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PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1016/j.rser.2019.06.018>

PUBLISHER

© Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in the journal Renewable and Sustainable Energy Reviews and the definitive published version is available at <https://doi.org/10.1016/j.rser.2019.06.018>.

LICENCE

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REPOSITORY RECORD

Kokaraki, Nikoleta, Christina Hopfe, Elaine Robinson, and Elli Nikolaidou. 2019. "Testing the Reliability of Deterministic Multi-criteria Decision-making Methods Using Building Performance Simulation". figshare. <https://hdl.handle.net/2134/37958>.

Testing the reliability of deterministic multi-criteria decision-making methods using building performance simulation

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Abstract: The design of a building is a decision problem with multiple stakeholders and several often conflicting criteria. Multi-Criteria Decision-Making (MCDM) methods are capable of handling decision problems with the abovementioned specific features. This paper focuses on the application and comparison of some of the most well-known and widely applied MCDM methods; namely AHP, TOPSIS, ELECTRE III, and PROMETHEE II. For this purpose, a framework that incorporates the decision-makers' preferences and the use of dynamic simulation of the potential building forms is developed and applied to a real-life case study. This procedure provides a holistic approach through which the design team arrive at a more appropriate decision. The examined methods yield similar results, showing broad agreement on the top ten alternatives, amongst which the decision-makers can decide. In particular, the majority of the examined methods (all except TOPSIS) concluded with the same optimal solution, a situation that provides confidence in the final decision. Furthermore, an investigation of four "what-if" scenarios indicates that TOPSIS is the most sensitive method to the examined changes in the subjective preferences.

Keywords: Multi-criteria decision making; AHP; TOPSIS; PROMETHEE II; ELECTRE III; Building performance simulation

1. Introduction

The design of a building is a decision-making process, in which multiple criteria and different professional disciplines exist. For instance, during the design stage of a building, the criteria involved can be how energy efficient the building will be, the indoor living conditions, the CO₂ annual emission rate etc. These aspects have different importance for the interested parties. The professionals involved in the design of a building are amongst others: architect, building services engineer, consultants, client, construction lead, project lead, local authorities etc. The final decision must consider the aspirations of the interested parties that compose the design team, as well as, the chosen performance criteria. The performance criteria act as a common framework, through which the design team will evaluate the potential design alternatives. The RIBA Plan of Work 2013 organises the process of briefing, designing, constructing, maintaining, operating and using building projects into a number of key stages [1]. According to RIBA Plan of Work 2013, during Stage 2 (Concept Design), the initial concept design is produced in line with the requirements of the Initial Project Brief. The project team also develops, in parallel with the Concept Design, a number of Project Strategies. There are several approaches in order to generate an appropriate set of alternatives/ possible design solutions (strategies) e.g. the brainstorming process or the Delphi process (Andresen, 2000).

These alternatives are produced by the stakeholders and directly reflect their preferences. Therefore, there is a high connection between the alternatives and the selected criteria as the latter also directly involves the stakeholders' desires. Thus, the decision process is extremely complex and it needs to be as transparent as possible in order to allow professionals to achieve an integrated design approach.

It is widely acknowledged that the prediction of the building's behaviour using simulation is efficient for the mitigation of risk and potential challenges that the building will face in the future. With the advance of technology, practitioners can incorporate Building Performance Simulation (BPS) into the design process of the building. Analysis of the dynamic behaviour of the building in the early design stage using BPS is far more effective and economical than

solving challenges when the building is already constructed (use phase) [2]. Thus, the use of BPS can support the decisions throughout the design process. However, it is often used to verify compliance with regulations, rather than to inform decision-making and its effective integration within the decision-making process remains poorly documented in the literature ([3].

1.1 Introduction to Multi-Criteria decision-making (MCDM) techniques

Multi-Criteria Decision-Making (MCDM) techniques consider the design process in a holistic manner, as they embrace multi-disciplinary approaches and ensure that all the important aspects are taken into account. There exists a plethora of methods that can lead to a compromise solution and, for the choice of the most appropriate method, many aspects need to be considered. Since most of the key performance indicators in building design problems are numerical, criteria are usually quantitative, focusing on the technical and economic aspects of these decision problems. Such methods ignore qualitative variables, e.g. the interested parties' preferences, a situation that will be addressed in this study.

Several techniques have been developed, capable of solving the same multi-criteria decision problem. Each of these methods uses numeric techniques to help decision-makers choose among a discrete set of alternative decisions A_j [4]. For this case study, the chosen deterministic MCDM methods are widely applied in the literature for decision problems in the sustainability and building fields.

The AHP method is based on a hierarchical tree structure, with the first level of the hierarchy corresponding to the general purpose of the problem, the second level to the criteria and the third level to the alternatives. AHP allows stakeholders to rank the criteria and the alternatives by their importance through a pairwise comparison, using a scale of absolute judgments from 1 to 9 (1 corresponding to elements with equal importance and 9 corresponding to the highest order dominance of one element over another).

TOPSIS is developed by [5], based on the concept that the chosen alternative simultaneously has the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution in a multi-dimensional computing space. This positive ideal solution is the one that maximises the beneficial criteria (such as aesthetics) and minimises the non-beneficial criteria (such as cost). The opposite scenario correlates with the negative ideal solution.

PROMETHEE is a method that uses the outranking principle to rank alternatives. It performs a pairwise comparison of alternatives in order to rank them with respect to a number of criteria. For this purpose, the preference functions of the criteria along with their corresponding thresholds needed to be defined. Further detail can be found in [6]. It is up to the decision-makers to define these parameters, however, their choice may significantly change the result. For the application of PROMETHEE II, following the guidelines presented in [7], the level (type IV) and the linear (type V) preference functions were chosen for the qualitative and the quantitative criteria of this case study respectively. Both selected preference functions require the determination of the indifference threshold q and strict preference threshold p . The indifference threshold q_j is the largest deviation, which is considered as negligible by the

decision-maker while the strict preference threshold p_j is the smallest deviation, which is considered as sufficient to generate a full preference. Following the advised principles in the literature ([8]; [9]), equations (1) and (2), below, were used to derive the indifference threshold q_j and the preference threshold p_j .

$$q_j = 5\%(g_{max} - g_{min}) \quad (1)$$

$$p_j = 3q_j = 15\%(g_{max} - g_{min}) \quad (2)$$

where g_{max} and g_{min} are the maximum and the minimum performance of the examined alternatives respectively.

The ELECTRE technique, similarly to PROMETHEE, was introduced to handle outranking relations by pairwise comparisons among alternatives. To this end, the concordance and discordance indices, and threshold values are used. The index of global concordance C_{ik} represents the amount of evidence to support the concordance among all criteria, under the hypothesis that the alternative A_i outranks, or dominates, the alternative A_k ; the discordance index defines the counterpart [4]. The threshold values used in this application are the same as in the PROMETHEE II application. This is a logical assumption as the decision-makers and the examined criteria remain the same for the two applications (i.e. ELECTRE III and PROMETHEE II methods). In the ELECTRE III application, the veto threshold v_j needs to be defined as follows [8].

$$v_j = 3(g_{max} - g_{min}) \quad (3)$$

Table 1 The selected MCDM methods along with their principle and their origins

MCDM methods	Principle	Origin	Citation
AHP	Hierarchical decomposition of the decision process	T. L. Saaty, 1971-1975	[10]
TOPSIS	The optimal decision should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution	Hwang and Yoon, 1981	[5]
PROMETHEE	Outranking principle; introduction of preference functions that mimic the decision-makers' behaviour	Benayoun et al., 1966	[11]
PROMETHEE II		Roy, 1968	
ELECTRE	Outranking principle; introduction of pseudo-criteria	Brans, 1982	[12]
ELECTRE III		Vincke and Brans, 1985	

1.2 Review of multi-criteria decision-making protocols in the context of sustainability and energy

The first part of the literature reviewed was on single MCDM method application and it is summarised in Table 2 along with the design alternatives, criteria, and other tools or methodologies equipped. The second part of the literature review includes previous scientific papers that investigated the suitability of the MCDM in the context of the sustainability field. For this purpose, the authors applied multiple MCDM methods to the same study and compared the results regarding the suitability of the methods, the ease of their application etc.

Table 2 Single MCDM use in the context of the sustainability and energy field

CITATION	METHOD	GENERAL PURPOSE	OTHER TOOLS/ METHODOLOGIES USED	CRITERIA
[13]	AHP & TOPSIS	Improvement of the thermal and energy performance of a residential building.	Building simulation tool and uncertainty analysis	Thermal comfort and energy consumption.
[14]	AHP	Decision involves the choice between two HVAC system designs.	Building Performance simulation and uncertainty analysis	Initial costs, thermal comfort, individual control, design flexibility etc.
[15]	AHP	Five refurbishment concepts were assessed by experts.		Energy savings, service cost saving, total investment, payback period and heat loss per building volume.
[16]	AHP	Four different passive house constructions types were investigated.		Economic, environmental and well-being criteria, each consisting of five sub-criteria (Qualitative such as aesthetics and quantitative such as embodied energy).
[17]	AHP	The selection of glazing alternatives for an office building in New Delhi, India incorporating experts' preferences.	Using data from the 3-dimensional daylighting analysis of the examined office space	Energy efficiency, upfront cost, embodied energy.

[18]	AHP	Evaluation of three building forms whilst incorporating stakeholders' preferences	Building Performance simulation and sensitivity analysis	Quantitative (energy consumption, thermal comfort..) and qualitative (building form) criteria
[19]	AHP	Experts from different academic fields assigned weights to a number of performance-risk indicators		The areas investigated were: i) functional ii) technical and iii) indoor environmental performance.
[20]	AHP	Comparison of four alternatives for energy infrastructure revitalization, such as the integration of solar technologies.		Achievement of the social, economic and environment goals, involvement of all professionals in energy activities etc.
[21]	AHP	The energy performance of various lighting systems and control strategies applied in open-plan offices were investigated.	using the specialized lighting simulation software Ecotect and Daysim.	Five indicators such as glare, general satisfaction level, color rendering etc.
[22]	ANP	Developed a way of decomposing the problem of building energy retrofits under the EPC mechanism into a network relationship	utilised the SuperDecision software that implements the ANP method	No criteria used. It was a preliminary analysis of how to structure the problem
[23]	ANP	Proposed a model for driving managers in the selection of key performance indicators (KPIs)		Relevance, reliability, comparability and understandability of the KPIs
[24]	PROMETHEE II	The ranking of 13 different options of southern orientated shading devices for integrating PV systems on them.	Simulation and Sensitivity analysis	Quantitative (PV panels' energy production) and qualitative (glare, aesthetics) criteria.
[25]	PROMETHEE II	The assessment of four different energy policy alternatives for the region of Crete.		Techno-economic, environmental and social criteria that include seven sub-criteria as overall.
[26]	PROMETHEE II	Evaluation of four renewable energy projects concerning the exploitation of a geothermal		Both quantitative (energy saved, return of investment) and qualitative, including entrepreneurial risk of

		resource.		investment.
[27]	ELECTRE III	Study of the most suitable renewable energy sources (solar thermal system, geothermal heat pump etc.) for a residential house.	Sensitivity analysis	Primary energy savings, payback time and CO ₂ emission reduction.
[28]	ELECTRE III	Ranking of office building retrofitting strategies.	numerical simulations with different specific computer programs	Annual energy use for heating, annual CO ₂ emissions, renovation costs (investment) among others.
[29]	ELECTRE II	The analysis of indoor air quality of an air-conditioned environment.	Experimental results	Thermal, acoustic comfort and indoor air distribution
[30]	ELECTRE III	Assessment of six HVAC systems.	Building performance simulation and Sensitivity analysis	Economic, energy, and environmental criteria as well as criteria of users' satisfaction.
[31]	ELECTRE III	To evaluate six architectural solutions with specific focus on the windows configuration.	Building performance simulation software Daysim 3.1 and Sensitivity analysis	The occupants' visual comfort (landscape view and daylight level on work plan) and the energy efficiency.
[32]	ELECTRE family	To determine the most suitable ventilation strategy during summer.	Simulation using TRNSYS code	Indoor air quality, thermal comfort and energy consumption.
[33]	TOPSIS & MAUT	To aid GB (Green Building) consultants in the selection of appropriate GB certification credits that are more likely to be fulfilled		Wastes in time and cost both in design and construction phases of a GB project delivery process
[34]	TOPSIS	To determine the best vertical addition to masonry buildings.	Numerical simulation programme based on linear dynamic analyses	Structural, environmental and economic performance parameters.
[35]	TOPSIS	The development of a methodology that integrates BIM with TOPSIS to aid the design team decide	BIM tool	environmental factors, economic factors and social well-being.

Table 3 includes all the results from literature that incorporated the use of BPS and the inclusion of subjective preferences.

Salminen et al. (1998) [36] applied MCDM methods in the context of environmental problems. They concluded that when it is possible, one should use more than one method for the same problem in order to gain confidence in the results. When that is not possible, the authors recommend ELECTRE III as the most suitable method among three techniques (SMART and PROMETHEE). Caterino et al. (2008) [37] investigated the applicability and effectiveness of four decision-making methods; ELECTRE, PROMETHEE I and II, VIKOR and TOPSIS in the context of seismic retrofit alternatives. They found that in ELECTRE, the decision-makers must fix some parameters that have a strong influence on the results and there is a scarcity of rational criteria for the setup of these parameters. For the above reasons, the authors do not suggest the ELECTRE method as a preferable tool to solve the decision task under examination. Furthermore, PROMETHEE II allows a complete ranking of options, but it requires a manipulation of the available information that not always has a logical meaning. According to Caterino et al. (2008) [37], the TOPSIS and VIKOR methods, among those considered, seem to be the most suitable for the examined decision problem. Selmi et al. (2013)[38] applied different MCDM methods, namely ELECTRE III, PROMETHEE I and II, TOPSIS, AHP and PEG to a case study concerned with seismic structural retrofitting of a reinforced concrete (RC) building. It was found that the application of ELECTRE III, PROMETHEE and AHP methods leads to the same best compromise design. Some difference is noted, however, for TOPSIS and PEG methods.

Further, Selmi et al. (2016) [39] applied the aforementioned criteria to another case study. Their use resulted in different Pareto-compromise designs and rankings, which vary more as the number of the considered conflicting criteria increases.

Tscheikner-Gratl et al. (2017) [40] analysed whether the application of multiple deterministic MCDM methods leads to different prioritization in an integrated rehabilitation management scheme for a real-world case. They concluded that for the examined case study with limited data, simple methods such as the AHP gave results similar to the ones obtained with the complex outranking method PROMETHEE III. For larger datasets with more influencing factors with better data quality, a more sophisticated method (PROMETHEE III, ELECTRE III, TOPSIS) will provide valuable results. Gilliams et al. (2005) [41] compared three common MCDM techniques to help decision makers choose among the afforestation strategies for a given class of agricultural land. They found that end users could have confidence in the solutions because the variation of the examined MCDM protocols was rather small. Furthermore, PROMETHEE II was slightly preferable to both ELECTRE III and AHP based on user-friendliness, the simplicity of the

model strategy, variation of the solution, and implementation. Karni et al. (1990) [42] concluded that ELECTRE, AHP and Simple Additive Weighting (SAW) rankings did not differ significantly when applied to three real-life case studies. The Weighted Linear Assignment Method (WLAM) ranking deviates from those obtained by the above-mentioned MCDM methods.

Zanakis et al. (1998) [43] compared eight MCDM protocols, namely ELECTRE, TOPSIS, Multiplicative Exponential Weighting (MEW), Simple Additive Weighting (SAW) and four versions of AHP under a different number of alternatives, criteria, and distributions. In general, all AHP versions behave similarly and closer to SAW than the other methods. ELECTRE is the least similar to SAW. TOPSIS behaves closer to AHP and differently from ELECTRE and MEW, except for problems with few criteria. Mela et al. (2012) [44] conducted a comparative analysis of six MCDM methods (WSM, WPM, VIKOR, TOPSIS, PROMETHEE II, PEG) in the context of building design. The three examined case studies are namely: optimisation of an office building, a hall building, and a single-family residential house. The two main findings were that (1) in most cases, different methods yield different solutions and (2) there is no single “best” method. Kolios et al. (2016) [45] conducted a comparative analysis among well-known and widely-applied methods in MCDM, namely WSM, WPM, AHP, TOPSIS, ELECTRE I and PROMETHEE I, when applied to the reference problem of the selection of wind turbine support structures for a given deployment location. The outcomes of this research highlight that TOPSIS and PROMETHEE better predict the optimum design alternative.

In many cases, different methods do not necessarily recommend the same optimal solution to the same problem which adds to the confusion concerning which method to choose for a particular type of problem [46].

The main finding of the above papers is that different multiple criteria methods may yield different ranking of the examined alternatives ([44], [40]). Since there is no single method that can be described as the most suitable, the use of more than one method can enhance confidence and reliability of the rankings ([47], [36], [40]). In addition, the authors avoid preferring one method over another since such a statement would require either solid theoretical rationale or comparison on a large number of cases with actual decision-makers [44].

Table 3 includes a distinction of the reviewed literature as regards the application of the MCDM methods along with the use of a building performance simulation software and/ or the incorporation of the decision-makers’ subjective judgments. Most of these papers incorporate the decision-makers’ subjective preferences with the use of questionnaires [22], workshops and meetings [48] etc. or with the prediction of their possible behaviour [18]. Building performance simulation tools were rarely equipped to provide information on the performance criteria. In particular, in eleven reviewed papers, the use of BPS provided data on the building’s thermal behaviour [18], daylight performance [31] and ventilation performance using CFD modelling [49].

Table 3: Literature ranking according to the use of BPS and stakeholders' preferences

CITATION	METHOD(S)	USE OF BUILDING PERFORMANCE SIMULATION	INCORPORATES SUBJECTIVE PREFERENCES	CITATION	METHOD(S)	USE OF BUILDING PERFORMANCE SIMULATION	INCORPORATES SUBJECTIVE PREFERENCES
[14]	AHP	✓	✓	[22]	ANP		✓
[15]	AHP		✓	[23]	ANP		✓
[16]	AHP		✓	[33]	TOPSIS & MAUT		✓
[17]	AHP	✓	✓	[34]	TOPSIS	✓	
[18]	AHP	✓	✓	[35]	TOPSIS		
[19]	AHP		✓	[14]	AHP TOPSIS	✓	
[20]	AHP		✓	[36]	ELECTRE III PROMETHEE I & II SMART		✓
[21]	AHP	✓	✓	[37]	ELECTRE TOPSIS VIKOR PROMETHEE I & II		✓
[24]	PROMETHEE II	✓	✓	[38]	ELECTRE III PROMETHEE I & II, TOPSIS, AHP, PEG		✓
[25]	PROMETHEE II		✓	[40]	ELECTRE III TOPSIS PROMETHEE III AHP, WSM		
[26]	PROMETHEE II		✓	[41]	ELECTRE III PROMETHEE II AHP		
[27]	ELECTRE III			[42]	ELECTRE AHP, SAW		✓
[28]	ELECTRE III	✓		[43]	ELECTRE, TOPSIS, WPM, WSM four versions of AHP		
[29]	ELECTRE II						
[30]	ELECTRE III	✓	✓	[44]	ELECTRE III PROMETHEE I & II, TOPSIS, AHP, PEG		✓
[31]	ELECTRE III	✓		[45]	WSM, WPM, AHP, TOPSIS, PROMETHEE I, ELECTRE I		✓
[32]	ELECTRE family	✓					

There has been limited research that incorporates the decision-makers' preferences and at the same time involves the use of Building Performance Simulation. In total, six scientific papers in the literature reviewed include both the experts' preferences and the use of a building simulation tool ([14], [17], [18], [21], [24], [30]). However, these papers only include the application of a single deterministic MCDM method. Furthermore, there is no excessive

literature on the decision process of the early stage building design. While criteria such as energy consumption, CO₂ emissions, and thermal comfort are used, BPS tools are scarcely equipped to inform decision-makers in the early building design stages.

Therefore, this paper aims to cover this literature gap and to investigate the degree of agreement and the suitability of some of the most widely applied deterministic MCDM methods, namely AHP, TOPSIS, ELECTRE III, and PROMETHEE II.

2. Methodology

The following section will explain the process of how different decision-making protocols have been compared using a real-world case study. This will be divided into the problem formulation, i.e. the different criteria that drove the decision problem. Then the framework of applying the protocols will be introduced. The building case study, as well as stakeholder and drivers, will be introduced.

2.1 Problem formulation, performance criteria and variables

In real-life building design procedures, several different disciplines are involved in the design stages. These professionals have their own distinct aspirations and preferences. For the design team of the examined case study, four key decision-makers were chosen: the architect, the client, the Findhorn community and the Passivhaus consultant. In this particular project, the community plays an important role in the decision-making process, as the building under investigation will be located at the entrance of the Findhorn Eco-village and it will serve as a visitors Centre. One of the requirements from the design brief was that the proposed Community Centre (or parts of it) complies with the Passivhaus standard and, therefore, an expert is required to act as the consultant throughout the process. It is worth mentioning that compromises are of vital importance, as, in most cases, there is no single design solution that all stakeholders perceive as optimal.

Establishing the performance criteria provides a common framework that the stakeholders can relate to when assessing design alternatives. Design alternatives with different characteristics are difficult to be compared unless there is a correlation between them, i.e. the decision-makers compare the alternatives with respect to their performance under the same criteria. The design options can be compared with respect to their annual energy consumption and/ or other key performance indicators. This will enhance communication within the design team and help the decision-makers focus on the important issues of the design developments.

The criteria or attributes allow decision-makers to evaluate the design options. The success of the design process is highly dependent on the selected performance criteria and, thus, they must be developed after careful consideration. All the important aspects described in the project brief need to be addressed for the avoidance of possible design failure. These criteria can be both quantitative such as cost-related criteria and qualitative such as subjective preferences on the design options.

The approach represents the decision-making process at the early design stage and therefore comprises only information that was given to the design team in the conceptual stage. This included energy performance and the affinity of the building to overheat, however not any information on economics. Regarding the examined decision problem, the criteria under consideration are as follows:

2.1.1 Energy efficiency

An energy efficient building is not only a building that emits fewer greenhouse gasses but also it costs less to operate (whilst maintaining comfortable indoor conditions), resulting in important annual energy savings. The energy efficiency is addressed by the annual energy consumption of the building ($\text{kWh}/\text{m}^2/\text{yr}$). One of the design briefs requests was that the building was to ideally comply with the Passivhaus standard, therefore having a much reduced heating demand of less than $15\text{kWh}/(\text{m}^2/\text{yr})$. For comparative purposes two building standards will be used in this paper, the Passivhaus the Scottish building regulations (see Table 2)

2.1.2 Occupants' comfort (thermal comfort)

Thermal comfort was divided into two sub-criteria; occupied hours that overheating was experienced, defined by a Predicted Mean Vote (PMV) of more than 0.5 and those that underheating was experienced, defined by a PMV of less than -0.5, as the ASHRAE Standard indicate that thermal comfort is achieved for a PMV within the compliance limits $[-0.5, 0.5]$ ([50]). The Predicted Mean Vote (PMV) model uses a seven-point thermal scale that runs from cold (-3) to hot (+3) with values close to zero being ideal.

2.1.3 Airtightness of the building envelope

The airtightness of the building envelope is an important aspect when considering the overall energy efficiency of the building and it is measured by the degree of infiltration in air changes per hour (ac/h). The airtightness in the UK is limited as per building regulations. The Passivhaus standard, however, is even more constrained. To reflect this, two different airtightness values have been used as shown in Table 2.

2.1.4 Subjective preferences on aesthetics of the proposed building forms, and

While the design of the building should focus on the functionality, a balance between functionality and aesthetics is desirable. The aesthetics is addressed by the stakeholders' preferences on the design alternatives. Conflicting preferences are represented by the decision makers often imposed by personal drivers and agendas.

2.1.5 Land use

The land use is addressed by the total floor area of the building, expressed in m² and it is used to express the building's compactness; compact building forms have a relatively small exposed surface area for a given floor area, hence, the influence of the external environment is reduced [51]. Furthermore, the land use criterion was used because the Findhorn community wanted more land with trees but also only a single storey building, which is just one aspect to demonstrate the complexity of the decision-making process.

Generating an appropriate set of design alternatives is of high importance for the success of the design process. The examined variables should be highly connected to the selected performance criteria. The values for the aforementioned variables are presented in Table 4, this procedure results in thirty-two design alternatives (Table 5). The application of the MCDM methods allows the decision-makers to compare the performance of these designs under the selected criteria.

Table 4 Variables and assigned values of 32 alternative designs ($2 \times 2 \times 2 \times 2 \times 2 = 2^5$) in total, including some of the decision-makers' preferences; the latter is shown in more detail in Figure 3

Variable	Number of options	Values	Description	Reference	Decision-makers' preferences on the design variables
Building Form	2	1. One storey	Spatial rearrangement of the rooms (building footprint area of 778.46 m ²)		Community
		2. Two storey	Detailed building (footprint area of 442.66 m ²)	[52]	Architect, Client, PH consultant
Window-to-Wall ratio on the south façade	2	1. 30%	Conventional medium glazed façade	[53]	PH consultant
		2. 50%	Highly glazed façade ¹	[48]	Architect, Community
Construction type	2	1. Passivhaus standard	U-values of the building elements satisfy their corresponding max values in the PH standard ²	[54]	PH consultant, Project brief
		2. Scottish regulations	Building form compliant with Section 6 of the Scottish regulations ²	[55]	Project Brief
Infiltration	2	1. 0.035 ac/h	Well-insulated envelope without thermal bridges	[56]	PH consultant
		2. 0.152 ac/h	Still complies with the Scottish regulations		
Shading	2	1. ON	Both overhangs and internal horizontal blinds were equipped		PH consultant
		2. OFF	Absence of internal and external shading objects ³		Architect

¹ A requirement of the community for local views.

² For details on the construction types see [56].

³ Except from the roof overlap that extends just a few centimeters from the building construction

Table 5 Parameter combinations that have been inserted to DesignBuilder

Alternative	Number of storeys	Window-to-Wall ratio	Building Regulations	Infiltration	3. Shading mode
[-]	[-]	[%]	[-]	[ac/h]	[-]
A1-1S-30%-SR-0.152-ON	1	30	Scottish Reg.	0.152	ON
A2-1S-30%-SR-0.152-OFF	1	30	Scottish Reg.	0.152	OFF
A3-1S-30%-SR-0.035-ON	1	30	Scottish Reg.	0.035	ON
A4-1S-30%-SR-0.035-OFF	1	30	Scottish Reg.	0.035	OFF
A5-1S-30%-PH-0.152-ON	1	30	Passivhaus	0.152	ON
A6-1S-30%-PH-0.152-OFF	1	30	Passivhaus	0.152	OFF
A7-1S-30%-PH-0.035-ON	1	30	Passivhaus	0.035	ON
A8-1S-30%-PH-0.035-OFF	1	30	Passivhaus	0.035	OFF
A9-1S-50%-SR-0.152-ON	1	50	Scottish Reg.	0.152	ON
A10-1S-50%-SR-0.152-OFF	1	50	Scottish Reg.	0.152	OFF
A11-1S-50%-SR-0.035-ON	1	50	Scottish Reg.	0.035	ON
A12-1S-50%-SR-0.035-OFF	1	50	Scottish Reg.	0.035	OFF
A13-1S-50%-PH-0.152-ON	1	50	Passivhaus	0.152	ON
A14-1S-50%-PH-0.152-OFF	1	50	Passivhaus	0.152	OFF
A15-1S-50%-PH-0.035-ON	1	50	Passivhaus	0.035	ON
A16-1S-50%-PH-0.035-OFF	1	50	Passivhaus	0.035	OFF
A17-2S-30%-SR-0.152-ON	2	30	Scottish Reg.	0.152	ON
A18-2S-30%-SR-0.152-OFF	2	30	Scottish Reg.	0.152	OFF
A19-2S-30%-SR-0.035-ON	2	30	Scottish Reg.	0.035	ON
A20-2S-30%-SR-0.035-OFF	2	30	Scottish Reg.	0.035	OFF
A21-2S-30%-PH-0.152-ON	2	30	Passivhaus	0.152	ON
A22-2S-30%-PH-0.152-OFF	2	30	Passivhaus	0.152	OFF
A23-2S-30%-PH-0.035-ON	2	30	Passivhaus	0.035	ON
A24-2S-30%-PH-0.035-OFF	2	30	Passivhaus	0.035	OFF
A25-2S-50%-SR-0.152-ON	2	50	Scottish Reg.	0.152	ON
A26-2S-50%-SR-0.152-OFF	2	50	Scottish Reg.	0.152	OFF

A27-2S-50%-SR-0.035-ON	2	50	Scottish Reg.	0.035	ON
A28-2S-50%-SR-0.035-OFF	2	50	Scottish Reg.	0.035	OFF
A29-2S-50%-PH-0.152-ON	2	50	Passivhaus	0.152	ON
A30-2S-50%-PH-0.152-OFF	2	50	Passivhaus	0.152	OFF
A31-2S-50%-PH-0.035-ON	2	50	Passivhaus	0.035	ON
A32-2S-50%-PH-0.035-OFF	2	50	Passivhaus	0.035	OFF

3.1 Building case study and simulation setup

A real-world case study is used for the application of the selected MCDM methods. The building under investigation is the Community Centre building in Findhorn, Scotland. It is widely acknowledged that commercial buildings are more complex and consume more energy than residential houses. In particular, the examined commercial building is a mixed-use zero carbon community centre planned for the Findhorn Eco-Community, in Scotland, UK [48]. The Community Centre is a 2-storey building composed of a shop, café, visitor/ reception space, storage space, and offices. The detailed model (final stage model) is displayed in Figure 1.

Figure 1(a) Detailed model of the Community Centre [487] and (b) Designbuilder model of Community Centre [52]

In current building design practice, there is a wide range of tools that support design evaluations such as dynamic building simulation or simplified design guidelines. Having obtained the thirty-two design alternatives (Table 7), their simulation under hourly weather data for a one-year period will provide useful information on their dynamic performance.

EnergyPlus was selected for developing and assessing the thirty-two building designs (alternatives). It is a detailed thermal simulation engine, widely reviewed and validated, that calculates a range of environmental performance criteria of a building (e.g. energy consumption, carbon emissions etc.). The choice of software tools was based on their widespread use in the research community [57]. EnergyPlus is capable of predicting the performance of the proposed buildings under the climate conditions of the local area (e.g. Findhorn, Scotland, UK). The hourly weather data of the nearby location Aberdeen/ Dyce Airport was used in order to simulate typical weather conditions of Findhorn, Scotland.

3.2 Description of Multi-Criteria Decision-Making (MCDM) framework

The deterministic problem can be expressed in a matrix form as shown in Equation (4) [14], where α_{ij} is the performance of the alternative A_j with respect to the criterion C_i .

$$\begin{array}{c}
 \begin{array}{cccc}
 w_1 & w_2 & \cdots & w_n \\
 C_1 & C_2 & \cdots & C_n
 \end{array} \\
 \begin{array}{c}
 \chi_1 \ A_1 \\
 \chi_2 \ A_2 \\
 \vdots \ \vdots \\
 \chi_m \ A_m
 \end{array}
 \begin{bmatrix}
 \alpha_{1,1} & \alpha_{1,2} & \cdots & \alpha_{1,n} \\
 \alpha_{2,1} & \alpha_{2,2} & \cdots & \alpha_{2,n} \\
 \vdots & \vdots & \ddots & \vdots \\
 \alpha_{m,1} & \alpha_{m,2} & \cdots & \alpha_{m,n}
 \end{bmatrix}
 \end{array} \quad (4)$$

A set of m alternatives $A_1, A_2, \dots, A_m$ and a set of n performance criteria $C_1, C_2, \dots, C_n$ are given. Furthermore, the values in the matrix indicate the performance α_{ij} (for the i^{th} alternative and the j^{th} decision criterion) of each alternative; w_j is the weight of the j^{th} criterion (i.e. the importance of the criterion) and χ_i is the ranking value of the i^{th} alternative. The weighting values are usually normalised in order to sum up to one.

In order to establish the performance matrix shown in Equation (4), it is important to evaluate the performance of each design option under the selected criteria. Particularly, the numerical values for the energy consumption and the thermal comfort criteria were obtained by the dynamic simulation of the thirty-two alternatives. The qualitative criterion “Aesthetics” introduces the subjective preferences of the decision-makers over the design options. The remaining criteria (i.e. the airtightness of the building envelope and the land use) are specific characteristics of the design options, obtained without the use of BPS.

The importance that each stakeholder places on these performance criteria is also important as equally-weighted criteria are rare. Furthermore, the selected decision-makers do not influence the final decision to the same extent and, as such, the stakeholders’ importance will affect the result.

Figure 2 includes the aforementioned framework adopted in this study in order to achieve an integrated design approach. Steps 1 to 3 were undertaken with all four decision making protocols (i.e. the steps that the decision-makers were involved in the design of the building). Step 4 analyses the results of all decision outcomes in separation and comparison.

Figure 2 The framework adopted for the selected MCDM application [18]

3.3 Stakeholder preferences/ influence matrix

For the purpose of this study, and as mentioned in the problem formulation, there were four chosen stakeholders (the architect, the client, the Findhorn Community, and the Passivhaus consultant). The stakeholders' preferences are a representation of their possible behaviour. Their involvement in the decision process will be described in two different phases. Firstly, their preferences regarding the selected performance criteria (i.e. criteria weightings) and, secondly, the stakeholders' subjective evaluations of the thirty-two design options were introduced into the decision process as a qualitative criterion (aesthetics). Furthermore, in real-life decision problems regarding the choice of a building design, not all stakeholders have the same influence on the result and, thus, their relative importance needs to be defined. Figure 3 includes their preferences with the first five values on the x-axis being the criteria and the remaining values being the variables of the design alternatives. Regarding some of the variables, stakeholders show no particular preference between the two examined values.

Specifically, when considering the stakeholders' preferences on the performance criteria, the architect attaches high importance to the aesthetics of the building. The aesthetics and the land use are the two most important criteria for the client, who is not the occupant of the building. Similarly, the Findhorn Community states that the two aforementioned criteria are the most important, as it is mostly concerned with the aesthetics and the attractiveness of the building. For the Passivhaus Consultant, energy consumption, thermal comfort, and airtightness are equally important and very strongly more important than the 'Land use' criterion. The aesthetics ('Building form' criterion) is an important aspect for its potential impact on the building's thermal performance, as building forms that are more compact consume less energy.

As far as the stakeholders' preferences on the design alternatives are concerned, from the architect's perspective, a tall building with a large glazed surface that will allow a view of the

sea is the optimal solution. The 2-storey building is ideal as it is the only case that makes the view of the sea possible [18]. The WWR on the south façade is preferred to be 50% rather than 30%. According to [58], in cold climates, small window area is preferable for north façades (less heat loss) whereas larger WWR is better for south façades as heat gain from the sun can decrease the need for heating. Further, shading devices such as blinds disrupt the view and they are not recommended. These three preferences result in the conclusion that alternatives No.26, No.28, No.30, and No.32 are perceived as optimal by the architect (see Table 5 for further description). It is assumed that the client's objective is a 2-storey building [18] with medium glazed façade, translating into a WWR=20%-50%. These preferences result in the alternatives No.17 to No.32 (all alternatives with two storeys). The community's desired decision is a single-storey highly-glazed building [48]. Therefore, alternatives No.9 to No.16 are optimal (i.e. all single-storey buildings with 50% WWR on the south façade). The Passivhaus consultant prefers a two-storey building due to its compactness. The best window-to-wall ratio on the south façade is 30%, as smaller south-facing glazing areas (about 25%) yield lower risks of overheating [56]. Further objectives of the PH consultant are namely: Passivhaus construction type, 0.035 ac/h infiltration, and shading ON. The best alternatives according to the PH consultant are No.23, No.24, No.31, and No.32.

Figure 3 illustrates the aforementioned stakeholders' preferences on the selected criteria and the design variables. A value of 'High', 'Medium' or 'Low' is used to express the importance that the stakeholders place on that criterion. The preference on the tested variables for each stakeholder is also shown in this Figure. As can be seen from Figure 3, there are stakeholders with no preference between the two tested values of the variables, i.e. only the Passivhaus consultant wants the building to comply with the PH standard and, as such, have an infiltration rate of 0.035 ac/h.

Figure 3 The stakeholders' preferences over the performance criteria and the design alternatives

Concerning this case study, the client has the highest influence, followed by the community and then the architect and the Passivhaus (PH) consultant. The community has the second most significant role [18], as the importance and involvement of the Findhorn Eco-community is high [48]. Throughout the conceptual and early design stages the community played a crucial part in the decision-making process. Extensive consultation and community engagement exercises formed the basis from which initial design concepts were produced and evaluated. BPS results played a major contributing role in establishing a multicriteria evidence

base from which to inform the decision-making process [48]. Figure 4 includes the stakeholders' importance, normalised to sum up to 100%. These percentages along with those concerning the stakeholders' preferences on the performance criteria and the design variables were derived using the AHP method.

In the case study building design, a highly-glazed façade is desirable to make the most of attractive views. Whilst this is a specific example, there are several other scenarios in which cultural aspects influence preferences and inform decision-making, often contrary to the needs of a thermally-efficient building.

Some decision-makers perceive historic buildings and vernacular design as something to be conserved, regardless of whether the buildings are of architectural significance. For instance, a study on energy efficient retrofitting found that homeowners in Cambridge, UK, show a preference for preserving aesthetically-pleasing historic features; an aim which often conflicts with a desire for energy efficiency [59]. Some participants in the study aimed to restore original features and use traditional materials and decisions were not made based on energy efficiency or for reasons of economy.

Conversely, there is a trend in contemporary architecture for buildings with large areas of glazing, which results in designs that are not rooted in a location. Generic designs are often adopted without due regard for local climatic conditions, which results in increased energy use ([60]; [61]). Scanferla and Motuziene (2017) [61] found that up to 29% reduction in energy use can be achieved in European office blocks by adopting optimal parameters for glazing area and specification, instead of selecting completely glazed buildings. In some instances, the buildings studied were striving to achieve energy efficient standards, but a preference for large areas of glazing was prioritised [61]. In this context, preferences for large areas of glazing compromise attempts to improve energy efficiency; hence, there is a balance to be struck between an aesthetic preference and building performance.

Finally, the decision matrix (Equation (4)) that contains both the quantitative (e.g. simulated data and characteristics of alternatives) and qualitative (stakeholders' subjective preference over the design forms) criteria is formulated. The decision matrix is common in the application of all the examined methods (i.e. AHP, TOPSIS, ELECTRE III, and PROMETHEE II).

Stakeholders' importance

Figure 4 Stakeholders' importance as derived using AHP

4. Results and analysis

The following section will show first the results from the BPS simulation; the comparison of the different MCDM protocols implementing the BPS results as well as the users' preferences. It will also show the impact of decision changes subjective to preference alterations and therefore test the reliability of these MCDM protocols.

4.1 Results from simulation setup

Prior to analyzing the stakeholders' preferences and applying the MCDM protocols, the simulation test results are obtained. Table 6 includes the ten best-resulting alternatives regarding the energy consumption and the thermal comfort performance indicators. The results from the thirty-two simulations indicate that Passivhaus constructions (single and two-storey building forms) perform better regarding the annual energy consumption criterion. As far as the occupied hours that overheating was experienced are concerned, the alternatives that behave better are 2-storey building forms that comply with the Scottish regulations. They also have shading ON and 30% Window-to-Wall Ratio on the south façade. As regards the underheating criterion, the adverse values are the most favourable, i.e. single-storey buildings that comply with the Passivhaus regulations, shading ON and 50% Window-to-Wall Ratio on the south façade. It is worth mentioning that thermal comfort was only examined in the south-facing reception office room that is located at the exact same location for both building forms.

Table 6 The ten best resulting design alternatives based on energy consumption, the overheating and the underheating criteria as achieved via EnergyPlus

4.2 Design alternatives weighting and MCDM outcomes

Previously, stakeholders' preferences over the performance criteria and the design alternatives were shown. The normalised stakeholders' preferences on the design alternatives are presented in Figure 5 and one can easily verify the stakeholders' goals and desires presented. It is worth mentioning that alternative No.32 is desirable by the majority of the stakeholders (all except community). For the community, alternative No.32 is within the least preferable design option.

Figure 5 Stakeholders' preferences over the 32 design options, derived using AHP (given as normalized weights), indicating that the community prioritizes options 9-16, the architect options 26,28,30,32, the client options 17-32, and the PH consultant 34, 35, 31, and 32. The blue line shows the overall weight (or desirability) for each option combined for all stakeholders

Having derived the decision matrix, the AHP method can be applied in order to obtain the final rankings of the alternatives. The application of the AHP method concludes to a weighted sum called Overall or Global Priority. Using these values (i.e. the overall priorities of the alternatives), the final ranking of the alternatives is possible. Table 7 displays the final ranking using the AHP method; it contains the alternatives from best to worst (e.g. descending order regarding their performance). As it can be observed from the results, two-storey building designs are preferred from single-storey. Furthermore, 50% Window-to-Wall ratio seems to be more preferred than 30% as overall. As far as the construction type, the infiltration and shading mode are concerned, no clear conclusion about their most beneficial variables can be reached.

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) attempts to choose alternatives that simultaneously have the shortest distance from the positive ideal

solution and the farthest distance from the negative-ideal solution. This positive ideal solution is one that maximises the beneficial criteria and minimises the non-beneficial criteria (such as cost). Conversely, the negative ideal solution (also called as an anti-ideal solution) maximises the non-beneficial criteria and minimises the beneficial criteria. In other words, the best alternative is the one which is closest to the ideal solution and farthest from the negative ideal solution ([62], [34]). The ranking of this analysis (TOPSIS method) is presented in Table 4, where alternatives are in descending order, i.e. alternatives are sorted regarding their performance from best to worst. TOPSIS ranks alternative No.24 as the best design, i.e. WWR of 30% is ranked as optimal in this situation. It is also obvious that alternatives with a more airtight envelope constitute the first positions of the ranking.

In order to establish the final ranking of the alternatives using ELECTRE III, the intersection of the two ascending and descending ranking lists is provided in Table 7.

The ELECTRE III algorithm builds two rankings using a descending and ascending distillation. The descending distillation selects the best alternatives first and ends with the worst ones last; whereas, the ascending distillation selects the worst alternatives first and ends with the best ones. The ranked alternatives in these two lists are compared and two incomparable alternatives in the same rank are evaluated according to the differences of their positions in the two distillations.

It is worth highlighting that through the intersection of the two rankings, it is not always possible to understand all the relationships between the alternatives. In this particular application, alternatives No.28, No.30 and No.32 belong to the same rank and, thus, they are incomparable. Similarly, alternatives No. 24, No.26 and No. 29 are incomparable. There exist more alternatives that were incomparable.

The agreement of this ranking and the ranking using the AHP method seems high. Furthermore, ELECTRE III distinguishes two-storey building forms as more suitable than the single-storey buildings. Passivhaus construction and 50% Window-to-Wall ratio are more favourable when using ELECTRE III.

For the application of PROMETHEE II to the examined case study, the level (type IV) preference function was chosen for the qualitative criterion and the linear (type V) preference function was selected to represent the behaviour of the decision-makers regarding the quantitative criteria of the case study. Both selected preference functions require the determination of the indifference threshold q and strict preference threshold p . According to the guidelines presented in the literature, the indifference and the preference thresholds were 5% and 15% of the maximum deviation respectively.

Regarding the PROMETHEE II ranking (Table 7), alternatives are presented from best to worst. Similarly, as in AHP and ELECTRE III, the alternatives are separated regarding their building form with two-storey design options being more desirable. Furthermore, alternative No. 24 obtained a high ranking, which is in accordance with the results of the TOPSIS application.

Table 7 Alternatives and their rank (with 'green' indicating high agreement and 'red' low agreement)

Alternatives	AHP RANK	TOPSIS RANK	ELECTRE III RANK	PROMETHEE II RANK
A1-1S-30%-SR-0.152-ON	32	32	22	32
A2-1S-30%-SR-0.152-OFF	31	30	21	31
A3-1S-30%-SR-0.035-ON	30	31	20	30
A4-1S-30%-SR-0.035-OFF	29	29	19	29
A5-1S-30%-PH-0.152-ON	28	28	19	26
A6-1S-30%-PH-0.152-OFF	27	27	18	27
A7-1S-30%-PH-0.035-ON	25	26	17	19
A8-1S-30%-PH-0.035-OFF	26	25	16	21
A9-1S-50%-SR-0.152-ON	24	24	15	28
A10-1S-50%-SR-0.152-OFF	22	22	14	25
A11-1S-50%-SR-0.035-ON	23	20	13	24
A12-1S-50%-SR-0.035-OFF	20	18	12	20
A13-1S-50%-PH-0.152-ON	21	21	12	23
A14-1S-50%-PH-0.152-OFF	19	19	12	22
A15-1S-50%-PH-0.035-ON	18	16	11	18
A16-1S-50%-PH-0.035-OFF	17	15	11	17
A17-2S-30%-SR-0.152-ON	16	23	10	16
A18-2S-30%-SR-0.152-OFF	14	14	8	15
A19-2S-30%-SR-0.035-ON	15	17	9	13
A20-2S-30%-SR-0.035-OFF	12	11	7	11
A21-2S-30%-PH-0.152-ON	13	13	8	12
A22-2S-30%-PH-0.152-OFF	11	8	5	8
A23-2S-30%-PH-0.035-ON	10	6	6	5
A24-2S-30%-PH-0.035-OFF	7	1	3	3
A25-2S-50%-SR-0.152-ON	9	12	6	14
A26-2S-50%-SR-0.152-OFF	5	7	3	10
A27-2S-50%-SR-0.035-ON	8	5	4	9
A28-2S-50%-SR-0.035-OFF	4	3	2	4
A29-2S-50%-PH-0.152-ON	6	9	3	7
A30-2S-50%-PH-0.152-OFF	2	10	2	6
A31-2S-50%-PH-0.035-ON	3	2	2	2
A32-2S-50%-PH-0.035-OFF	1	4	1	1

Table 7 shows all rankings using the examined deterministic MCDM methods. In this way, the degree of agreement between the four methods can be seen. Using ELECTRE III, many alternatives were found incomparable, leading to a partial ranking. Thus, even if all the examined MCDM methods ranked alternative No.1 as the worst, in ELECTRE III alternative No. 1

is at the 22nd rank instead of 32nd due to the above-mentioned phenomenon. This situation makes the comparison of the four rankings challenging.

In real-life decision situations, the agreement in the ranking of the examined methods is only important for the top ten (or less) design options, as the final decision most probably will be a judgment among these alternatives. When considering that situation, TOPSIS and PROMETHEE II suggest the same alternatives, i.e. alternatives No.24, No.28, No.31, and No.32. However, the AHP method excludes alternative No. 24 and proposes alternative No. 26 as fifth. In ELECTRE III, alternatives No.24, No.26 and No.29 are incomparable and so there is no information on which one of them is the fifth best alternative. However, ELECTRE III indicates that both alternatives No.24 and No.26 behave well under the examined criteria. As it can be observed, the examined methods derive close optimum solutions with alternative No.32 being the most favoured by all the examined methods except TOPSIS.

4.3 Analysis of the differences of the MCDM rankings

It is important to observe the differences among the rankings of the four examined methods that include all the thirty-two alternatives in order to obtain a more holistic understanding. The pairwise absolute ranking differences between the four examined methods are displayed in Figure 6. The y-axis indicates the frequency of occurrence described as a percentage of the total. As it can be seen from Figure 6, ELECTRE III and AHP methods highly agree in their rankings (absolute agreement occurs for 72% of the time, i.e. same ranking for 23 out of the 32 alternatives), with a maximum absolute difference of two ranks. It is clear that the ranking obtained by the TOPSIS method highly deviates from that of the remaining methods, as the equivalent absolute differences reach seven and eight ranking positions (Figure 7). Furthermore, PROMETHEE II ranking deviates from that of the AHP and ELECTRE III methods, being slightly closer to the TOPSIS ranking.

Absolute ranking difference

Rank dev 0 Rank dev 1 Rank dev 2 Rank dev 3 Rank dev 4
Rank dev 5 Rank dev 6 Rank dev 7 Rank dev 8 Rank dev 9

Figure 6 Pairwise absolute differences between the methods TOPSIS-AHP, TOPSIS-ELECTRE III and TOPSIS-PROMETHEE II, demonstrated as absolute ranking per method (top) and per rank in a spider diagram (bottom)

Each method is compared with every other method in a pairwise comparison. The difference in rank between the methods for each alternative is calculated. The number of occurrences of each numeric difference between the methods is also calculated. The results are then combined and illustrated in the form of a probability density function, as shown in Figure 6

Table 8 includes the percentages of occurrence for the presented absolute differences in the rankings obtained by the examined methods. In this table, the high degree of agreement between the rankings obtained by the AHP and ELECTRE III method can also be observed. If an assumption is made that a 2-rank deviation is considered acceptable, the rankings of ELECTRE III and PROMETHEE II are also similar (75% of the time a 2-rank difference is observed). The same scenario is not observed for the rankings of TOPSIS and ELECTRE III methods, as there exist rank differences between seven and eight positions. Thus, even if 81% of the time the absolute rank differences were less or equal to two, the existence of high differences in the rankings make their agreement impossible.

It is worth mentioning that the conclusions about ELECTRE III ranking remain sensitive to the randomly selected ranks for the incomparable alternatives. In the effort to reinforce these conclusions, the same analysis was conducted for all the possible ranks of the incomparable alternatives and the same conclusions were observed. Therefore, the high degree of agreement between the AHP and ELECTRE III methods is clearly observed, as the highest deviation observed is two ranks. Furthermore, TOPSIS and ELECTRE III rankings deviate by maximum seven ranking positions, making their agreement impossible. ELECTRE III and PROMETHEE II rankings seem to agree for about 69%-75% of the time (less or equal to two-rank difference).

Table 8 Frequency of occurrence of the absolute differences in ranking positions between the examined alternatives

Rank difference	Frequency of occurrence					
	TOPSIS - AHP	ELECTRE III- AHP	PROMETHEE II- AHP	ELECTRE III- TOPSIS	PROMETHEE II- TOPSIS	ELECTRE III- PROMETHEE II
0	31%	72%	34%	34%	19%	38%
≤ 1	53%	91%	56%	63%	38%	56%
≤ 2	69%	100%	66%	81%	63%	75%
≤ 3	88%	100%	75%	88%	75%	81%
≤ 4	91%	100%	84%	94%	94%	94%
≤ 5	91%	100%	97%	94%	94%	97%
≤ 6	94%	100%	100%	94%	94%	97%
≤ 7	97%	100%	100%	97%	100%	100%
≤ 8	100%	100%	100%	100%	100%	100%

While the conclusions so far are important for the overall understanding of the agreement of the four examined methods, it is also critical to specify the exact location of these deviations. High deviations (i.e. above three ranks) that occur within the highly ranked alternatives are more crucial than those that happen in the lower part of the ranking (i.e. for the least favourable alternatives). Figure 8 provides a way of displaying the differences among the four rankings for the ten highest ranked positions of the alternatives obtained by the AHP method. All the examined methods concluded roughly to the same set of alternatives as the AHP method. The two green lines (ELECTRE III max rank and ELECTRE III min rank) indicate the possible ranks of the alternatives that were found incomparable (i.e. their highest and their lowest possible rankings respectively). From Figure 8, AHP and ELECTRE III highly agree in their rankings, while TOPSIS and PROMETHEE II show a similar trend. Particularly, both TOPSIS and PROMETHEE II ranked alternatives No.30 and No.25 in less favourable positions whereas they indicate that alternatives No.23 and No.24 behave better as AHP and ELECTRE III propose.

Figure 7 Ranking of the ten top-ranked alternatives when using AHP and the differences from their equivalent rankings

Regarding the top-ranked alternative, the majority of the methods concluded to alternative No.32, whereas TOPSIS indicates that alternative No.24 is the best. The only difference between these two alternatives is the WWR (50% and 30% for alternative No.32 and No.24 respectively, see Table 5), as they are both 2-storey PH buildings with an air infiltration of 0.035 ac/h and shading mode OFF. From Figure 3, a WWR of 50% is desirable by the majority of the stakeholders and, thus, alternative No.32 seems more appropriate.

4.4 Sensitivity analysis

The degree to which the final decision and the overall ranking of the alternatives change when small changes in the stakeholders' subjective preferences are introduced is an important aspect under examination. Three sources of uncertainties regarding subjective preferences will be investigated, namely: criteria weightings, stakeholders' design preferences and stakeholders' relative importance over the decision process. It is usual that interested parties can change their preferences in the process of building design, as new information is gained and, thus, the decision process is more transparent. When decision makers have a greater insight into the consequences of their actions, they can easily change their perspective and opinions.

Four distinct scenarios were chosen as in previous literature [18]. The first scenario is the base case study. In scenario 2, the selected performance criteria have equal importance for all the stakeholders. Equally-weighted criteria is a common situation, against which the sensitivity of the results is tested. In this case study the selected performance criteria are six and thus each one has a weight factor of $100\%/6 = 16.667\%$. Scenario 3 incorporates a change in the stakeholders' relative importance. In more details, the influence of community over the design solutions was increased, with 35%, 50%, 10% and 5% the community, client, architect, and PH consultant relative importance respectively (see Figure 3 for the previous influence of each

stakeholder). Scenario 4 investigates the change in preference of the client. From Figure 3, the client's preferences result in the alternatives No. 17 to No.32 (2-storey building forms, see Table 5), which accounts for a wide set of selections. In scenario 4, the client considers a WWR of 50% to be a bit more desirable, concluding to alternatives No.25 to No.32 as more preferred. Table 9 includes all the above-mentioned scenarios.

Table 9 Examined scenarios and their description

What-if scenarios	
Scenario 1	The base case study of the design options
Scenario 2	Equally weighted criteria
Scenario 3	Impact of greater community importance
Scenario 4	Change in the aesthetic preference of the client

In order to obtain a clearer insight into the results, only the ten top-ranked alternatives are examined, namely alternatives No.23 to No.32. In real-life decision problems, the final decision will be a judgment among these alternatives, as tools cannot solely conclude with the right decision and human judgment is important [63]. Thus, the impact that the different scenarios have on the ranking of these alternatives is more important. For these alternatives, a high degree of agreement between the examined methods exists for the base case scenario. Figure 9 includes the absolute differences between scenario 1 (base case) and the remaining three scenarios regarding the aforementioned ten top-ranked alternatives. The y-axis indicates how often the absolute differences in the x-axis happened. ELECTRE III concluded to incomparability of some alternative and, as such, two different situations exist regarding the maximum and the minimum possible ranking of those incomparable alternatives.

Figure 8 Percentage of occurrence of absolute differences between the district scenarios for the AHP, TOPSIS, ELECTRE III, and PROMETHEE II applications

AHP ranking seems to be less sensitive to preference changes as the differences between the four scenarios are negligible (less than two ranks difference). Concerning the TOPSIS method, the rankings differ highly from scenario to scenario. Particularly, the final ranking of TOPSIS (scenario 1) is only insensitive to scenario 3, i.e. the impact of the greater community influence is very low. ELECTRE III and PROMETHEE II rankings in scenario 1 are only sensitive to the scenario where the criteria weights are equal (scenario 2).

It is beneficial to understand why the TOPSIS method proposes alternative No.24 as the best alternative and diverts from the remaining methods that propose alternative No.32. When someone considers the behaviour of alternative No.24, the results using Building Performance Simulation indicate that it performs better than alternatives No.28, No.30 to No.32 regarding the annual energy consumption and the overheating hours. Regarding the underheating hours, all the aforementioned alternatives behave the same. Therefore, the highest deviation that the performance of alternative No.24 has from that of the above-mentioned alternatives is in its performance under the 'overheating hours' criterion.

As a conclusion, the "what-if" scenarios in Table 6 contributed to the investigation of the robustness of the results when applying the selected deterministic MCDM methods. In all the examined scenarios, the MCDM methods concluded more or less to the same ten top-ranked alternatives, namely No.23- No.32.

5. Discussion

From the application of the selected methods, general conclusions on their advantages and disadvantages can be reached. AHP, as stated by many authors in the literature, is a powerful and easy-to-apply method. However, when checking for inconsistency, there is no Random Consistency Index (RI) for $n=32$ alternatives. According to Saaty (1990) [64], the number of elements being compared must be small (not more than 9) to improve consistency and the corresponding accuracy of measurement. However, the uncertainties that the use of AHP has in the stakeholders' judgments on the design alternatives are common for the application of all the examined methods.

TOPSIS methodology is based on a logical principle, making its application easy and understandable by the decision-makers. As far as the use of ELECTRE III is concerned, it often concludes to a partial ranking of some alternatives as the intersection of the ascending and descending procedures may lead to non-comparability. As stated in the literature, due to the above-mentioned situation, ELECTRE III may or may not reach the preferred alternative [65]. In addition, the introduction of pseudo-criteria in ELECTRE III requires three parameters to be identified, namely the indifference, preference, and veto thresholds. Both their definition and the existence of guidelines on the way to obtain their values can help decision-makers decide thresholds that reflect their way of decision-making. However, the final ranking of the alternatives depends on the thresholds' values.

Concerning the PROMETHEE II application, the above-mentioned indifference and preference thresholds must be identified in addition to the stakeholders' preference functions. While there are guidelines on how to select the preference functions and their corresponding thresholds, the final ranking may change if the decision-makers change the way they choose a solution.

Furthermore, while AHP and TOPSIS methods are easy to use, the application of ELECTRE III and PROMETHEE II are rather complicated and time consuming without the use of specific software. This is also stated in the literature ([66]; [47]); nonetheless, more sophisticated MCDM methods, i.e. ELECTRE III and PROMETHEE II, may yield results that are more accurate.

Generally, changes in the subjective inputs may change the final rankings and, thus, the more the subjective sources, the higher the degree of uncertainty and ambiguity of the results. The “what-if” scenarios helped identify whether the final rankings are sensitive to changes in subjective preferences. As far as the decision-makers’ judgments are concerned, It was found that AHP and TOPSIS are the least and the most sensitive respectively.

As regards the degree of agreement among the examined methods, the ranking of the alternatives was similar regardless of whether AHP or ELECTRE III methods were used. This is an important conclusion if someone considers that ELECTRE III is a more sophisticated method, based on a very different principle than the AHP method. The simplicity and the relative ease of use of the AHP method do not mean that it provides poor results. Adversely, from the present comparative analysis, the AHP and ELECTRE III applications concluded to very similar rankings. This indicates that the AHP method is capable of providing consistent results.

As far as the TOPSIS method is concerned, its ranking highly deviates from that of the remaining methods, as the equivalent absolute differences reach eight ranking positions. Furthermore, PROMETHEE II ranking differs from that of the AHP and ELECTRE III methods, being slightly closer to the TOPSIS ranking.

In real-life decision situations, the final decision most probably will be a judgment among the ten top-ranked alternatives. According to Ruwanpura and Ariaratnam (2007) [63], tools cannot solely conclude with the right decision, as it must involve human judgment. Therefore, the agreement in the ranking of the examined methods is important for those highly ranked alternatives. When considering that situation, the examined methods concluded roughly to the same set of alternatives, i.e. No.24, No.28, and No.30 to No.32. In particular, when considering only the ten top-ranked alternatives, it is reasonable that the ranking is the same regardless of whether AHP or ELECTRE III was used. However, there also exists a high degree of agreement between the TOPSIS and PROMETHEE II methods.

If the final decision was concluded by the deterministic MCDM methods and not by the judgment of the decision-makers after obtaining the rankings of the MCDM methods, then AHP, PROMETHEE II, and ELECTRE III rankings indicate that alternative No.32 is the best. However, alternative No.24 was ranked as first by TOPSIS possibly due to its good behaviour regarding the overheating hours’ criterion. It is not uncommon that different MCDM methods yield different results (see [40]; [44]), however, Selmi et al. (2013) [38] concluded to the same situation, i.e. AHP, ELECTRE III, and PROMETHEE II result in the same optimal solution whereas TOPSIS differs.

6. Limitations of the research

There are several limitations to this analysis. Firstly, Building Performance Simulation (BPS) is subject to uncertainties such as numerical and scenario uncertainties. Regarding the scenarios, for the single-storey design options, the location of some rooms is different as in the two-storey

building forms. This will also have an impact on the numerical results of the simulations. In addition, the Window-to-Wall Ratios (WWRs) are similar to their counterparts but the exact windows location may differ. This leads to the conclusion that less sunlight penetrates the single-storey building forms as rooms that had windows in the two-storey buildings, they are located in the middle of the building without any access to direct sunlight.

As previously stated, subjective preferences can easily change with the introduction of more detailed information and, thus, they are a source of uncertainty. It is worth mentioning that the stakeholders' preferences on the performance criteria and design alternatives were assumptions, which, for the most part, were based on existing knowledge of their interests. Four "what-if" scenarios contributed to the evaluation of the results' robustness; however, there exist more sources of uncertainties especially in the application of the ELECTRE III and PROMETHEE II methods. In these two methods, thresholds and preferences functions need to be fixed by the decision-makers, making the decision process even more complex. However, the design process inevitably involves subjective judgments, as the decision process includes multiple stakeholders with their distinct, probably conflicting, interests and preferences.

Furthermore, Saaty (1990) [64] proposed a way to check for consistency in the AHP method when obtaining the subjective preferences of the stakeholders. The pairwise comparison needs to be homogeneous otherwise significant errors may occur in the ranking. For this purpose, the elements under comparison must not be more than nine as inconsistencies may occur [64]. The number of the examined performance criteria is six and the stakeholders' pairwise comparison was checked and found consistent. However, the design options are thirty-two and therefore the stakeholders' preferences on the design alternatives may be inconsistent.

7. Conclusions

The review of previous scientific papers that investigated the suitability of the MCDM in the context of the sustainability field demonstrated that there is no excessive literature on the decision process of the early stage building design, incorporating the use of BPS tools.

Therefore, this paper aimed to cover this gap and to investigate the degree of agreement and the suitability of some of the most widely applied deterministic MCDM methods, namely AHP, TOPSIS, ELECTRE III, and PROMETHEE II, in the context of a low energy design project.

The majority of the examined MCDM methods (all except TOPSIS) resulted to the same optimum solution, a situation that provides confidence in the final decision. As stated by [36], "one should use more than one method to gain confidence in the results". Since there is no single method that can be described as the most suitable, the use of more than one method can enhance confidence and reliability of the rankings ([47]; [40]; [36]).

The examined deterministic MCDM methods provide more or less the same set of optimal design options and, usually, it is up to the decision-makers to decide. The multi-criteria decision-making methods provide an insight into the decision process, making decision-makers capable of making a choice among the proposed solutions. In this way, decision-makers are

able to explore the alternatives, understand the consequences of their actions and the impact of the design variables.

Since comparative studies on the application of MCDM methods in the building design field are limited, many questions need to be further addressed. This analysis provided a framework through which decision-makers can communicate while incorporating both quantitative and qualitative aspects of the design. Building Performance Simulation (BPS) is a useful tool that provides an indication of the performance of the examined building designs. Additional scenario changes, such as achieving resilience via future weather scenarios and evaluating the alternatives under varying climatic impact, can further be investigated. Furthermore, an investigation of the changes that different threshold values and/ or preference functions will have on the ELECTRE III and PROMETHEE II rankings respectively could provide useful insight into the robustness of the results under the aforementioned variables.

Acknowledgement

The contribution of the Eco Design Partnership is gratefully acknowledged for providing all the required information on the examined case-study building.

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