expressing unknown information in unknown environments. Therefore, to keep up with the current state in solving the uncertainty and vagueness issues, FWZIC and FDOSM methods need to be extended into the T-SFSs environment (called T-spherical FWZIC [T-SFWZIC] and T-spherical FDOSM [T-SFDOSM]) to present an adequate and robustness COVID-19 vaccine distribution.

2. Methodology

The designed methodology is divided into two phases. In the first phase (decision matrix adoption), the used decision matrix in the COVID-19 vaccine distribution is adopted, which consists of the criteria of COVID-19 vaccine distribution and vaccine recipients. In the second phase (development), the proposed extensions of T-SFWZIC combined with T-SFDOSM are formulated. T-SFWZIC is presented for assigning the weights to the criteria followed by prioritising vaccine recipients based on T-SFDOSM. These phases are discussed in more detail in the following sections. Figure 1 shows the summarised methodology.

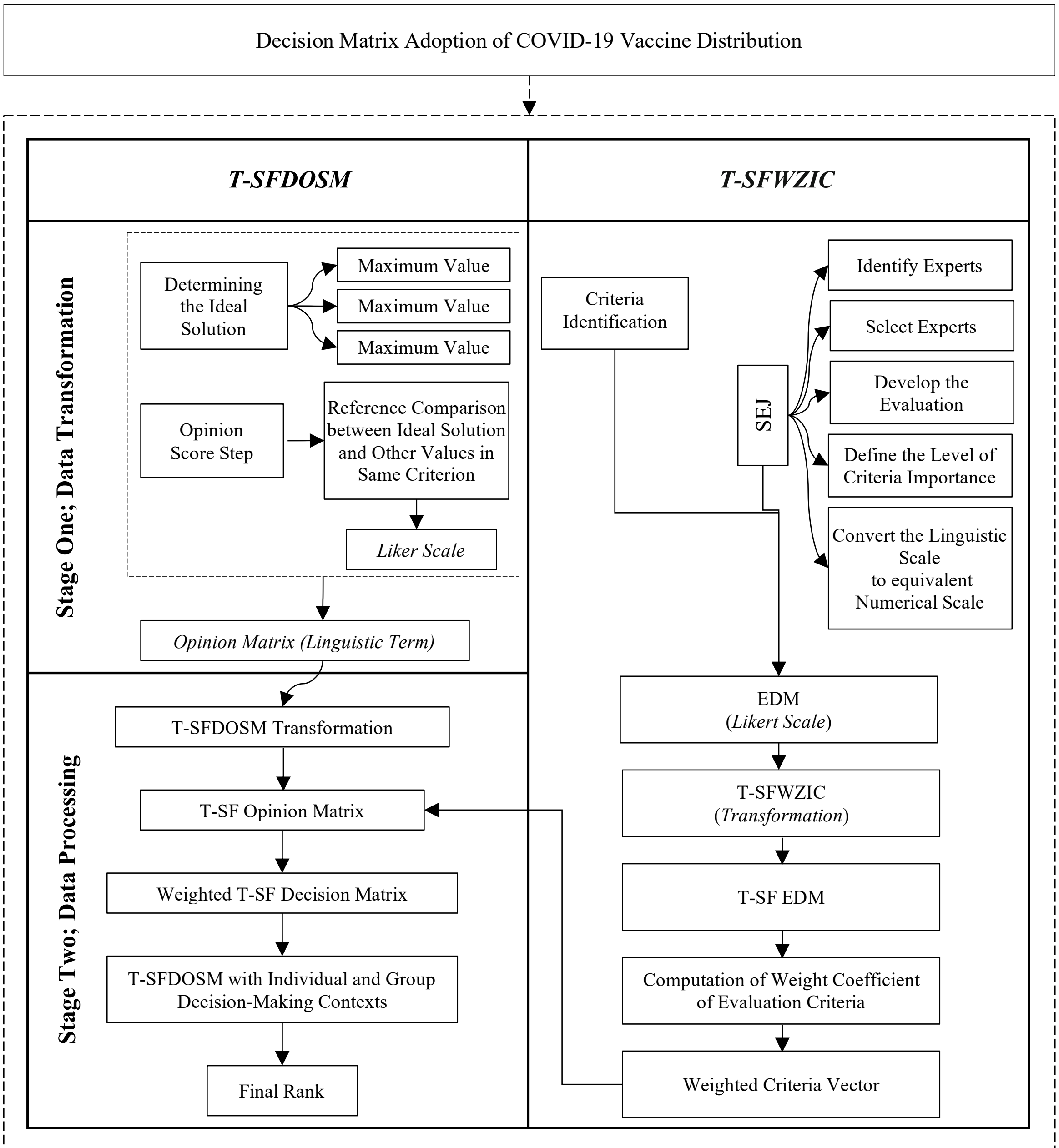

Figure 1: Methodology phases

2.1. Phase I: Decision Matrix Adoption

The first phase of the proposed methodology is presented to discuss the decision matrix used in the process of COVID-19 vaccine distribution. Reference [13] formulated the decision matrix based on three sequential steps including criteria identification, vaccine recipients as alternatives and data generation of alternatives to provide an artificial dataset of vaccine recipients cases (Table 1).

Table 1: Decision matrix used in COVID-19 vaccine distribution [13]

VR	C1	C2	C3	C4	C5	VR	C1	C2	C3	C4	C5
1	Pharmacist	Hypertension, diabetes	31	Green	NA	151	–	NA	53	Green	NA
2	Pharmacist	NA	59	Yellow	Hard of hearing	152	–	NA	59	Red	epilepsy
3	Doctor	Diabetes	37	Green	NA	153	–	Cardiovascular	83	Orange	hard of hearing
4	Pharmacist	Obesity	47	Yellow	NA	154	Health worker	Respiratory	59	Yellow	NA
5	Health Worker	NA	29	Green	Vision impairment	155	Health worker	NA	59	Red	NA
6	Electricity supplier	NA	29	Red	Hard of hearing	156	Doctor	NA	41	Green	NA
7	Teacher	NA	31	Green	NA	157	Nurse	NA	29	Green	NA
8	Teacher	NA	31	Yellow	NA	158	Doctor	Diabetes	43	Red	NA
9	Police officer	NA	47	Red	NA	159	Medical goods sales	Diabetes	43	Green	NA
10	Teacher	NA	37	Green	NA	160	Medical goods sales	Obesity	37	Orange	NA
11	–	Respiratory	59	Red	NA	161	Medical goods sales	Diabetes	37	Green	NA
12	–	Cardiovascular	7	Red	NA	162	Fire service employee	NA	41	Orange	epilepsy
13	–	Diabetes	3	Orange	NA	163	–	NA	17	Yellow	NA
14	–	Diabetes	43	Yellow	NA	164	–	NA	23	Green	NA
15	–	Respiratory	37	Yellow	NA	165	–	Hypertension	59	Yellow	NA
16	Pharmacist	NA	43	Green	NA	166	–	NA	43	Green	NA
17	Pharmacist	NA	41	Yellow	NA	167	–	NA	19	Orange	NA
18	Doctor	Respiratory	41	Green	NA	168	Medical goods sales	NA	41	Yellow	epilepsy
19	Nurse	NA	29	Orange	NA	169	Fire service employee	Diabetes	47	Yellow	NA
20	Pharmacist	Cardiovascular	37	Red	NA	170	Fire service employee	NA	59	Orange	NA
21	–	Cardiovascular	41	Orange	NA	171	Fire service employee	Respiratory	61	Orange	vision Impairment
22	–	NA	13	Green	NA	172	Doctor	NA	59	Green	NA
23	–	NA	11	Green	NA	173	Health worker	Cardiovascular	61	Orange	NA
24	–	Respiratory	89	Yellow	Vision impairment	174	Midwife	NA	23	Red	NA
25	–	NA	61	Green	NA	175	Nurse	Hypertension	43	Red	NA
26	Medical goods sales	Hypertension	43	Orange	Hard of hearing	176	Health worker	Respiratory	43	Red	NA
27	Medical goods sales	Diabetes	47	Green	NA	177	Health worker	Diabetes	41	Red	NA
28	Teacher	Respiratory	59	Yellow	NA	178	Doctor	NA	41	Yellow	NA
29	Police officer	NA	47	Yellow	NA	179	Doctor	Hypertension	29	Yellow	NA
30	Police officer	NA	53	Green	NA	180	Employee postal	NA	29	Red	NA
31	Midwife	Diabetes	31	Orange	NA	181	Medical goods sales	Cardiovascular	43	Yellow	vision Impairment
32	Health Worker	NA	47	Red	Hard of hearing	182	Religious staff	Respiratory	59	Red	NA
33	Nurse	Hypertension, cardiovascular	43	Yellow	NA	183	journalist	Hypertension	53	Red	NA
34	Midwife	Obesity	23	Orange	NA	184	Electricity supplier	NA	53	Red	NA
35	Doctor	Obesity, hypertension	61	Yellow	NA	185	Specialist education professional	NA	23	Red	NA
36	Pharmacist	NA	59	Green	NA	186	Medical goods sales	NA	23	Red	NA
37	Specialist education professional	Cardiovascular, hypertension	59	Orange	NA	187	–	NA	1	Yellow	NA
38	Electricity supplier	NA	41	Orange	NA	188	–	NA	29	Orange	NA
39	Police officer	NA	31	Yellow	NA	189	–	Diabetes	59	Red	epilepsy
40	Religious staff	Cardiovascular	59	Yellow	Hard of hearing	190	–	NA	7	Green	NA
41	Teacher	Hypertension	47	Orange	NA	191	–	NA	41	Orange	NA
42	Health Worker	NA	37	Orange	NA	192	–	NA	31	Green	NA
43	Doctor	NA	37	Green	NA	193	Midwife	NA	31	Yellow	NA
44	Nurse	Diabetes	41	Green	Hard of hearing	194	Midwife	Hypertension	53	Yellow	NA
45	Pharmacist	Diabetes	53	Red	NA	195	Health worker	NA	43	Green	NA
46	Doctor	Obesity	41	Green	NA	196	Health worker	NA	61	Red	vision Impairment

47	–	Cardiovascular	97	Red	Vision impairment	197	Nurse	Respiratory	23	Yellow	NA
48	–	NA	31	Orange	NA	198	Delivery worker	NA	31	Green	NA
49	–	NA	29	Orange	NA	199	Medical goods sales	NA	47	Orange	NA
50	–	NA	53	Red	NA	200	Medical goods sales	Cardiovascular, hypertension	61	Orange	NA
51	–	Obesity	53	Orange	NA	201	Medical goods sales	NA	37	Green	epilepsy
52	–	NA	47	Orange	NA	202	Specialist Education professional	Respiratory	23	Red	NA
53	Journalist	NA	31	Yellow	NA	203	Police officer	NA	43	Yellow	NA
54	Journalist	NA	31	Orange	NA	204	–	NA	2	Red	NA
55	Journalist	Diabetes	59	Green	NA	205	–	NA	2	Green	NA
56	Teacher	NA	41	Yellow	NA	206	–	Diabetes	67	Red	epilepsy
57	Probation staff	NA	31	Green	Hard of hearing	207	–	NA	2	Orange	NA
58	Pharmacist	NA	43	Yellow	NA	208	–	NA	2	Yellow	NA
59	Pharmacist	NA	53	Yellow	NA	209	–	NA	5	Green	NA
60	Nurse	NA	59	Green	NA	210	Medical goods sales	NA	29	Green	NA
61	Midwife	NA	23	Yellow	NA	211	Fire service employee	NA	29	Yellow	NA
62	Health Worker	NA	61	Green	Hard of hearing	212	Medical goods sales	NA	41	Red	NA
63	–	NA	47	Red	NA	213	Midwife	NA	23	Orange	NA
64	–	NA	19	Orange	NA	214	Health worker	NA	61	Orange	NA
65	–	Hypertension	83	Yellow	Vision impairment	215	Doctor	NA	61	Red	NA
66	–	NA	5	Orange	NA	216	Doctor	NA	59	Yellow	NA
67	Doctor	NA	29	Orange	NA	217	Health worker	Obesity	59	Green	epilepsy
68	Nurse	NA	31	Yellow	NA	218	Midwife	Diabetes	41	Red	NA
69	Fire service employee	NA	29	Yellow	NA	219	–	Respiratory	89	Green	hard of hearing
70	Employee postal	Respiratory	53	Green	NA	220	–	NA	7	Orange	NA
71	Journalist	Hypertension	61	Red	NA	221	–	Cardiovascular	83	Orange	epilepsy
72	–	NA	19	Orange	NA	222	Medical goods sales	NA	47	Yellow	NA
73	–	NA	61	Orange	NA	223	Specialist education professional	NA	41	Red	epilepsy
74	–	NA	61	Green	NA	224	Medical goods sales	Respiratory	61	Green	NA
75	Pharmacist	Obesity	41	Orange	NA	225	–	NA	43	Orange	NA
76	Midwife	Respiratory	37	Yellow	NA	226	–	Obesity	59	Orange	NA
77	Doctor	NA	23	Orange	NA	227	–	NA	3	Green	NA
78	Midwife	Respiratory	59	Red	NA	228	–	Hypertension	89	Orange	hard of hearing
79	Health Worker	Hypertension	41	Yellow	Epilepsy	229	–	NA	17	Green	NA
80	Doctor	NA	59	Yellow	NA	230	Doctor	Hypertension	41	Yellow	NA
81	Nurse	NA	37	Red	NA	231	Health worker	NA	61	Red	NA
82	Religious staff	Hypertension	53	Green	NA	232	Nurse	Respiratory	61	Orange	NA
83	Delivery worker	NA	23	Yellow	NA	233	Health worker	NA	47	Green	NA
84	Employee postal	NA	23	Green	NA	234	Midwife	NA	61	Orange	NA
85	Specialist education professional	Obesity, diabetes	61	Yellow	Vision impairment	235	–	Hypertension	89	Red	hard of hearing
86	Fire service employee	Respiratory	59	Orange	NA	236	–	NA	1	Orange	NA
87	Pharmacist	Obesity	23	Red	NA	237	–	Hypertension	79	Green	NA
88	Doctor	NA	41	Orange	NA	238	Probation staff	NA	23	Yellow	NA
89	Health Worker	NA	47	Red	NA	239	Religious staff	Diabetes	53	Orange	NA
90	–	NA	13	Orange	NA	240	Electricity supplier	NA	41	Orange	NA
91	–	NA	7	Green	NA	241	Religious staff	Hypertension	59	Red	NA
92	–	NA	11	Orange	NA	242	–	Hypertension	71	Red	NA
93	–	Diabetes, hypertension	97	Yellow	Epilepsy	243	–	NA	2	Yellow	NA
94	–	NA	89	Yellow	Epilepsy	244	–	Cardiovascular	47	Orange	NA
95	Probation staff	NA	41	Red	NA	245	Doctor	NA	43	Red	NA
96	Journalist	Cardiovascular, hypertension	61	Red	NA	246	Midwife	Respiratory	61	Red	NA

97	Medical goods sales	Obesity	59	Yellow	NA	247	Pharmacist	NA	53	Green	hard of hearing
98	Charity staff	NA	59	Orange	NA	248	Midwife	Diabetes, hypertension	31	Yellow	NA
99	Doctor	NA	53	Yellow	NA	249	Midwife	NA	59	Yellow	NA
100	Doctor	NA	53	Red	NA	250	Midwife	NA	47	Orange	NA
101	Pharmacist	NA	37	Orange	NA	251	Probation staff	Cardiovascular, hypertension	61	Red	NA
102	–	NA	47	Green	NA	252	Employee postal	NA	41	Green	NA
103	–	NA	47	Green	NA	253	Specialist education professional	NA	43	Green	NA
104	–	NA	61	Orange	NA	254	Delivery worker	Hypertension	59	Orange	NA
105	–	NA	71	Yellow	NA	255	journalist	Respiratory	61	Red	vision Impairment
106	Electricity supplier	NA	43	Red	NA	256	–	NA	1	Red	NA
107	Charity staff	NA	37	Red	Hard of hearing	257	–	NA	1	Red	NA
108	Religious staff	NA	47	Orange	NA	258	–	Obesity	31	Yellow	NA
109	Pharmacist	NA	43	Red	NA	259	–	NA	11	Green	NA
110	Doctor	Cardiovascular, hypertension	47	Yellow	NA	260	Nurse	NA	23	Red	NA
111	–	Obesity	29	Green	NA	261	Pharmacist	NA	47	Orange	NA
112	–	NA	5	Red	NA	262	Pharmacist	Hypertension	53	Yellow	NA
113	–	NA	41	Red	NA	263	Fire service employee	NA	23	Green	NA
114	–	NA	59	Orange	NA	264	Religious staff	NA	23	Red	NA
115	–	NA	3	Green	NA	265	Electricity supplier	Cardiovascular	53	Orange	hard of hearing
116	Midwife	NA	29	Red	NA	266	Religious staff	Respiratory	53	Orange	NA
117	Nurse	Obesity, diabetes	29	Yellow	NA	267	teacher	NA	31	Yellow	NA
118	Midwife	Diabetes	58	Green	Hard of hearing	268	Specialist education professional	Hypertension	41	Yellow	NA
119	Health Worker	NA	53	Orange	NA	269	–	NA	5	Green	NA
120	Electricity supplier	Cardiovascular	61	Red	NA	270	–	NA	2	Red	NA
121	Employee postal	Respiratory	31	Orange	NA	271	–	NA	59	Green	NA
122	Journalist	Obesity	53	Orange	NA	272	–	NA	37	Red	NA
123	Teacher	NA	37	Green	NA	273	–	Obesity	61	Green	NA
124	–	Diabetes	61	Green	NA	274	–	Hypertension	97	Red	hard of hearing
125	–	Respiratory	97	Yellow	Hard of hearing	275	Health worker	Diabetes	41	Orange	NA
126	–	Respiratory	79	Green	NA	276	Nurse	Respiratory	31	Yellow	NA
127	Religious staff	Respiratory	43	Red	NA	277	Nurse	NA	59	Orange	NA
128	Religious staff	Obesity, diabetes	43	Green	Hard of hearing	278	–	Hypertension	37	Yellow	NA
129	Religious staff	NA	29	Green	NA	279	–	NA	1	Green	NA
130	Nurse	Respiratory	29	Green	NA	280	–	Cardiovascular	61	Orange	NA
131	Health Worker	NA	53	Green	NA	281	–	Diabetes	83	Red	epilepsy
132	midwife	Obesity, diabetes	29	Orange	NA	282	–	Obesity	73	Red	NA
133	Health Worker	NA	37	Orange	NA	283	Teacher	Cardiovascular, hypertension	61	Red	NA
134	Health Worker	NA	47	Orange	NA	284	Specialist education professional	Obesity, diabetes	61	Red	NA
135	–	Obesity	73	Red	NA	285	–	NA	5	Green	NA
136	–	NA	13	Yellow	NA	286	–	NA	97	Orange	NA
137	–	NA	59	Yellow	NA	287	Religious staff	NA	29	Red	NA
138	–	NA	2	Yellow	NA	288	Police officer	Diabetes	61	Red	NA
139	Charity staff	NA	37	Yellow	NA	289	Journalist	NA	47	Yellow	vision Impairment
140	Charity staff	NA	53	Orange	NA	290	Medical goods Sales	NA	47	Green	NA
141	Delivery worker	Diabetes	59	Orange	Epilepsy	291	Midwife	NA	31	Yellow	NA
142	Electricity supplier	Obesity	43	Orange	NA	292	Doctor	Hypertension	37	Orange	NA
143	Nurse	Respiratory	29	Orange	NA	293	Health worker	NA	41	Green	NA
144	Doctor	NA	53	Orange	NA	294	Health worker	NA	37	Yellow	NA
145	Pharmacist	Obesity	53	Yellow	NA	295	–	NA	5	Green	NA
146	Teacher	NA	37	Green	NA	296	–	NA	19	Orange	NA
147	Fire service employee	NA	43	Green	NA	297	–	Hypertension	73	Orange	NA
148	Teacher	NA	47	Yellow	NA	298	–	NA	7	Orange	NA

149	Specialist education professional	NA	31	Orange	NA	299	Medical goods sales	NA	47	Red	NA
150	–	NA	37	Yellow	NA	300	Religious staff	NA	31	Red	NA

Remarks: VR = vaccine recipients, C1 = vaccine recipient memberships, C2 = chronic disease conditions, C3 = age, C4 = geographic locations severity and C5 = disabilities.

In this decision matrix, the mechanism of vaccine distribution is achieved to serve the vaccine recipients who represent the alternatives based on five criteria, namely, vaccine recipient memberships, chronic disease conditions, age, geographic locations severity and disabilities. After that, an adequate augmented dataset is adopted from [13]. In this adopted dataset, 300 cases of vaccine recipients were generated as proof of concept. Although the generalisation and inclusion of more than 300 cases are possible, the insights from the generated cases usually can satisfy the concepts of the presented work, from which the results can then meet the desired goals. A coding scheme using the exception-handling model was developed in Python to generate the augmented dataset of the 300 cases based on the five discussed criteria. The most suitable probabilities and certain assumptions about COVID-19 vaccine alternatives were generated. In that date set, the rule-based control scheme was based on expert opinions with precise descriptions for the criteria. After generating the dataset, a panel of three experts subjectively validated it to increase the veracity of the data to the best extent possible and cover most recipients' situations. The three expert panellists were identified and selected from related study areas (i.e. molecular biology, immunology, biomedical engineering, medical biotechnology and clinical microbiology). According to the same expert panel, C3 and C4 (age and geographic locations severity) have ranges of measures and are considered benefit criteria. Moreover, other criteria belong to the categorical type. Lastly, this decision matrix is introduced to the next phase (development) to start with the distribution process.

2.2. Phase II: Development

This phase presents the development of the proposed vaccine distribution methodology based on new extensions of MCDM methods. T-SFWZIC was used to achieve the criteria weighting, whereas T-SFDOSM was used for ranking the vaccine recipients. The following subsections describe each method separately along with the relevant mathematical expressions.

2.2.1. Formulation of T-SFWZIC

The T-SFWZIC method is an extension of the original FWZIC [85], which has five steps for criteria weight determination (Figure 1). The following show the complete details of the five steps:

Step 1: Criteria Definition

This step has two processes. The first process is the exploration and presentation of the predefined set of evaluation criteria, and the second process is the classification and categorisation of all the collected criteria. As discussed before, the criteria used in the process of COVID-19 vaccine distribution are identified in Section 2.1. Furthermore, the defined and selected criteria were evaluated by the same panel of experts (those in phase 2.1), which is explained in the next step.

Step 2: Structured expert judgement (SEJ)

To evaluate and define the level of importance for the criteria identified, the same panel of three experts was utilised. After exploring and identifying the list of prospective experts, the selection and nomination commenced, and the SEJ panel was established. Lastly, an evaluation form was developed to obtain the consensus of all the SEJ panellists for each criterion, followed by the conversion of the linguistic scale to its equivalent numerical scale.

a) **Identify experts:** Anyone who has knowledge about a subject cannot be considered an expert. Instead, an 'expert for a given subject' is used here to designate a person whose present or past field involves the subject in question and who is regarded by others as knowledgeable about the subject. These individuals are occasionally designated in the literature as 'domain' or 'substantive' experts to distinguish them from 'normative experts', that is, experts in statistics and subjective probability. In the current study, the expert selection method was based on a bibliometric analysis of all authors and co-authors of studies that have listed vaccine distribution criteria.
b) **Select experts:** After identifying the set of experts, the experts who will be involved in the study were selected. In general, the largest number of experts consistent with the level of resources should be used. In this study, three experts were chosen for a given subject. All potential experts named during the expert identification phase were contacted via email to determine whether they were interested and whether they considered themselves potential experts for the panel. After the list of candidate experts was established, the three experts collaborated as expert judgement panellists.

c) **Develop the evaluation form**: The development of an evaluation form is a crucial step because this instrument is used to obtain expert consensus. Before finalising the evaluation form, the questionnaire underwent reliability and validity testing, and all the three experts selected in the previous step reviewed it.

d) **Define the level of importance scale:** In this step, the selected group of three experts defined the level of importance/significance of each criterion using a five-point Likert scale. No theoretical reason exists to rule out different lengths of the response scale [86]. The options reflect an underlying continuum rather than a finite number of possible attitudes. Various lengths ranging from 2 to 11 points or higher are used in surveys. Five has become the norm in Likert scales probably because this number strikes a balance between the conflicting goals of offering sufficient choices (as providing only two or three options means measuring only the direction rather than the strength of opinion) and making things manageable for respondents (few people have a clear idea of the difference between the eighth and ninth points in an 11-point agree–disagree scale). Research confirmed that data from Likert items (and those from similar rating scales) become significantly less accurate when the number of scale points decreases to below five or increases to above seven. However, these studies provided no reasons for preferring five-point scales to seven-point scales.

e) **Convert linguistic scale to equivalent numerical scale:** As mentioned, all preference values are identified in the subjective form, which cannot be used for further analysis unless they are converted into numerical values. Thus, in this step, the level of importance/significance of each criterion recorded by each expert on the linguistic Likert scale was converted to an equivalent numerical scale, as shown in Table 2.

Table 2: Five-point Likert scale and equivalent numerical scale

Numerical scoring scale	Linguistic scoring scale
1	Not important
2	Slight important
3	Moderately important
4	Important
5	Very important

A Likert scale assumes that the vaccine distribution criteria have different important levels that should be assigned by an expert. The importance level is assigned using a linguistic scale that facilitates the process of the evaluation criteria. The importance levels range from 'not important' to 'very important'. However, when an additional analysis needs to be conducted on the scores obtained by experts, extracting any useful information from linguistic scores is difficult unless converted into numerical values. Thus, an equivalent numerical value has been provided along with each linguistic term where measuring the importance level of the vaccine distribution criteria is possible.

Step 3: Building the Expert Decision Matrix (EDM)

The previous step clarifies how the experts were selected and how their preferences were indicated. In this step, the EDM is constructed. The main parts of the EDM are the vaccine distribution criteria and the alternatives, as shown in Table 3.

Table 3: EDM

Experts	C1	C2	…	Cn
E1	Imp (E1/C1)	Imp (E1/C2)	…	Imp (E1/Cn)
E2	Imp (E2/C1)	Imp (E2/C2)	…	Imp (E2/Cn)
E3	Imp (E3/C1)	Imp (E3/C2)	…	Imp (E3/Cn)
...	…	…	…	…
Em	Imp (En/C1)	Imp (En/C2)	…	Imp (Em/Cn)

**Imp represents the importance level.

According to Table 3, a crossover is made between the vaccine distribution criteria and the SEJ panel. Each criterion (Cj) in the attribute intersects with each selective expert (Ei), where the expert has scored a suitable level of importance for each criterion. The EDM is the base for further analysis steps in the proposed method, which are illustrated in the next sub-sections.

Step 4: Application of T-SFS membership function

The membership function and the subsequent defuzzification process of T-SFS are applied to the EDM data where the data are transformed to a T-SF EDM to increase their precision and ease of use in further analysis. However, in MCDM, the problem is uncertain and imprecise because assigning a precise preference rate to any criterion is difficult. The advantage of using the fuzzy method is the use of vague numbers instead of crisp numbers to determine the relative value of attributes (criteria) and address the issue of imprecise and uncertain problems [87-89]. The T-SFS is an objective having the form of [77, 90] and as defined in Eqs. (1) and (2).

$$P = \{\langle m, (\mu_d(m), v_d(m), s_d(m))\rangle \mid m \in M\}, \quad (1)$$

where $\mu_d: M \to [0,1]$ is the membership function, whereas $v_d: M \to [0,1]$ is the non-membership function of element $m \in M$, and $s_d: M \to [0,1]$ is the hesitate function to p and must fulfil the restriction seen in Eq. (2).

$$0 < (\mu_d(m))^T + (v_d(m))^T + (s_d(m))^T \leq 1, \quad (2)$$

where $T \geq 1$.

The degree of hesitancy is presented in Eq. (3) [90].

$$\pi_m(m) = \sqrt[T]{1 - (\mu_d(m))^T + (v_d(m))^T + (s_d(m))^T}. \quad (3)$$

The applied arithmetic operation using T-SFS utilised the following equations. T-SFS summation and aggregation operations can be seen in Eq. (4) [91].

$$\mathrm{T-SAM}(\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n) = \left\{\left[1 - \prod_{i=1}^{n}(1 - \mu_{\tilde{p}_i}^2)\right]^{1/T}, \prod_{i=1}^{n} v_{\tilde{p}_i}, \left[\prod_{i=1}^{n}(1 - \mu_{\tilde{p}_i}^2) - \prod_{i=1}^{n}(1 - \mu_{\tilde{p}_i}^2 - s_{\tilde{p}_i}^2)\right]^{1/T}\right\}. \quad (4)$$

The division operation was performed using Eqs. (3) and (5). However, Eq. (5) was adopted from [92], which is used in the spherical fuzzy set. Thus, in this study, the square within this operation has been converted to the power *t* to fulfil the T-SFS structure.

$$p_1 \oslash p_2 = \left(\left(\frac{(\mu_{p1}^T(2-\mu_{p2}^T)}{1-(1-\mu_{p1}^T)\cdot(1-\mu_{p2}^T)}\right)^{\frac{1}{T}}, \frac{(v_{p1}^T - v_{p2}^T)^{\frac{1}{T}}}{(1-v_{p1}^T \cdot v_{p2}^T)^{\frac{1}{T}}}, \frac{(s_{p1}^T - s_{p2}^T)^{\frac{1}{T}}}{(1-s_{p1}^T \cdot s_{p2}^T)^{\frac{1}{T}}}\right), if\ \frac{\mu_{p2}^T}{\mu_{p1}^T} \geq \frac{1-s_{p2}^T}{1-s_{p1}^T}\ \frac{1+s_{p1}^T}{1+s_{p2}^T} \geq 1. \quad (5)$$

Eq. (6) shows the equation of T-SFS division on crisp value [83]. The value of each linguistic term with T-SFS is shown in Table 4.

$$\tilde{P} \oslash \lambda = \left\{(1 - (1 - \mu_{\tilde{P}}^T)^{1/\lambda})^{1/T}, v_{\tilde{P}}^{1/\lambda}, s_{\tilde{P}}^{1/\lambda}\right\}, \quad (6)$$

where $\lambda > 0$.

The defuzzied (crisp) value of a T-SFS fuzzy number is defined as follows in Eq (7) [77]:

$$Score(\tilde{p}) = \mu_{\tilde{p}}{}^T - s_{\tilde{p}}{}^T. \quad (7)$$

Table 4: Linguistic terms and their equivalent T-SFS [93]

linguistic scale	T-SFS
Not important	(0.15, 0.85, 0.1)
Slight important	(0.25, 0.75, 0.2)

Moderately important	(0.55, 0.5, 0.25)
Important	(0.75, 0.25, 0.2)
Very important	(0.85, 0.15, 0.1)

Table 4 indicates that all linguistic variables are converted into T-SFS, assuming that the fuzzy number is the variable for each criterion for Expert K. In other words, Expert K (a vaccine distribution expert) was asked to identify the importance level of the vaccine distribution criteria within the variables measured using a linguistic scale.

Step 5: Computation of the final values of the weight coefficients of the evaluation criteria
Based on the fuzzification data for the criteria in the previous step, the final values of the weight coefficients of the evaluation criteria $(w1, w2, \ldots, wn)^T$ are calculated in this step as follows.

a) The ratio of fuzzification data is computed using Eqs. (3), (4) and (5); the preceding equations are used with T-SFS, where Eq. (8) symbolises the process as shown in Table 5.

Table 5: T-SF EDM

Criteria/ Experts	$\widetilde{C1}$	$\widetilde{C2}$	…	$\widetilde{Cn}$
E1	$\frac{Imp(\widetilde{E1}/C1)}{\sum_{j=1}^{n} Imp(\widetilde{E1}/C_{1j})}$	$\frac{Imp(\widetilde{E1}/C1)}{\sum_{j=1}^{n} Imp(\widetilde{E1}/C_{1j})}$	…	$\frac{Imp(\widetilde{E1}/C1)}{\sum_{j=1}^{n} Imp(\widetilde{E1}/C_{1j})}$
E2	$\frac{Imp(\widetilde{E2}/C1)}{\sum_{j=1}^{n} Imp(\widetilde{E2}/C_{2j})}$	$\frac{Imp(\widetilde{E2}/C2)}{\sum_{j=1}^{n} Imp(E2/C_{2j})}$	…	$\frac{Imp(\widetilde{E2}/Cn)}{\sum_{j=1}^{n} Imp(E2/C_{2j})}$
...	…	…	…	…
Em	$\frac{Imp(\widetilde{Em}/C1)}{\sum_{j=1}^{n} Imp(\widetilde{Em}/Cm_j)}$	$\frac{Imp(\widetilde{Em}/C2)}{\sum_{j=1}^{n} Imp(\widetilde{Em}/C_{mj})}$	…	$\frac{Imp(\widetilde{Em}/Cn)}{\sum_{j=1}^{n} Imp(\widetilde{Em}/C_{mn})}$

$$\frac{Imp(\widetilde{E1}/C1)}{\sum_{j=1}^{n} Imp(\widetilde{E1}/C_{1j})}, \qquad (8)$$

where $Imp(\widetilde{E1}/C1)$ represents the fuzzy number of *Imp (E1/C1)*.

b) The mean values are computed to find the final fuzzy values of the weight coefficients of the evaluation criteria $(\widetilde{w1}, \widetilde{w2}, \ldots, \widetilde{wn})^T$.
The T-SF EDM is used to compute the final weight value of each criterion using Eq. (6), where Eq (9) symbolises the process.

$$\widetilde{w_j} = \left(\sum_{i=1}^{m} \frac{Imp(\widetilde{E_{ij}}/C_{ij})}{\sum_{j=1}^{n} Imp(\widetilde{E_{ij}}/C_{ij})}\right)/m\ ), \text{ for } i = 1,2,3,..m \text{ and } j = 1,2,3,..n\,. \qquad (9)$$

c) Defuzzification is performed to find the final weight; Eq. (7) is used as the defuzzification method. To calculate the final values of the weight coefficients, the weight for the importance of each criterion should be assigned given the sum of the weights of all the criteria for the rescaling purpose applied in this stage as well.

2.2.2. Formulation of T-SFDOSM

T-SFDOSM is the extended version of FDOSM proposed in [94], which is used in the proposed COVID-19 vaccine distribution methodology (Figure 1). The following section provides information about the first stage of T-SFDOSM, which is the data transformation unit. After this, the second stage, data processing, is presented.

Stage One: Data transformation unit

According to [95], the transformation of the DM into an opinion matrix is achieved using the following steps.

Step 1:

Select the ideal solution of each sub-criterion used in the DM of COVID-19 vaccine distribution. Therefore, the ideal solution is defined as shown in Eq. (10).

$$A^* = \left\{\left[\left(\max_i v_{ij} \,\middle|\, j \in J\right), \left(\min_i v_{ij} \,\middle|\, j \in J\right), (Op_{ij} \in I.J) | i = 1.2.3. \dots . m\right]\right\}, \tag{10}$$

where max is the ideal value for benefit criteria (i.e. C3 and C4), min is the ideal solution for cost criteria (no cost criteria are identified in the COVID-19 vaccine distribution) and Op_{ij} is the ideal value for critical/categorical criteria (i.e. C1, C2 and C5) when the ideal value lies between the max and min. The critical value is determined by the decision-maker.

Step 2:

Reference comparison is made between the ideal solution and other values for each of the criteria used in the COVID-19 vaccine distribution criteria. A five-point Likert scale is used. The ideal solution selection step is followed by comparing the ideal solution with the value of vaccine recipients in the same criterion, as shown in Eq. (11).

$$Op_{Lang} = \left\{\left(\left(\tilde{v}_{ij} \otimes v_{ij} \,\middle|\, j \in J\right). \middle| i = 1.2.3. \dots . m\right)\right\}, \tag{11}$$

where $\otimes$ represents the reference comparison between the ideal solution and the value of alternatives in the same criterion.

The final output of this block indicating the linguistic term is the opinion matrix that is ready to be transformed into a fuzzy opinion matrix by using T-SFS, as expressed in Eq. (12).

$$Op_{Lang} = \begin{matrix} A_1 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} op_{11} & \cdots & op_{1n} \\ \vdots & \ddots & \vdots \\ op_{m1} & \cdots & op_{mn} \end{bmatrix}. \tag{12}$$

Stage Two: Data-processing unit

The opinion matrix of each Likert scale refers to the output of the transformation unit. The final block begins by transferring the opinion matrix into a fuzzy opinion DM by converting the linguistic terms of the opinion matrix into T-SFS using Table 6.

Table 6: T-SF Opinion Matrix [93]

Linguistic scale	T-SFSs
No difference	(0.85, 0.15, 0.1)
Slight difference	(0.75, 0.25, 0.2)
Difference	(0.55, 0.5, 0.25)
Big difference	(0.25, 0.75, 0.2)
Huge difference	(0.15, 0.85, 0.1)

This study presents two contexts (i.e. individual and group decision-making [GDM]) with three decision-makers for distributing the COVID-19 vaccine.

2.2.2.1. Individual Context of T-SFDOSM

T-SFS is applied with FDOSM in this stage. The obtained explicit weights of each COVID-19 distribution criterion (Section 2.2.1) were introduced to T-SFDOSM to prioritise the vaccine recipients thoroughly. The T-SFDOSM uses Eq. (13) to aggregate the fuzzy opinion matrices to produce a score for each alternative.

$$\mathrm{T-SWAM}(\tilde{p}_1, \tilde{p}_2, \dots, \tilde{p}_n) = \left\{\left[1 - \prod_{i=1}^{n}(1 - \mu_{\tilde{p}_i}^2)^{w_i}\right]^{1/T}, \prod_{i=1}^{n} \nu_{\tilde{p}_i}^{w_i}, \left[\prod_{i=1}^{n}(1 - \mu_{\tilde{p}_i}^2)^{w_i} - \prod_{i=1}^{n}(1 - \mu_{\tilde{p}_i}^2 - s_{\tilde{p}_i}^2)^{w_i}\right]^{1/T}\right\}. \tag{13}$$

Eq. (13) multiplies the weights with each criterion value; this concept can calculate the effectiveness of weights in T-SFDOSM used in COVID-19 distribution thoroughly. Then, the defuzzification process of each alternative is computed using Eq. (7). After that, vaccine recipients can be prioritised. Each vaccine recipient will be assigned a value, and they will be ordered based on the best value. The vaccine recipient with the highest score will have the highest priority.

2.2.2.2. Group Context of T-SFDOSM

Considering the variations in the distribution ranking of the COVID-19 vaccine amongst decision-makers, aggregated decisions obtained from various evaluators are necessary to unify the distribution ranking. Thus, this study utilised the GDM context with T-SFDOSM to unify all the variations in the distribution ranking of the decision-makers and arrive at the final distribution ranking. Furthermore, the arithmetic mean was used to arrive at the final score of GDM, as expressed in Eq. (14). The highest score value is the best vaccinator. In this case, the decision makers' opinions were combined after arriving at the final distribution ranking of vaccine recipients.

$$Group\ PFDOSM = \oplus S^*, \tag{14}$$

where ⊕ = AM; S* = The final rank for each expert.

3. Discussion Results

This section presents the evaluation and differentiation results of COVID-19 vaccine recipients to formulate the vaccine distribution mechanism. The section is divided into two subsections. Section 3.1 provides the results of the T-SFWZIC method and the constructed criteria weights; in particular, the three experts' judgment is converted using mathematical calculations to show the overall weights within this section. Section 3.1 displays the distribution results of the COVID-19 recipients based on the individual decision-making T-SFDOSM and GDM T-SFDOSM and are then presented.

3.1. Criteria Weighting Results

This section provides the weight determination results of the COVID-19 vaccine distribution criteria using the T-SFWZIC method developed in Section 2.2.1. After performing the involved steps, the T-SFWZIC method process resulted in GDM contexts weights (obtained from the three experts) without any inconsistency following the method philosophy. In addition, the obtained weights applied for T values (i.e. T = 2, T = 4, T = 6, T = 8 and T = 10) and Table 7 illustrates the final weight results of the five criteria for vaccine distribution. According to step 4, the process of the NS membership function is employed to transform crisp values into equivalent fuzzy numbers. After that, the process of transformation and the fuzzification of the experts' opinions on the significance of the five criteria are also presented. The ratio values of the criteria are computed according to Eqs. (3) and (6), followed by computing the mean of the experts' preference for each criterion to determine the fuzzy weight. Then, Eq. (7) is employed to determine the final weight for each of the five criteria as explained in step 5. Finally, the computed ratio and fuzzy value of the final weights of the five criteria are calculated.

Table 7 T-SFWZIC results of weights determination

Criteria/T	C1 = Vaccine Recipient Memberships	C2 = Chronic Disease Conditions	C3 = Age	C4 = Geographic Location Severity	C5 = Disabilities
T-SFWZIC (T = 2)	0.2019	0.2015	0.2064	0.1935	0.1967
T-SFWZIC (T = 4)	0.2050	0.1929	0.2246	0.1738	0.2036
T-SFWZIC (T = 6)	0.2064	0.1834	0.2307	0.1732	0.2063
T-SFWZIC (T = 8)	0.2042	0.1813	0.2333	0.1770	0.2042
T-SFWZIC (T = 10)	0.2006	0.1820	0.2364	0.1803	0.2006

Table 7 displays the final weight results, which indicate the importance of all five vaccine distribution criteria based on the proposed extended T-SFWZIC. For all T-SFWZIC values (T = 2, T = 4, T = 6, T = 8 and T = 10), the age (C3) received the highest weight as the first important criteria, followed by vaccine recipient memberships (C1) as the second important criteria, whereas geographic locations severity (C4) received the lowest weight as the fifth important criteria. In addition, chronic disease conditions (C2) received the third important criteria for the T = 2 value and received the fourth important criteria for T values (4, 6, 8 and 10). Finally, disabilities (C5) received the fourth importance criteria for the T = 2 value, the third importance criteria for T values (4 and 6) and the second important criteria for T values (8 and 10).

These final benchmarking results can be achieved by using the T-SFDOSM method as described in the next section; practically, these weight values need to be provided for the T-SFDOSM to compute the benchmarking results of the 300 vaccine recipients.

3.2. Benchmarking Vaccine Recipient's Results

The results and discussions presented in this section pertaining to the distribution of the COVID-19 vaccine are based on individual (Section 2.2.2.1) and GDM contexts (Section 2.2.2.2). The results of the opinion matrix and fuzzy opinion matrix used in the distribution of the COVID-19 vaccine are obtained. By using the five scales, the three decision-makers provided their opinions on converting the DM into the opinion matrix. According to Eq. (9), the decision-makers determined the ideal solution value based on the COVID-19 vaccine distribution criteria (i.e. vaccine recipient memberships, chronic disease conditions, age, geographic locations severity and disabilities). The opinion matrix was created by comparing the ideal solution with other values per criterion or each alternative using linguistic terms. The opinion matrix of each decision-maker is converted into a fuzzy opinion matrix. Thereafter, the fuzzy opinion matrix of the 300 vaccine recipients from the decision-maker is obtained (Table 1). Moreover, the T-SFDOSM method was applied to the resulting T-SF opinion matrices to achieve the distribution of the COVID-19 vaccine. Table 8 presents the results of the COVID-19 vaccine distribution based on the individual T-SFDOSM decision-making context for the three decision-makers resulted from T = 2, T = 4, T = 6, T = 8 and T=10 with a sample of 10 vaccine recipients. The remaining is presented in Table A1 in the Appendix.

Table 8: Vaccine distribution results based on individual T-SFDOSM (first 10 alternatives)

T = 2						
Alternatives	Expert 1		Expert 2		Expert 3	
	Score	Final rank	Score	Final rank	Score	Final rank
VR1	0.243892	245	0.354449	206	0.341019	227
VR2	0.51641	88	0.614038	48	0.57606	55
VR3	0.407582	140	0.419373	156	0.407582	180
VR4	0.301573	234	0.403859	178	0.391517	196
VR5	0.257675	241	0.331057	231	0.404083	188
VR6	0.457439	120	0.468103	126	0.457439	150
VR7	0.180057	269	0.260008	247	0.341019	227
VR8	0.241288	247	0.316424	236	0.391517	196
VR9	0.517317	84	0.459162	141	0.566905	72
VR10	0.180057	269	0.197592	274	0.341019	227
T = 4						
Alternatives	Expert 1		Expert 2		Expert 3	
	Score	Final rank	Score	Final rank	Score	Final rank
VR1	0.34703	245	0.43058	206	0.419721	224
VR2	0.517837	59	0.577581	32	0.549922	48
VR3	0.457287	137	0.465739	157	0.457287	179
VR4	0.387907	234	0.456057	166	0.44682	193
VR5	0.36231	240	0.418344	210	0.459309	178
VR6	0.47601	121	0.483828	140	0.47601	159
VR7	0.284399	269	0.364185	247	0.419721	224
VR8	0.338647	247	0.401586	236	0.44682	193
VR9	0.505188	88	0.476933	146	0.530083	78
VR10	0.284399	269	0.307558	274	0.419721	224

T = 6						
Alternatives	Expert 1		Expert 2		Expert 3	
	Score	Final rank	Score	Final rank	Score	Final rank
VR1	0.414308	245	0.470713	204	0.464584	224
VR2	0.506707	59	0.535593	31	0.520474	48
VR3	0.483351	133	0.487122	156	0.483351	179
VR4	0.44421	234	0.482765	163	0.478343	192
VR5	0.426704	240	0.463822	210	0.484303	178
VR6	0.490923	121	0.494168	135	0.490923	158
VR7	0.358207	269	0.428054	247	0.464584	224
VR8	0.407058	247	0.453407	236	0.478343	192
VR9	0.502069	81	0.491279	144	0.511786	77
VR10	0.358207	269	0.380778	274	0.464584	224
T = 8						
Alternatives	Expert 1		Expert 2		Expert 3	
	Score	Final rank	Score	Final rank	Score	Final rank
VR1	0.452048	245	0.487942	204	0.484661	224
VR2	0.502322	61	0.515248	31	0.507687	48
VR3	0.493743	133	0.49531	157	0.493743	179
VR4	0.473044	234	0.493621	163	0.491661	192
VR5	0.460925	240	0.484214	219	0.494075	178
VR6	0.497051	121	0.498209	135	0.497051	158
VR7	0.406983	269	0.46205	247	0.484661	224
VR8	0.447616	247	0.478709	236	0.491661	192
VR9	0.500813	79	0.497203	143	0.504232	77
VR10	0.406983	269	0.426363	274	0.484661	224
T = 10						
Alternatives	Expert 1		Expert 2		Expert 3	
	Score	Final rank	Score	Final rank	Score	Final rank
VR1	0.472911	245	0.495008	208	0.493271	227
VR2	0.500768	61	0.5064	33	0.50277	49
VR3	0.497653	143	0.498309	157	0.497653	181
VR4	0.486963	234	0.497675	168	0.496812	194
VR5	0.478928	240	0.493073	219	0.497772	178
VR6	0.499077	120	0.499467	134	0.499077	153
VR7	0.43889	269	0.479851	247	0.493271	227
VR8	0.470577	247	0.490309	236	0.496812	194
VR9	0.500268	88	0.49914	143	0.501411	79
VR10	0.43889	269	0.454543	274	0.493271	227

As mentioned previously in Section 2.2.2, the highest alternative must have the highest score, and the lowest alternative must have the lowest score value. However, to provide additional analyses for the individual T-SFDOSM final rank results, Table 9 shows the best fourth alternatives (VR) obtained from the three experts for all T values.

Table 9: Individual ranking results of the best four alternatives for various values of T

Experts\T	Expert 1	Expert 2	Expert 3
T = 2	VR281 > VR221 > VR93 > VR274	VR221 > VR281 > VR232 > VR206	VR221 > VR281 > VR189 > VR274
T = 4	VR281 > VR221 > VR93 > VR274	VR221 > VR281 > VR232 > VR206	VR221 > VR281 > VR274 > VR189
T = 6	VR281 > VR221 > VR93 > VR274	VR221 > VR281 > VR232 > VR206	VR221 > VR281 > VR274 > VR189
T = 8	VR281 > VR221 > VR93 > VR274	VR221 > VR281 > VR232 > VR206	VR221 > VR281 > VR274 > VR189
T = 10	VR281 > VR221 > VR93 > VR274	VR221 > VR281 > VR232 > VR206	VR221 > VR281 > VR274 > VR189

As shown in Table 9, we aim to analyse the effect of variation in T value on the individual T-SFDOSM ranking results. For this purpose, we presented the best four alternatives (VR) for various values of T, and the ranking results are given for the three experts. Table 9 shows that varying T has a limited effect on ranking for the best four alternatives of each expert. For example, for the first expert with all T values, the best alternative is VR281 followed by VR221 as the second rank, VR93 as the third rank and VR274 as the fourth rank. In the same context, the results are also similar for the second and third experts. However, the little effectiveness for T values on the best four alternatives does not provide the precise conclusion on the overall 300 alternatives. Therefore, to discuss the real effectiveness of T values on T-SFDOSM individual ranking results, we calculate the overall variations that occurred in the ranking orders for the individual ranking for each expert that presented in Table A1 in the APPENDIX. The results showed that, for expert 1, 228 out of 300 alternatives (76%) were changed and received the different rank orders, whereas 72 alternatives (24%) received the same ranking order and not changed when T values are applied (T = 2, T = 4, T = 6, T = 8 and T = 10). Moreover, for expert 2, 229 out of 300 alternatives (76.3%) were changed and received different rank orders, whereas 71 alternatives (23.6%) received the same ranking order and have not been changed. Finally, for expert 3, 246 out of 300 alternatives (82%) were changed and also received different rank orders, whereas 54 alternatives (18%) received the same ranking order and have not to be changed. Although little variance has been observed for the best four ranking orders amongst alternatives (Table 9), these orders do not reflect the complete picture of how T values affected the ranking results. Therefore, as a conclusion for the above discussion, we found that a big variance has occurred on the ranking orders and score values based on T values, indicating the existence of T values' effectiveness on vaccine distribution.

From another perspective, we found that the ranking results changed amongst the three experts. Therefore, this case shows the significance of variation in experts' preferences in decision analysis amongst experts. For example, Table 9 and Table A1 (APPENDIX) show that, for expert 1 in the case of T = 2, the VR281 is the best alternative rank and obtained the score of 0.758775, whereas for experts 2 and 3, the VR221 is the first alternative rank and obtained the score 0.731969. After reviewing the scores and ranking orders results for the individual T-SFDOSM, we found differences amongst the three experts obtained for the vaccine recipients. Overall, no unique prioritisation result was observed based on the opinions provided by the three experts. Given this variance, GDM, considering all the experts' opinions, is essential to provide final and unique prioritisation. Furthermore, GDM is necessary to solve the problem of variations in the final rank. Therefore, we present the results of the GDM context for all T values in Table A2 in the APPENDIX. As mentioned in Section 2.2.2.2, the final results of the three decision-makers were aggregated by using Eq. (14), and the final GDM raking for COVID-19 vaccine distribution was obtained. In addition, Table 10 shows the results of the COVID-19 vaccine distribution based on the GDM T-SFDOSM for the three decision-makers resulted from T = 2, T = 4, T = 6, T = 8 and T = 10 with a sample of 10 vaccine recipients.

Table 10: Vaccine distribution results based on GDM T-SFDOSM (first 10 alternatives)

Alternatives	T = 2		T = 4		T = 6		T = 8		T = 10	
	Score	Final rank	Score	Final rank	Score	Final rank	Score	Final rank	Score	Final rank

VR1	0.31312	242	0.399111	234	0.449868	234	0.474883	234	0.487064	237
VR2	0.568836	61	0.548447	45	0.520925	43	0.508419	43	0.503313	43
VR3	0.411513	167	0.460104	156	0.484608	152	0.494265	152	0.497872	155
VR4	0.36565	203	0.430261	203	0.468439	203	0.486109	204	0.493817	212
VR5	0.330938	223	0.413321	220	0.458276	221	0.479738	223	0.489924	232
VR6	0.460994	131	0.478616	132	0.492005	131	0.497437	128	0.499207	127
VR7	0.260361	257	0.356102	257	0.416948	257	0.451231	258	0.470671	262
VR8	0.316409	237	0.395684	239	0.446269	239	0.472662	240	0.4859	241
VR9	0.514461	96	0.504068	103	0.501711	103	0.500749	102	0.500273	102
VR10	0.239556	270	0.337226	270	0.401189	276	0.439336	276	0.462235	276

Table 10 and Table A2 (APPENDIX) illustrate that, for all T values, the highest-ranked (rank 1) recipient is VR221, with the highest score of 0.757245. After reviewing the profile data of this alternative, VR221's criteria specifications related to C1, C2, C3, C4 and C5, as he is not from vaccine recipient memberships, include having cardiovascular disease, 83 years old, from orange geographical location and disabled with epilepsy. Although VR221 did not belong to any recipient memberships (C1), the weight of the age criterion (Table 7 which indicates that age weight received higher priority for all T values based on the three experts) played a major role in the decision-making process and provided the alternative with a high priority. Hence, the remaining criteria varied somewhat in terms of importance.

From another perspective, VR180 is almost located in the middle of ranking results, that is, rank 146 when T = 2 and obtained a score value of 0.44272; rank 151 for T = 4, T = 6 and T = 8 and obtained score values of 0.46522, 0.485626 and 0.494799, respectively; rank 150 for T = 10 and obtained a score value of 0.498175. The criteria specifications of VR180 related to C1, C2, C3, C4 and C5, as he is a recipient membership (employee postal), are not affected by chronic disease, 29 years old, from red geographical location and not affected with disabilities. A satisfactory ranking result had been assigned to alternative VR180, specifically the vaccine distribution criteria specifications are relatively averagely important and earned a middle priority.

The lowest-ranked recipients were the alternatives VR22, VR166, VR205, VR229, VR269 and VR285, and they obtained the same ranking order (rank 293) and same scores for all T values. They received scores 0.174299, 0.277296, 0.351137, 0.400839 and 0.433967for T = 2, T = 4 T = 6, T = 8 and T = 10, respectively. The closeness of the criteria specifications for these alternatives is the reason for admitting them in the same order of priority and for obtaining the same score. For example, the criteria specifications of VR22 related to C1, C2, C3, C4 and C5, as he is not from vaccine recipient memberships, are not affected by chronic disease, 13 years old, from green geographical location and having disabilities, respectively. In conclusion for those in the worst ranked, all of their profile data do not have vaccine recipient memberships and are not affected by any chronic condition, younger age, from green or yellow geographic locations severity and slightly affected by disabilities.

From another perspective, in line with the discussion analyses presented previously for individual T-SFDOSM of how the T values were affected the first four ranking results (Table 9), Table 11 presents the best four alternatives based on GDM T-SFDOSM.

Table 11: GDM T-SFDOSM ranking of the best and worst four alternatives for various values of T

Experts\T	Best 4 alternatives
T = 2	VR221 > VR281 > VR274 > VR206
T = 4	VR221 > VR281 > VR274 > VR93

T = 6	VR221 > VR281 > VR274 > VR93
T = 8	VR221 > VR281 > VR274 > VR93
T = 10	VR221 > VR281 > VR274 > VR93

Table 11 shows that for T = 4, T = 6, T = 8 and T = 10, the best alternative is VR221 followed by VR281 as the second-best rank, VR274 as the third-best rank and VR93 as the fourth-best rank. In the same context for ranking results when T = 2, the best three rank alternatives are similar to other T values, namely, VR221, VR281 and VR274. The only different result is that VR206 has the best fourth rank according to T = 2.

To discuss the effect of T values on GDM T-SFDOSM, we also calculate the variations that occurred in the ranking orders for the GDM ranking results (Table A2 in the APPENDIX) when T values are applied (T = 2, T = 4, T = 6, T = 8 and T = 10). In these contexts, 268 out of 300 alternatives (89.3%) were changed and received different rank orders when these T values are applied, whereas 32 alternatives (10.7%) received the same rank order and have not been changed. Therefore, as a conclusion of how T values affect GDM T-SFDOSM ranking orders, the big variance also has been occurred in line with the individual T-SFDOSM. Thus, T values play a key role in the overall ranking for the COVID-19 vaccine distribution for individual and GDM T-SFDOSM and should be considered. Finally, the rank of COVID-19 vaccine distribution is in line when comparing the GDM results with the opinion matrices. Thus, this rank is considered the final ranking results for COVID-19 vaccine distribution, which will be evaluated in detail in the next section.

4. Evaluation

According to the literature review studies, the systematic ranking and sensitivity analysis assessments have been most widely used in the evaluation of the MCDM results. Thus, the efficiency of the proposed work for COVID-19 vaccine distribution is evaluated and tested through those assessments. Firstly, the systematic ranking of the vaccine recipients' ranking results is evaluated. Secondly, the effect of changing the criteria weight on the ranking result is examined and analysed over different scenarios.

4.1. Systematic ranking evaluation

In the first evaluation process, to assess the prioritisation results for COVID-19 vaccine distribution and substantiate the obtained COVID-19 vaccine distribution GDM results, the prioritised vaccine recipients were divided into different groups following their prioritisation order. In this section, the systematic ranking evaluation process for the COVID-19 vaccine distribution results is discussed. To substantiate the COVID-19 vaccine distribution GDM results obtained, the validation process was performed by dividing the vaccine recipients into different groups. This process has been followed in various MCDM studies [96-98]. The number of groups or the number of vaccine recipients within each group does not affect the validation result [99-101]. To validate the group COVID-19 vaccine distribution results, several procedures are performed as follows: (1) All opinion matrices were aggregated to produce a unified opinion matrix. (2) The vaccine recipients within the unified opinion matrix were sorted/ordered according to GDM results. (2) The vaccine recipients were divided into six equal groups. (3) The mean ($\bar{x}$) for each group is calculated thereafter (Eq. (15)).

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i. \tag{15}$$

The comparison process was based on the result of the mean in each group. The lowest mean values of each group lead to valid results because the decision-makers have assigned the lowest linguistic terms to the ideal solution of each criterion, which is the philosophy of FDOSM. Thus, the first group is assumed to have the lowest mean to check the result validity and is compared thereafter with the second group, and so on. The second group's mean result must be higher than that of the first group. The same applies to the third, fourth, fifth and sixth groups. If the evaluations are consistent with the assumption, then the results are valid. Table 12 presents the validation results for the group results obtained using the proposed T-SFDOSM.

Table 12: Validation of group distribution results

Group #	T = 2	T = 4	T = 6	T = 8	T = 10
	Mean value				
Group 1	2.701333	2.697333	2.697333	2.698667	2.697333
Group 2	3.236	3.229333	3.230667	3.229333	3.233333

Group 3	3.549333	3.554667	3.553333	3.553333	3.556
Group 4	3.86	3.865333	3.866667	3.874667	3.869333
Group 5	4.117333	4.117333	4.116	4.108	4.108
Group 6	4.444	4.444	4.444	4.444	4.444

As shown in Table 12, the initial observation of the ranking results of the six groups shows that all groups are systematically distributed across all the five scenarios (T1, T2, T3, T4 and T5) as the ranking results of the second group start from the end of the ranking results of the first group and so on for the other groups. In all the scenarios, the mean value of the first group was smaller than the mean results for the following group 2. Moreover, this consequent process was carried whilst considering that a group mean is smaller than the mean of the next corresponding group in each scenario. When the latter is achieved across all the groups, the systematic ranking is deemed valid. Judging by all the mean values in all the scenarios across all the groups, no group nor scenario was against the rule, and thus, all the scenarios across all the groups are valid. The statistical validation results indicate that the T-SFDOSM results of COVID-19 vaccine distribution extended by the groups are valid and have been systematically ranked.

4.2. Sensitivity analysis evaluation

In this second evaluation process, the sensitivity of the proposed T-SFWZIC method against the changing criteria weight is analysed. Thus, the sensitivity analysis predicts the effect of changing criteria weights on the systematic ranking results of the vaccine distribution results. To analyse the sensitivity, firstly, the most important criterion should be identified for each T value. In this study, out of the five criteria, C3 = age was the most important for all T values as presented in Table 7. To examine the effect of changing criteria weights, nine different scenarios for each T value generated from the relativity of criteria weight were computed using Eq. (16) [102]. The relative change for each criterion over the most important one (age) with respect to each T value was computed using the elasticity coefficient (α_c) as shown in Table 13.

$$w_c = (1 - w_s) \times (w_c^o / W_c^0) = w_c^o - \Delta x \alpha_c, \quad (16)$$

where for T value:

- w_s is the higher significant contribution,
- w_c^o represents the original weight values computed using T-SFWZIC,
- W_c^0 is the total of original weights for the changing criteria weight values, and
- Δx is the range of change applied on the five criteria weight values, which represents the limit values of the most significant criterion in this study (age), as follows:
  - For T = 2, $-0.206 \leq \Delta x \leq 0.793$
  - For T = 4, $-0.224 \leq \Delta x \leq 0.775$
  - For T = 6, $-0.230 \leq \Delta x \leq 0.769$
  - For T = 8, $-0.233 \leq \Delta x \leq 0.766$
  - For T = 10, $-0.236 \leq \Delta x \leq 0.763$

Table 13: Elasticity coefficient (α_c) for changing weights.

T value	Criteria	C1	C2	C3	C4	C5
T = 2	α_c	0.254472	0.25391	0.260088	0.243788	0.24783
T = 4	α_c	0.264418	0.248818	0.289657	0.224172	0.262592

T = 6	α_c	0.268242	0.23842	0.299846	0.225139	0.268199
T = 8	α_c	0.266341	0.236491	0.304314	0.230827	0.266341
T = 10	α_c	0.262761	0.238411	0.3096	0.236068	0.262761

C1 = Vaccine Recipient Memberships, C2 = Chronic Disease Conditions, C3 = Age, C4 = Geographic Location Severity, C5 = Disabilities.

As shown in Table 13, the T Value for each criterion has changed the weight values according to Eq. 16. For all (α_c) with respect to T values (T = 2, T = 4, T = 6, T = 8 and T = 10), the age (C3) received the highest weight as the first important criteria, whereas geographic locations severity (C4) received the lowest weight as the fifth important criteria. Then, the interval range of Δx for T values is used to generate nine new weighting values for each criterion by dividing it into nine equal relative values based on the number of scenarios, as shown in Table 14.

Table 14: New weight values for each criterion of nine scenarios for T values

	C1	C2	C3	C4	C5
T = 2					
T-SFWZIC	0.201948	0.201502	0.206405	0.193469	0.196676
S1	0.254472	0.25391	0.00E+00	0.243788	0.24783
S2	0.222663	0.222172	0.125	0.213314	0.216851
S3	0.190854	0.190433	0.25	0.182841	0.185872
S4	0.159045	0.158694	0.375	0.152367	0.154894
S5	0.127236	0.126955	0.5	0.121894	0.123915
S6	0.095427	0.095216	0.625	0.09142	0.092936
S7	0.063618	0.063478	0.75	0.060947	0.061957
S8	0.031809	0.031739	0.875	0.030473	0.030979
S9	1.00E−05	1.00E−05	0.99996	1.00E−05	1.00E−05
T = 4					
T-SFWZIC	0.205029	0.192934	0.2246	0.173823	0.203614
S1	0.264418	0.248818	0.00E+00	0.224172	0.262592
S2	0.231365	0.217716	0.125	0.19615	0.229768
S3	0.198313	0.186614	0.25	0.168129	0.196944
S4	0.165261	0.155511	0.375	0.140107	0.16412
S5	0.132209	0.124409	0.5	0.112086	0.131296
S6	0.099157	0.093307	0.625	0.084064	0.098472
S7	0.066104	0.062205	0.75	0.056043	0.065648
S8	0.033052	0.031102	0.875	0.028021	0.032824
S9	1.00E−05	1.00E−05	0.99996	1.00E−05	1.00E−05
T = 6					
T-SFWZIC	0.206364	0.183422	0.230678	0.173205	0.206331
S1	0.268242	0.23842	0.00E+00	0.225139	0.268199
S2	0.234712	0.208617	0.125	0.196997	0.234674
S3	0.201181	0.178815	0.25	0.168854	0.201149
S4	0.167651	0.149012	0.375	0.140712	0.167624
S5	0.134121	0.11921	0.5	0.11257	0.134099
S6	0.100591	0.089407	0.625	0.084427	0.100575
S7	0.06706	0.059605	0.75	0.056285	0.06705
S8	0.03353	0.029802	0.875	0.028142	0.033525

S9	1.00E−05	1.00E−05	0.99996	1.00E−05	1.00E−05
T = 8					
T-SFWZIC	0.2042	0.181315	0.233313	0.176972	0.2042
S1	0.266341	0.236491	0.00E+00	0.230827	0.266341
S2	0.233048	0.20693	0.125	0.201974	0.233048
S3	0.199756	0.177368	0.25	0.17312	0.199756
S4	0.166463	0.147807	0.375	0.144267	0.166463
S5	0.13317	0.118246	0.5	0.115414	0.13317
S6	0.099878	0.088684	0.625	0.08656	0.099878
S7	0.066585	0.059123	0.75	0.057707	0.066585
S8	0.033293	0.029561	0.875	0.028853	0.033293
S9	1.00E−05	1.00E−05	0.99996	1.00E−05	1.00E−05
T = 10					
T-SFWZIC	0.200641789	0.182048978	0.236408168	0.180259275	0.200641789
S1	0.262761	0.238411	2.22E−16	0.236068	0.262761
S2	0.229915	0.20861	0.125	0.206559	0.229915
S3	0.19707	0.178809	0.25	0.177051	0.19707
S4	0.164225	0.149007	0.375	0.147542	0.164225
S5	0.13138	0.119206	0.5	0.118034	0.13138
S6	0.098535	0.089404	0.625	0.088525	0.098535
S7	0.06569	0.059603	0.75	0.059017	0.06569
S8	0.032845	0.029801	0.875	0.029508	0.032845
S9	1.00E−05	1.00E−05	0.99996	1.00E−05	1.00E−05

Based on Table 14, these ninth new weight values for each T value are employed to assess the sensitivity of the 300 vaccine recipients' prioritisation towards changing criteria weights. The aim is to determine how target T-SFWZIC weights are affected based on changes for the nine scenarios for each T value. Figure 2 illustrated the influences of changing the criteria weight over the first 10 ranks only for T = 2. Figures A1, A2, A3 and A4 in the Appendix illustrate the influences of changing the criteria weight over the first 10 ranks of T = 4, T = 6, T = 8 and T = 10, respectively. Incontrovertibly, the criteria weights play a vital role in changing the priority of each vaccine recipient; these nine-scenario results for all T values support the research assertion about the significant contribution of these five criteria. Notably, although this change is logical and likely, maintaining the results in most of the nine scenarios proved the efficiency of the proposed integration methods in handling such sensitive cases with a large-scale dataset and producing supportive results for the outcomes of systematic ranking.

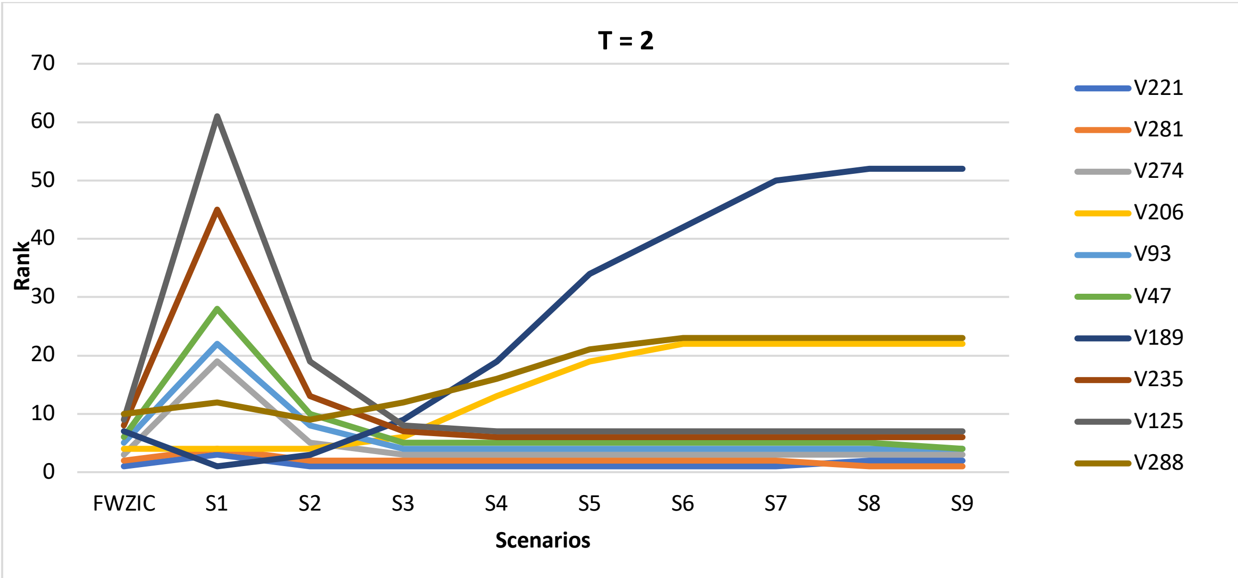

Figure 2: Sensitivity analysis of first 10 vaccine receipts ranks in nine scenarios (T = 2).

Based on sensitively analysis results visualised in Figures 2, A1, A2, A3 and A4, the new ranking results obtained based on ninth scenario weights for all T values need to be compared with previous ranking results obtained based on T-SFWZIC weights (Table 7 shows the weights). The sensitive analysis comparisons can be discussed from two points of view as follows:

(A) ***Effectiveness of the first three ranks***: the comparison with respect to the first three ranking alternatives needs to be discussed because those vaccine recipients received important orders. For T = 2, scenarios S3, S4, S5, S6 and S7 have the same ranking results as T-SFWZIC which are obtained by the first three alternatives (V221, V281 and V274), whereas other scenarios (S1, S2, S8 and S9) were relatively different. For T = 4, T = 6 and T = 8, scenarios S3 to S9 have the same ranking results as T-SFWZIC, which are obtained by the first three alternatives (V221, V281 and V274), whereas only scenarios S1 and S2 were relatively different. For T = 10, only scenarios S3 to S7 have the same ranking results as T-SFWZIC, which is obtained by the first three alternatives (V221, V281 and V274), whereas only scenarios S1 and S2 were relatively different. When comparing the above new results with the first three ranks that were obtained from T-SFWZIC weights, the results revealed that no big differences exist that have been changing the first three ranking results for the sensitively of T values. However, the first three ranks cannot provide the full sensitive analyses for the overall changes that occurred in the ranking results. Therefore, the overall effect should be discussed.

(B) ***Effectiveness of overall ranks:*** after reviewing the overall ranking results, we found that the changing behaviour of the nine scenarios with respect to each T value has widely occurred. Moreover, how exactly the overall new ranking results are affecting the previous ranking results obtained from T-SFWZIC weights should be measured. We can measure this effectiveness by calculating the changing occurred in the orders between both ranks, and then, we calculate the changing percentage between both ranking orders. In other words, for example, for T = 2, the number of changes that occurred in the ranking orders obtained from T-SFWZIC weights after applying S1 weights is 296 (98.67%), whereas only four orders are not changed and have the same orders. Table 15 explains the overall effectiveness analyses that occurred on the ranking results between the ninth scenario and T-SFWZIC weights.

Table 15: Overall effectiveness (percentages %) between ranks of ninth scenario and T-SFWZIC weights

	Scenarios	T = 2	T = 4	T = 6	T = 8	T = 10
Changing percentage (%) in rank towards T-SFWZIC	S1	98.67%	98.33%	99.33%	98.67%	98.67%
	S2	85.33%	92.67%	92.67%	89.00%	85.33%
	S3	68.33%	62.67%	52.67%	51.67%	68.33%
	S4	91.33%	90.67%	92.00%	87.67%	91.33%
	S5	92.00%	92.33%	92.00%	92.33%	92.00%
	S6	92.67%	92.33%	92.00%	92.00%	92.67%

S7	92.67%	91.67%	91.33%	91.67%	92.67%
S8	93.33%	91.67%	91.33%	91.67%	93.33%
S9	93.33%	91.67%	92.00%	90.00%	93.33%
mean	89.74%	89.33%	88.37%	87.19%	89.74%

Table 15 presents the final sensitive analyses for all scenarios with respect to all T values. The highest mean value is obtained by T = 2 and T = 10 (89.74%). The lowest mean value is obtained by T = 8 (87.19%). These interesting results indicate that the rank stability is almost highly sensitive with all T values, and then, ranking obtained by T-SFWZIC weight is affected by the nine scenarios. Surely, these widely changing results in the weights numbers are defiantly changing the overall ranking results. This concept is already reported and considered one of the four MCDM issues which is '*important criteria*'. If we reviewed these issue concepts, then we can realise that the '*important criteria*' has been sensitively recognised and proven here for the presented study which is vaccine distribution. At this step, sensitivity analysis is conducted to investigate the priority ranking stability; however, the sensitivity of the priority ranks of T values for the nine scenarios is influenced by the criteria weights changing. Furthermore, the overall rank for all vaccine recipients changed except for some priority ranks (the first three ranks). This fact is probably caused by some important issues of criteria importance and has been demonstrated for T-SFWZIC weights.

Finally, the Spearman correlation coefficient (SCC) was employed to evaluate the relationship between the results of the 15 scenarios statistically [102]. Figure 3 shows the high-level correlation amongst the nine scenarios for all 300 vaccine recipients for T = 2. Figures A5, A6, A7 and A8 shows the remaining correlations for other T values.

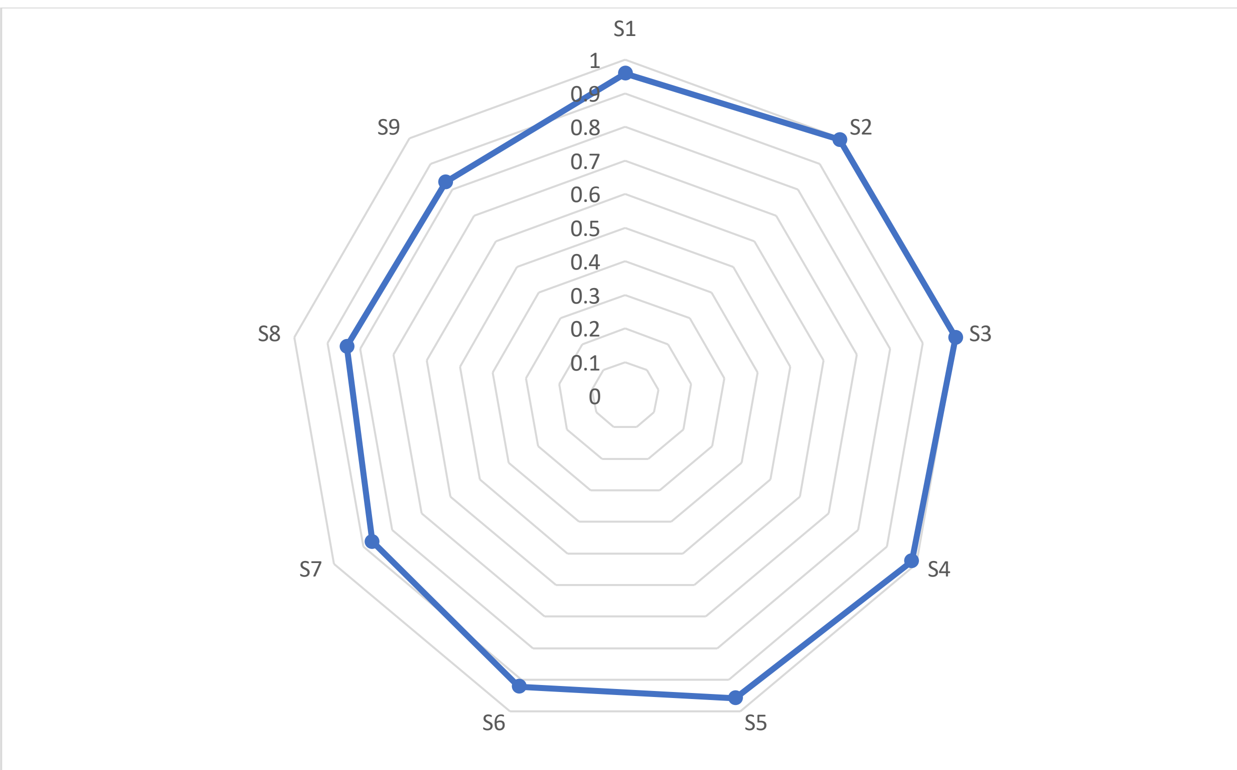

Figure 3: Correlation of ranks among nine scenarios for all 300 vaccine recipients for T = 2.

Figure 3 illustrates the correlation analysis results for the vaccine recipients' ranking for the nine scenarios, according to the obtained correlation values for T = 2. A high correlation of ranks is observed in all scenarios. For scenarios S1 to S6, the SCC values were approximately 0.9, whereas, in other scenarios (S7 to S9), the SCC results were approximately 0.8 with a mean value of 0.929 for all scenarios. In the same context results, for T = 4 and T = 6, the first six scenarios obtained SCC values approximately 0.9 with the remaining obtained approximately 0.8 with mean values of 0.934 and 0.936, respectively, for all scenarios. For T = 8 and T = 10, the first seven scenarios obtained SCC

values approximately 0.9 with the remaining obtained SCC approximately 0.8 with mean values of 0.938 and 0.940, respectively, for all scenarios.
In conclusion, the high SCC mean value corresponds to T = 10 (0.940); however, all the T values are relatively similar to one another based on correlation analyses. Thus, this high correlation value indicates a significant correlation of the rank outcomes, which in turn supports the systematic ranking results amongst T values.

5. Conclusion

This study contributes to the body of knowledge of the MCDM methods by proposing new formulations of FWZIC and FDOSM based on the T-SFSs environment. The reason for such formulations was to perform both methods with no restrictions on their constants and obtain more degree of freedom in handling the uncertainty in the data. To achieve the study objective, the proposed methodology was presented in two phases, namely, decision matrix adoption and development (Figure 1). The result was an inductive methodology based on the detailed weighting and prioritisation steps presented within each MCDM method. The evaluation process was performed based on systematic ranking and sensitivity analyses, which proved the robustness of the proposed work. Notably, the sensitivity analysis results show that the weight importance posts a considerable issue for the distribution of the COVID-19 vaccine. Thus, assigning the importance weights for the distribution criteria used in the prioritisation of vaccine recipients is very important. However, this study has two main limitations. Firstly, T-SFWZIC and T-SFDOSM methods were formulated considering only one T-SFSs aggregation operator in addition to using one defuzzification technique only to produce the final weighting and ranking results. Secondly, the importance measurement reflected on each DM’s preferences was not considered in the proposed methods. Several future directions can be achieved as follows: (1) Presenting and processing a large-scale dataset of COVID-19 vaccine recipients considering all probabilities frequently augmented for each alternative and distribution criteria. (2) Performing the proposed MCDM methods based on two levels: firstly, each vaccine recipient membership will be prioritised, and secondly, each alternative within each membership will be prioritised followed by accumulating them effectively. (3) Several fuzzy types, such as interval type-2 hesitant [103], intuitionistic and interval-valued [104] and neutrosophic [102], can be adopted in the FDOSM and/or FWZIC to effectively overcome the uncertainty limitation.

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