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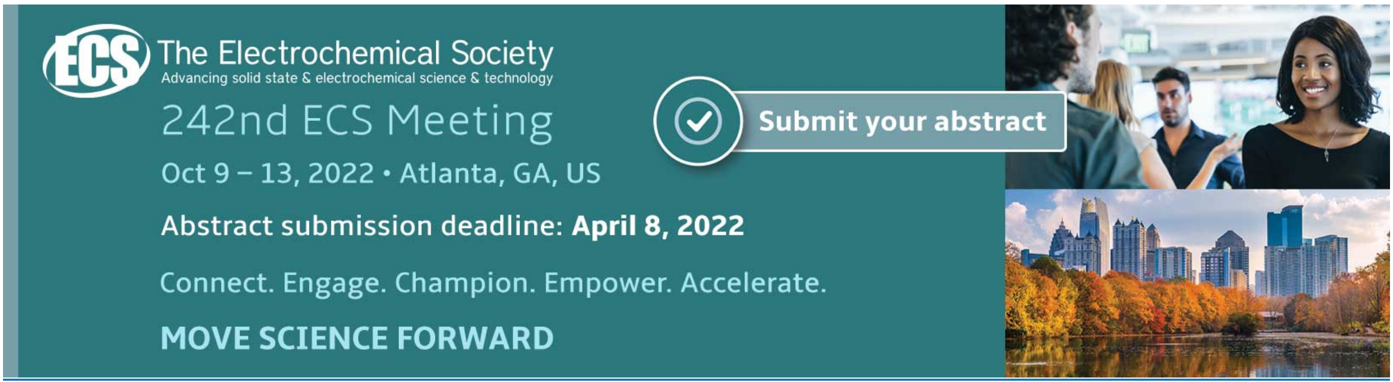

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Multiple Criteria Decision Analysis under uncertainty in sustainable construction: a neutrosophic modified best-worst method

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Abstract. Capturing uncertainty in multiple criteria decision analysis (MCDA) is not a new theme but a largely developing topic which is in close connection with uncertainty theories such as fuzzy set and grey systems theories. Due to growing complexity of construction processes mainly because of implementation of sustainability aspects it would be necessary to take advantage of a novel MCDA methodology as an efficient tool to handle the uncertainty in sustainable construction decision making. In this study, we utilise a novel neutrosophic modified best-worst method (NM-BWM) to deal with the uncertainty in decision making in the context of sustainable construction. The method is an integration of neutrosophic set theory (NST) and the modified best-worst method (M-BWM). The NST can provide insights on efficient uncertainty handling of decision makers (DMs) subjective judgements. The BWM is a MCDA method which utilises two vectors of pairwise comparisons (the best criterion to others and others to the worst criterion) to obtain the weights of evaluation criteria. Merits of the BWM include its capability in effectively remedying the inconsistency derived from pairwise comparisons as well as simplicity and less pairwise comparisons compared to other similar methods like analytic hierarchy process (AHP). We show the applicability of the method in a case study with focus on the implementation of sustainable construction.

1. Introduction

The way of thinking in simple logical contexts often leads to overlooking medium- or long-term effects on our immediate environment. Contrary to the objectives of sustainable development, future generations are endangered [1]. The drastic situation of climate change, as well as the increased number of storms, floods, droughts and forest fires, is thus rather due to the actions of mankind in the seventies [2]. As a result, climate protection and disaster control represent increasingly complex challenges for architects and engineers. Sustainable construction is the buzzword at the centre of this development. In order to deal with complex systems and the associated inherent dynamics of the system ”building”, systemic thinking is indispensable [3],[4].

The following article addresses the implementation of sustainability aspects in the early design stage of buildings. With a variety of criteria to consider, the tasks for architects are becoming increasingly complex. The human brain is not able to assess the effects of changes in one factor on more than four interrelated influencing factors [5]. In particular, medium- and long-term effects cannot be assessed without tools for such a large number of related factors. Construction projects exceed this number of interacting criteria by a multitude. One approach to make the complexity of numerous influential criteria manageable are multiple criteria decision making (MCDM) methods.

In the present article the application of a neutrosophic modified best-worst method (NM-BWM) is discussed in order to facilitate and thus advance the implementation of sustainability aspects in the early design stage of buildings - in which numerous non-quantifiable factors and multipe decision makers (DMs) are present. In real-world decision-making environment, there is an uncertainty in DMs opinions which cannot be dealt with properly in the original BWM. In the original BWM, two vectors of pairwise comparisons including best-to-others and others-to-worst vectors are treated with the same level of importance. The NM-BWM can help overcome this shortcoming by incorporating the NST into the original BWM in order to capture the uncertainty of DMs on two vectors. The NST has two main advantages over other similar uncertainty theories like fuzzy set theory; firstly, the information about rejection has effectively quantified in the NST and secondly it has the capability to independently quantify the indeterminacy membership, which adds an extra level of suitability to it for structuring DMs' confidence value acquisition process [6].

2. Literature Background

In this section the literature background of applied methods is described. It includes the subsections sustainability assessment in construction industry (2.1), multi attribute decision making in construction industry (2.2), best-worst method (2.3) and neutrosophic set theory (2.4).

2.1. Sustainability Assessment in Construction Industry

Due to the uniqueness of each individual building, planning according to recurring procedures and processes is not feasible. In addition to the complexity of a building, which is already given by static and physical building requirements, the design process is increased by sustainability requirements. Through standards harmonized at the European level (hEN) and through numerous normative and voluntary instruments - e.g. ISO 14000 series of standards "Environmental management" [7], [8] the implementation of sustainable construction is being promoted. In 2008, the ISO 15392 "Sustainability in building construction - General principles" [9] created a uniform understanding of sustainability in the construction industry [10]. According to the European framework of CEN/TC 350 next to the three classical dimensions of sustainability - environmental dimension, economic dimension and social dimension - additionally functional and technical qualities have to be considered within the sustainability assessment of buildings [11], [12], [13], [14]. Due to the multi criteria interdependencies of sustainability criteria, holistic consideration can only be achieved by a complete set of criteria [15]. Numerous building certification systems (BREAAM[1], LEED[2], DGNB[3], etc.) have already developed complete criteria catalogues for the sustainability assessment of buildings and are suitable for the assessment of the building performance [16]. The implementation of sustainable construction is a multidimensional concept that is gaining relevance in all areas of society [17]. Barbier states that sustainable development involves the simultaneous maximization of environmental, economic and social system goals [18]. However, as Munda has shown, it is generally not possible to maximize different goals at the same time. Therefore, a compromise should be found between different objectives, which can be achieved by applying MCDM methods [19]. The current challenges in the operationalization of holistic design and construction processes are mainly based on imprecise stakeholder requirements and the current lack of suitable methods for controlling life-cycle processes [20].

2.2. Multi Attribute Decision Making (MADM) in Construction Industry

Multiple attribute decision making (MADM) or multiple criteria decision aiding (MCDA) have been increasingly popular in various decision-making fields [49], [50]. For instance, Wang et al. [21] indicated this popularity in sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems.

In the course of the literature search numerous articles using MADM-methods for the different application in construction industry were found [22]. Already when selecting materials, decision makers have to consider numerous factors (mechanical properties, physical properties, material costs, durability, etc.). A model for the selection of building materials that weights criteria based on the three-pillar sustainability approach was proposed by Akadiri [23]. According to Jahan et al., MADM-methods such as TOPSIS, ELECTRE and AHP are the most frequently used methods in the course of material selection [24]. MADM-methods are also used for the selection of construction machinery. Temiz & Calis investigated the correct selection of an excavation machine for a construction site and compared the methods AHP and PROMETHEE [25]. For the selection of cranes Skibniewski & Chao investigated the application of AHP already in 1992 [26]. In addition, MADM-methods are also applied in the selection of concrete pumps [27]. A further field of application of MADM-methods are transport and logistics. Machharis & Bernardini investigated the application of multi criteria decision methods in transport projects [28]. According to Turcksin et al. the most frequently applied

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[1] https://www.breeam.com

[2] https://new.usgbc.org/leed

[3] https://www.dgnb-system.de/de/system/zertifizierungssystem/index.php

decision methods in transport projects are MADM methods (AHP, ANP, MAUT, MAVT), outranking methods (PROMETHEE, ELECTRE) and regime analyses [29]. MADM-methods are also widely used in the field of logistics. Tuzkaya investigated the impact of transport processes on the environment, Wang & Chang applied MADM-methods in the field of green urban logistics or Moghaddam et. al in the field of clean energy for energy efficient buildings [30], [31], [32]. Within environmental topics MADM-methods were used in waste management, energy management, waste water treatment, water quality or air quality [33]. One method developed very late in the history of MCDM and rarely applied in the field of sustainable construction until now is the best-worst method (BWM).

2.3. Best-Worst Method (BWM)

In the field of construction industry BWM was applied in piping selection [34] and in areas of risk assessment [35], [36]. The BWM can help DMs in defining the weights of criteria in a decision-making problem. In BWM, firstly the best criterion (i.e. the most favourable) and the worst criterion (i.e. the least favourable) must be determined by the DM. Secondly, pairwise comparisons are carried out between each of the two criteria (i.e. best and worst) and other criteria. Then, weights of criteria are determined by solving a mathematical model. The simplicity of use, less number of pairwise comparisons and more consistent comparisons compared to other similar methods like AHP have made BWM a reliable method.

2.4. Neutrosophic set theory (NST)

Atanassov [38] introduced intuitionistic fuzzy sets (IFSs) as an extension of the well-known fuzzy set theory of Zadeh [39] to overcome its drawbacks by providing non-membership degree [40]. Smarandache generalised the IFS into the neutrosophic set (NS) to show insights on a more efficient DMs subjective judgements uncertainty handling [41]. It shows fuzzy information utilising the functions of truth, indeterminacy and falsity like IFSs. The distinction between NSs and IFSs is that the function of indeterminacy in NSs is independent of truth and falsity functions [42]. However, application of NSs in practical problems had been challenging because values of truth, indeterminacy and falsity functions were within]0-,1+[[42],[43]. To deal with this issue, Wang et al. [21] introduced single-valued neutrosophic sets (SVNSs) where truth, indeterminacy and falsity functions are real elements of [0,1] [42]. A single-valued trapezoidal neutrosophic number (SVTNN) is also considered as a generalisation of intuitionistic numbers. Recently, SVNSs has received increased attention by researchers from various fields of decision making.

In detail, in this article, the modification of BWM in combination with NST is applied which is called NM-BWM. The applied method is called neutrosophic modified best-worst method (NM-BWM). A decisive question in the selection of the appropriate MCDM method is the handling of uncertainties in the course of the evaluation. In the literature several approaches for the explicit consideration of uncertainties in MCDM methods are outlined which shows the importance of this topic. For mathematical basic definitions of the NST refer to [41].

3. The Neutrosophic Modified BWM (NM-BWM)

The original BWM is described in [37], [44] which follows a five-step approach, while the applied NM-BWM has two additional steps explained in [6]:

(i) DM's Uncertain Confidence on the Best-to-others Preferences
The neutrosophic value of the DM's confidence on the best-to-others preferences (ρ^{+}) is a SVTNN (Table 1). It reveals the degree of DM's confidence on best to-others vector.

Table 1: The confidence rating scale

Linguistic Phrase	**Score**	**SVTNN**	**Crisp Value**
No Confidence	0	$\langle(0.0,0.0,0.0,0.0),0.0,0.0,0.0\rangle$	0.00
Low Confidence	1	$\langle(0.2,0.3,0.4,0.5),0.6,0.2,0.2\rangle$	0.26
Fairly Low Confidence	2	$\langle(0.3,0.4,0.5,0.6),0.7,0.1,0.1\rangle$	0.38
Medium Confidence	3	$\langle(0.4,0.5,0.6,0.7),0.8,0.0,0.1\rangle$	0.50
Fairly High Confidence	4	$\langle(0.7,0.8,0.9,1.0),0.8,0.2,0.2\rangle$	0.68
High Confidence	5	$\langle(1.0,1.0,1.0,1.0),0.9,0.1,0.1\rangle$	0.90
Absolutely High Confidence	6	$\langle(1.0,1.0,1.0,1.0),1.0,0.0,0.0\rangle$	1.00

(ii) DM's Uncertain Confidence on Others-to-worst Preferences
The neutrosophic value of the DM's confidence on the others-to-worst preferences (ρ^-) is a SVTNN (Table 1). It reveals the degree of DM's confidence on others-to-worst vector.
Finally, by solving model (1) the optimal weights of criteria are achieved.

$$\begin{array}{lrcll} \min & \varepsilon\left(\frac{\rho^-+\rho^+}{\rho^-\rho^+}\right) & & & \\ \text{s.t.} & & & & \\ & \frac{W_B}{W_j}-\frac{\varepsilon}{\rho^+} & \leq & a_{Bj} & \forall j\in N \\ & \frac{W_B}{W_j}+\frac{\varepsilon}{\rho^+} & \geq & a_{Bj} & \forall j\in N \\ & \frac{W_j}{W_W}-\frac{\varepsilon}{\rho^-} & \leq & a_{jW} & \forall j\in N \\ & \frac{W_j}{W_W}+\frac{\varepsilon}{\rho^-} & \geq & a_{jW} & \forall j\in N \\ & \sum_j W_j & = & 1 & \\ & W_j & \geq & 0 & \forall j\in N \end{array} \tag{1}$$

4. Case Study

For a first application of the new developed NM-BWM in early design stages of buildings a case study was conducted. The interaction of building components, technical equipment and materials is of crucial importance for the sustainable performance of a building. An important step in early, sustainability-oriented design is the support for the selection of building components that fulfill all requirements of the involved DMs right from the beginning of a construction project. In the course of the case study, the developed NM-BWM approach is tested based on the decision problem "window selection".

4.1. Decision Problem

Window properties - i.e. aesthetics, size, position, relationship between transparent and opaque areas, frame, glazing - have a large impact on the building performance [48]. It is well known that a well-designed and constructed window must perform a number of functions - e.g. sun protection, glare protection, ventilation options, protection against the weather, sound insulation or burglary protection - simultaneously, which can lead to trade-offs in the design stage. Since the focus is on the application of the newly developed NM-BWM method, 8 window types and 6 criteria were selected to define the decision matrix.

4.1.1. Window Types (A1-A8)

In the applied case study a window type consists out of the frame and the glazing. The chosen frame types were timber frames, PVC-frames, aluminium frames and timber-aluminium frames. The glazing distinguishes between double glazing and triple glazing.

Table 2: Selection of window types

	Frame	Glass
A1	Timber	Double glazing
A2	Timber	Triple glazing
A3	PVC	Double glazing
A4	PVC	Triple glazing
A5	Aluminium	Double glazing
A6	Aluminium	Triple glazing
A7	Timber - Aluminium	Double glazing
A8	Timber - Aluminium	Triple glazing

4.1.2. Criteria (C1-C6)

Window selection decision can affect many other criteria. In our study, the identified criteria are exemplary and have been derived from the building certification system DGNB[4]. Regarding the literature, [47] has also analysed 6 exemplary criteria.

(i) **Global Warming Potential (C1) - [$kgCO_2 - eq.$]**
In all phases of their life cycle, buildings cause emissions. The objective of life cycle assessment is to gain information about the total life cycle, to reduce buildings emissions throughout their entire life as much as possible. The measurement of the indicator Global Warming Potential (GWP) happens in kg CO_2 - equivalents. To calculate the CO_2 - potential the EcoInvent V3.3 database[5] was used. The impact assessment was carried out with the EPD2013 method implemented in SimaPro[6]. For the life cycle assessment according to ÖNORM EN 15978 [44], in the case study, the modules A1-A3 were considered only.

(ii) **Initial Construction Cost (C2) - [€]**
All stages in the life cycle of a building generate costs: Construction, Operation, Maintenance and End-of-life [45]. From an economic view, the aim is therefore to minimise the buildings total life cycle costs (LCC). The quality of windows contributes to the building performance in terms of sociocultural and functional, technical, environmental as well as economic qualities. Therefore, out of a holistic sustainability perspective, the initial construction cost for windows must be considered. The costs for the chosen window types were calculated in [46].

(iii) **Sound Transmission (C3) - [dB]**
A minimum level of acoustic quality is necessary to ensure that a building can be used as intended, since the acoustic quality of the room is an important indicator of the comfort and satisfaction of its users. Windows with better sound insulation can contribute to an overall higher sound insulation of the whole building. The indicator for the measurement is the Rw value in dB. The Rw-values for the chosen window types were calculated in [46].

(iv) **Heat Transfer (C4) - [$W/(m^2K)$]**
Thermal comfort in buildings makes an essential contribution to an overall efficient working and living environment. The suitability of the indoor room climate depends on the temperature of the room, the temperature of the surfaces surrounding people, the air velocity in the room and also the relative air humidity in the cooling as well as in the heating period. Assessing the quality of the building envelope in terms of temperature and humidity requires an evaluation of the individual requirements for each of its components. For the measurement in this study, the Uw value of windows (frame+glass) was taken into account. The U-values for the chosen window types were calculated in [46].

(v) **Installation Time (C5) - [h]**
Construction time is a key indicator of the success of any project, as both construction costs and quality are strongly influenced by construction time. The time required to install each component thus contributes to the total construction time of a building. An indicator to characterise the installation time is the effort value. For the component window, the effort value is given as h/pc (hours per piece). The installation time for the chosen window types was calculated in [46].

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[4] https://www.dgnb-system.de/de/system/zertifizierungssystem/index.php
[5] https://www.ecoinvent.org/database/ecoinvent-33/ecoinvent-33.html
[6] https://simapro.com

(vi) **Recyclability (C6)**
The construction sector is one of the largest sources of material flows in the world. Construction accounts for almost 50 % of national waste. This criterion describes the recycling options for different window types according to the different materials. For the individual assessment, we use a qualitative evaluation scale such as *excellent recyclability* (1,0), *good recyclability* (1,5), *moderate recyclability* (2,0), *bad recyclability* (2,5), and *very bad recyclability* (3,0).

4.2. Decision Matrix

The decision matrix which shows the performance of each window type (A1-A8) under each criterion (C1-C6) is represented in Table 3.

Table 3: Decision matrix

	C1 [$kgCO_2 - eq.$]	**C2** [€]	**C3** [dB]	**C4** [$W/(m^2K)$]	**C5** [h]	**C6** [-]
A1	188	268	35	1,434	3,795	1
A2	227	336	37	1,159	3,795	1
A3	246	224	38	1,371	3,226	2
A4	366	290	40	1,096	3,226	2
A5	684	403	37	1,5	4,175	2
A6	723	448	38	1,229	4,175	2
A7	334	493	38	1,402	4,554	1,5
A8	373	672	36	1,128	4,554	1,5

4.3. Decision Makers Profile

To obtain the importance weights of criteria (C1-C6), eight DMs who were recognised with their high experience and knowledge in the field of sustainable construction have been asked to participate in the study. They have been contacted by email to provide their pairwise comparisons of 6 criteria using a scale of 1 (equally important) to 9 (extremely more important) based on the original BWM. The participated DMs profile along with their weights (as they were not equally experienced) is provided in Table 4.

Table 4: Decision makers profile and importances weights

	Years of Experience	**Education**	**Weights**
DM1	20	Below BSc	0,13
DM2	31	MSc	0,23
DM3	25	MSc	0,17
DM4	4	MSc	0,08
DM5	6	BSc	0,08
DM6	3	MSc	0,05
DM7	20	MSc	0,13
DM8	20	PhD	0,13

5. Results and Discussion

After obtaining the consistent pairwise comparison data of eight DMs (CR<0.1) then the NM-BWM has been applied and weights of six criteria (C1-C6) have been computed as shown in Table 5. The aggregated weight of each criterion based on obtained weights of eight DMs has been also calculated and revealed in Table 5.

Table 5: Aggregated criteria weights of decision makers

	DM1	**DM2**	**DM3**	**DM4**	**DM5**	**DM6**	**DM7**	**DM8**	**Aggregated Weights**
C1	0,2000	0,3214	0,5217	0,2414	0,2258	0,2060	0,2500	0,2738	0,3044
C2	0,2286	0,1607	0,0580	0,1034	0,2258	0,2698	0,0417	0,1788	0,1450
C3	0,1714	0,0357	0,0580	0,1724	0,1613	0,5151	0,2083	0,0604	0,1277
C4	0,2000	0,3214	0,1739	0,2414	0,1613	0,1714	0,2083	0,1788	0,2206
C5	0,0286	0,0536	0,0580	0,3448	0,3226	0,1349	0,0417	0,0323	0,0957
C6	0,1714	0,1071	0,1304	0,2069	0,1935	0,1663	0,2500	0,2758	0,1778

The decision matrix (Table 3) has been normalised knowing that all the six criteria are of cost nature meaning the lower value of them is better. The final normalised decision matrix has been represented in Table 6. Applying obtained weights of each criterion (C1-C6) shown in Table 5 and getting the weighted average of the normalised values in Table 6, the total weight of each window type (A1-A8) has been obtained as shown in Table 6.

Table 6: Normalised decision matrix and total weights of window types

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**Total Weights**	**Ranking**
A1	0,7400	0,6012	0,1250	0,0440	0,1667	0,5000	0,4429	2
A2	0,6860	0,5000	0,0750	0,2273	0,1667	0,5000	0,4459	1
A3	0,6598	0,6667	0,5000	0,0860	0,2916	0,0000	0,3508	3
A4	0,4938	0,5685	0,0000	0,2693	0,2916	0,0000	0,3201	4
A5	0,0539	0,4003	0,0750	0,0000	0,0832	0,0000	0,0920	8
A6	0,0000	0,3333	0,0500	0,1807	0,0832	0,0000	0,1025	7
A7	0,5380	0,2664	0,0500	0,0653	0,0000	0,2500	0,2676	5
A8	0,4841	0,0000	0,1000	0,2480	0,0000	0,2500	0,2593	6

Findings (Table 5) showed that based on involved DMs opinions, global warming potential (C1) is the most significant criterion in choosing the best window type. The other significant criteria are as follows respectively: heat transfer (C4), recyclability (C6), initial construction cost (C2), sound transmission (C3), and installation time (C5). The obtained two most important criteria highlight the significance of preserving the heat while providing thermal comfort (i.e. C4) and at the same time taking into consideration the global warming potential (i.e. C1).

The analysis of results (Table 6) revealed that the second window type (A2) with timber frame and triple-glazing is the best choice followed by A1 (timber frame and double-glazing), A3 (PVC frame and double-glazing), A4 (PVC frame and triple-glazing), A7 (timber-aluminium frame and double-glazing), A8 (timber-aluminium frame and triple-glazing), A6 (aluminium and triple-glazing) and A5 (aluminium and double-glazing) respectively. According to the high CO_2 - potential of the alumium frame (see Table 3) the findings are in line with DMs preferences.

6. Conclusion

In this study, a NM-BWM method was applied to capture uncertainty in the DMs opinions in order to obtain weights of criteria derived from the building certification system DGNB. The identified criteria are global warming potential (C1), initial construction cost (C2), sound transmission (C3), heat transfer (C4), installation time (C5) and recyclability (C6). The weights of criteria then used to reveal among a list of eight predefined window types (A1-A8) which ones can perform more/less appropriately in the early sustainable building decision-making process in terms of various six criteria. The analysed eight window types are A1 (timber frame and double-glazing), A2 (timber frame and triple-glazing), A3 (PVC frame and double-glazing), A4 (PVC frame and triple-glazing), A5 (aluminium frame and double-glazing), A6 (aluminium frame and triple-glazing), A7 (timber-aluminium frame and double-glazing) and A8 (timber-aluminium frame and triple-glazing).

The results confirmed that global warming potential (C1) is the most significant criterion in choosing the best window type while installation time (C5) is the least important one in that manner. Furthermore, A2 (timber frame and triple-glazing) is the best window-type choice under various six criteria and A5 (aluminium frame and double-glazing) is least proper one.

One of the limitations of this study which opens an avenue for future research directions is the partial incomprehensiveness of the derived criteria and explored window types. In future studies, researchers may take advantage of a more comprehensive list of criteria to investigate alternatives not only window type but also other components of sustainable buildings. The other shortcoming was a limited number of DMs or experts which can be increased in future investigations to improve the validity of the findings.

The application of MCDM methods in early design stages of buildings was identified as a research gap. Many different MCDA methods were applied for single issues within the field of sustainable construction - e.g. material selection, selection of energy systems, selection for waste management types, window selection - but not for the holistic design of a new building in early design stages. Reasons for that are the numerous criteria and the missing alternatives in the early design stage.

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