SCALABLE AND QUANTITATIVE DECISION SUPPORT FOR THE INITIAL BUILDING DESIGN STAGES OF REFURBISHMENT

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ABSTRACT

Decision-making within the building industry often involves various criteria of very different natures. Some are qualitative, others quantitative, some are objective, others subjective, but ultimately, they should all be aggregated and handled holistically in order to support decision-making. This process can also be referred to as multi-criteria decision-making (MCDM). Some aspects of MCDM are often conducted unconsciously and non-transparently. By implementing mathematical methods that have been proved applicable for MCDM, multi-criteria decision-making processes can be handled more consciously and transparently and thus be made reproducible. The calculation method presented allows quantitative sustainability and qualitative indicator values to be accounted for with the level of importance desired.

The MCDM method used is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). As the model has already been described well in the scientific literature and is used frequently, the aim is to illustrate how TOPSIS can be applied for transparent decision-making within the building industry in the context of urban renewal and refurbishment schemes through case studies of various scales and descriptions.

The case studies focused on in this paper incorporate a variety of specific pre-chosen criteria, including environmental performance, functional parameters and technical parameters. The case studies cover different parameters of refurbishment in a major hospital compound in Denmark due to be taken out of operation. One central design decision is whether to refurbish or demolish the old hospital buildings.

The results reveal that decision support is first of all dependent on how the decision-making tool is applied and what choices are made in relation to the actual calculations. However, by implementing a *mathematically based* MCDM method like that being assessed in the case studies presented, the decisions and their arguments become transparent and are easily communicated within a project group. As a result, the tool is considered to be universally applicable across most decision-making contexts within the building industry.

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Multi-Criteria Decision Making (MCDM), mathematical decision support, building design, transparent decision making, refurbishment, urban renewal

1. INTRODUCTION

Often when a seminal construction project-related decision is warranted there are many diverse parameters to consider, which in some cases might have major consequences for the future fate of the project. Experience shows that when a specific solution is chosen, the consequences are only considered prospectively and almost never retrospectively, meaning that the validity of the consequences considered in a given decision-making context is (almost) never proved. In large refurbishment and urban renewal projects, the economic, social and environmental consequences of making the right decisions are often very large. It is thus important to invest time and labour in decision-making in order to avoid undesirable consequences. Decisions relating to urban construction projects most often also affect the (elusive) environmental sustainability performance of the project and hence may impact on both local and global populations far into the future, as expressed by environmental impact indicators such as land use, global warming or resource depletion.

When designing, constructing or renovating constructions, decision-making is often based on know-how and experience from previous projects (Harputligil et al. 2011). Weighting different decision-making criteria is often based on economic parameters (RAIA 2003) and might require the application of pre-defined (tender-defined) criteria weighting. The state of the art in terms of criteria selection is through criteria definition by a professional jury and the inclusion of several stakeholders with different interests (Toppenberg et al. 2013). As the many stakeholders involved have different interests, decision-making easily becomes complicated.

This paper investigates the implementation of mathematical methods in relation to multi-criteria decision-making (MCDM) within the building industry. The aim is to avoid decision-making based solely on a single criterion such as the economy. Urban renewal and large refurbishment projects often have a political context. Achieving more transparency in the decision-making process would allow stakeholders to keep track of decisions, give reasons for them and state on what basis any compromises have been made.

This paper therefore presents an analysis of the usability and application of a mathematically based MCDM tool, based on Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) in the context of large- and small-scale refurbishment projects within the building industry.

1.1 Case study: Odense University Hospital, Denmark

The background to the cases illustrating the use of TOPSIS is a request for a decision on whether to demolish or renovate individual derelict buildings in a large hospital compound in Odense, Denmark. The compound consists of approximately seventy buildings. See examples of the building designs of the compound in Figure 1. Figure 2 illustrates the overall composition of the structures from different periods, representing a multitude of construction techniques, functions, qualities, conditions and sizes.

FIGURE 1. Examples on building types on site. Top left: Characteristic concrete building (Built 1960s-1970s). Top right: Red Masonry buildings (Built 1912). Bottom left: Barracks (Built 1980s). Bottom right: An example of newer steel construction (Built 2000s).

In total, the floor area consists of approximately 300,000 square meters and contains buildings constructed from 1912 to 2014. The core question is hence *"How (objectively) can we arrive at a demolition versus renovation decision for all these individual buildings?"* If renovation is chosen, an additional question arises, namely "*Which renovation strategy should be used for each specific building?*" A decision to renovate a particular building might involve a further choice between various scenarios, for instance, minor refurbishment, total refurbishment, transformation by adding new structures, or demolition and constructing a new building.

The buildings in the compound consist of a large amount of building materials, which have already impacted on the environment to various degrees and, depending on the decision, will continue to do so until the materials are disposed of. Environmental sustainability has become a key factor in the building sector, and the consequences of construction project-related decisions and actions are critical to the environment (DesigningBuildingsWiki 2017; Vatalis et al. 2013; Wilkinson et al. 2014). At the same time, digitalization has rendered Life Cycle Assessment (LCA) operational even in the early design phase, making it possible to estimate the embodied impacts of existing structures. In that context, preservation and refurbishment always seem be the most sustainable option, though in practice this might prove too costly. Hence, one of the key parameters that is integrated into the case studies presented below is the inclusion of sustainability as a decision-making contributor by integrating LCA into the decision-making process. LCA is of particular interest to refurbishment projects because the methodology can inform decision-making by quantifying and hence expressing the environmental impacts quantified (depending on the choice of impact assessment method) across approximately eighteen indicators and the energy already embodied in the existing structures. Here embodied impacts equals 'embodied energy (i.e., embodied gross calorific value)' and 'embodied global warming', the latter being expressed in kg CO_2-eq.

1.2 MCDM in the Built Environment

The family of MCDMs includes many different approaches and mathematical systems, some of which have been applied to different examples of construction. The mathematical method known as Analytical Hierarchy Process (AHP) has been tested on the project management of a building project (Lo and Tzeng 2011), as well as by architects in evaluating building sustainability in the early design phase (Markelj et al. 2014) and in making sustainability assessments of existing buildings (Villarinho Rosa and Haddad 2013). A project by (Si et al. 2016) further investigated the use of AHP for decision-making in retrofitting of existing building with appropriate green technologies.

An investigation using MCDM in relation to the evaluation of new design proposals has been conducted using the tools Multi-Attribute Value Function (MAVF), AHP and Preference Function Modelling (PFM) (Binnekamp 2010). In evaluating the environmental sustainability performance of hotel construction projects, attempts have been made to implement two different MCDM models: Step-wise Weight Assessment Ratio Analysis (SWARA), and Complex Proportional Assessment (COPRAS) (Hashemkhani Zolfani et al. 2016). However, it is the aim of the present project to inquire into new ways of informing decisions in the design and planning of refurbishment projects by integrating LCA and cultural heritage assessments through the application of TOPSIS. (Pavlovskis et al. 2017) looked into redevelopment possibilities for former industrial building which were abandoned. By using MCDM method 'Weighted Aggregated Sum Product Assessment with Grey values (WASPAS-G), a proposed number of redevelopment alternatives were suggested and ranked according to the most rational project.

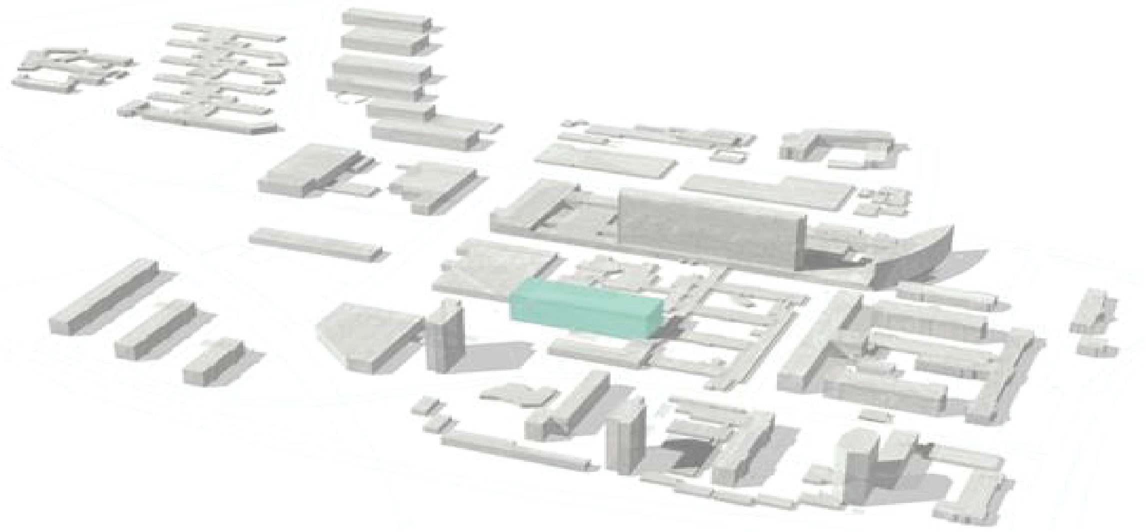
Implementation of fuzzy TOPSIS has been tried by (Wang et al. 2009) to support decision making, based on subjective and objective criteria, as to which heating, ventilation and air condition (HVAC) system is the optimal to use in a project with set criteria. The method is thus used before, however on a smaller scale.

Also (Kamali et al. 2018) looked into using MCDM methods to support decision-making in the process of investigating a life cycle sustainability performance framework in the form of aggregated sustainability indices for residential modular buildings. In order to define a set of performance criteria they used AHP for quantifying a group decision-making process. The method Elimination and Choice Translating Reality (ELECTRE) was then used to rank the defined performance criteria within sustainability categories: environmental, social and economic. TOPSIS was used to develop and evaluate aggregated sustainability indices within the determined performance criteria (Kamali et al. 2018).

2. METHOD

The research presented is based on two case studies at the macro- and micro-levels and literature reviews. The framework for the case study is a large hospital compound in Odense, Denmark, which is intended to be derelict in the coming years. The macro-scale case study addresses the topic of which buildings across the entire site should be demolished or refurbished, if any, and

FIGURE 2. Overview of the macro level: all buildings are evaluated for preservation (grey). Micro level: only one building is evaluated for different future scenarios (blue).



does not cover energy balances or Indoor Environmental Qualities (IEQ). The micro-scale case study focuses on the design of an individual building and does cover energy balances and IEQ parameters. Thus, the macro-scale case study is urban scale, whereas the micro-scale is at building level (see illustration in Figure 2).

The design and planning processes of the case studies are based on a thorough literature review covering LCA, refurbishment design processes, systems for assessing architectural quality and cultural heritage, and MCDM theory and models.

In terms of the parameters describing the buildings assessed, the case study relies on the method of MCDM fuelled by various criteria, among others LCA and Survey of Architectural Values in the Environment (SAVE) (Kulturarvstyrelsen 2011; Tønnesen and Didriksen 1997). SAVE is a Danish framework used to identify and quantify architectural and cultural heritage values in urban environments and buildings—expressed as one preservation value. The preservation values are used in renovation aspects and express a level of limitations for renovation actions made on buildings in order to preserve the listed qualities.

The above-mentioned criteria are project specific chosen criteria and may differ in other case studies.

2.1 MCDM methodology

The MCDM method chosen for the case study was TOPSIS (Beg and Rashid 2014; Hwang and Yoon 1981; Roszkowska 2011; 'TOPSIS' n.d.). TOPSIS was selected because of its overall match with existing processes in the industry, revealing a potential to be both operational and understandable. In addition, TOPSIS was chosen, instead of e.g., the AHP method, because of its ability to handle quantitative arguments as was needed for the case studies. No other MCDM methods able to handle quantified arguments were tested in this study.

The overall TOPSIS concept is to assess a range of solutions and from them to find the solution which has the shortest overall geometric distance to a defined ideal solution across all covered parameter-based criteria. The method quantifies a given solution's distance from the optimum solution (defined as either beneficial or negative) across all given criteria. The base assumption in TOPSIS is the existence of 'm' alternative solution scenarios and 'n' criteria (i.e., building parameters). The mathematics behind the method is based on linear algebra.

The evaluation steps used when applying TOPSIS are as follows:

1. Define alternatives, m, (scenarios) and criteria, n, (building parameters)
2. Determine whether the criteria represent a positive or negative attribute
3. Normalization: the criteria are normalized in order to obtain comparable scales across all the criteria covered
4. Weighting of each criteria
5. Definition of ideal and negative ideal score
6. Definition of distance towards each ideal score
7. Summation of the relative distances for all criteria for each alternative towards the ideal solution

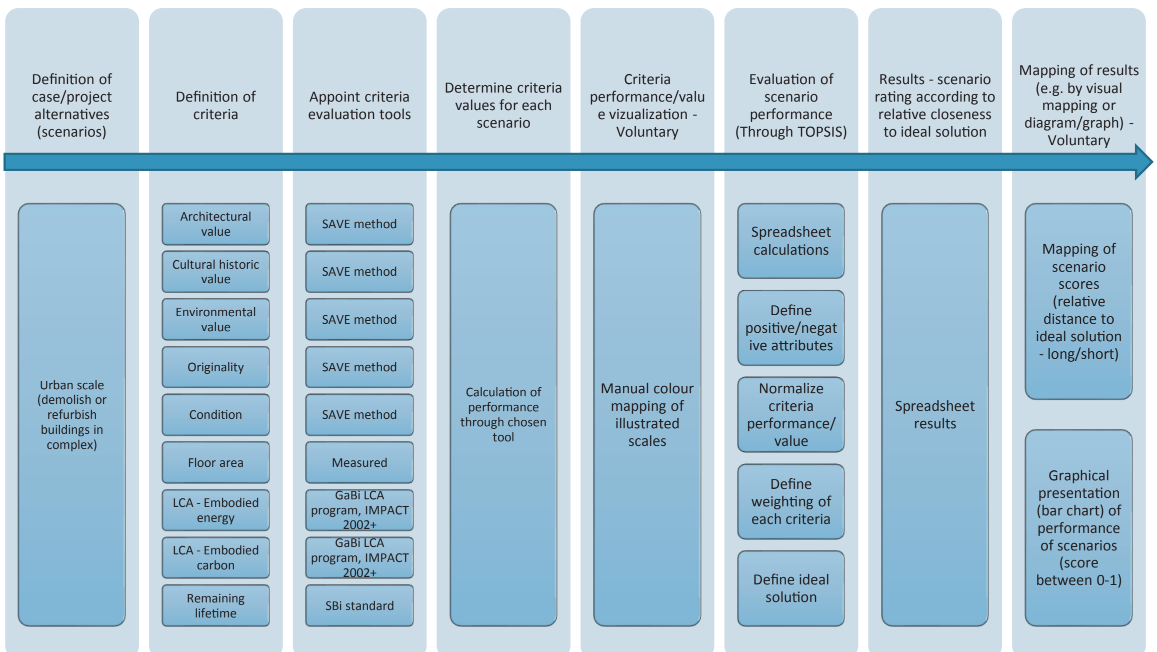
The calculations were performed using spreadsheets, which made the assessment accessible and transferable between the various cases, both macro and micro. The most important step, however, was to remember to distinguish between the criteria that represented a positive and those that represented a negative attribute, as this impacts on the relative closeness to the optimum solution and hence the overall 'performance' ranking of the different scenarios.

An illustration of the work process is shown in Figure 3. The figure also exemplifies the work process, using the macro-scale case study to illustrate how the steps are applied.

2.2 LCA methodology

The environmental assessments (i.e., LCAs) were based on the materials used in the existing buildings (or in the building design proposals for replacing them), as well as on the embodied

FIGURE 3. Process/work flow diagram of the methodology followed. Top: generic work process. Bottom: example of process flow using steps from the macro-scale case study.



energy and embodied carbon of the individual buildings. To quantify these impacts, the material masses, though highly simplified due to the limited accessibility of data, were estimated and subsequently multiplied by the impact potentials found for a unit mass of that specific material. The impact potentials used in this project are embodied energy in the form of (life-cycle aggregated) energy (gross calorific value), measured in MJ, and embodied carbon (i.e., life-cycle aggregated GHG emissions), measured in kg-CO_2 equivalents emitted to air. These are found using the product system modelling software GaBi (GaBi n.d.), with datasets from Ecoinvent v3.1 (EcoInvent n.d.).

The Life Cycle Impact Assessment (LCIA) methodology used for the macro-scale case study is IMPACT 2002+ (Humbert et al. 2012). For the micro-scale case study the LCIA methodology used is ReCiPe 1.08—Hierarchist (Goedkoop et al. 2013a). The inventory data were gathered using Ecoinvent v3.1 (EcoInvent n.d.) were processed in GaBi LCA Software, version 7.3 (GaBi n.d.). The assessed impact categories are limited to the most easily understandable and generally known impact potentials: Global Warming (GWP) and Energy.

2.3 SAVE methodology

SAVE assessments of buildings are based on five different parameters: architectural quality, cultural-historical quality, environmental quality, originality and condition (Kulturarvstyrelsen 2011). Normally as part of the SAVE methodology all five different criteria are evaluated on a scale between 1 and 9 (1 being the best and 9 the worst). When all five parameters are evaluated, one preservation value for the building (or urban area) is given qualitatively (and thus not calculated as it does in MCDM). In the present MCDM evaluation all five arguments were included individually in the assessment. It should be noted that what is labelled 'environmental' in SAVE has nothing to do with LCA but refers to the built environment, that is, the urban context of the individual building.

2.4 Decision criteria

2.4.1 Macro-scale case study

The qualities or rather criteria for each building are divided into three categories: physical, environmental and architectural. The physical values assessed were floor area and years of service life remaining according to the estimated life of the main building materials (Aagaard et al. 2013; Møller et al. 2012) and the construction period. The environmental values were obtained by assessing the embodied energy and embodied carbon for each building. The architectural values assessed were based on the SAVE method, which was developed by the Danish Plan Protection Agency.

Each criterion is given a certain weight according to its importance. Weighting is obviously subject to discussion, but the process applied here is transparent. For instance, the remaining service life may be given a higher weight than originality, using the argument that an unoriginal building (where non-original features have been added), which is in good condition and has a hundred years of service life left, is more attractive to refurbish than an original building in a bad physical state and only twelve months of estimated service life left. An overview of the weights and tools applied for each criterion can be seen in Table 1.

Concerning the environmental parameters relating to the macro-scale case study, the focus is on embodied energy and on evaluating the energy needed to produce the building materials (from raw materials to plant or construction site) when it is built. As an indicator, embodied

TABLE 1. Overview of weighting and tools applied to the macro-scale case.

Criteria	Weight	Tool	Explanation
Architectural value	5	SAVE (Kulturarvstyrelsen 2011)	As a part of the SAVE method, architectural quality is often given considerable weight compared to most of the other criteria. It is further assumed to be of great importance that the compound is of great architectural and aesthetic quality.
Cultural historical value	5	SAVE (Kulturarvstyrelsen 2011)	As part of the SAVE method, cultural quality often weighs high compared to most of the other criteria. It is assumed that the cultural quality and history of buildings and area are of importance when it comes to preserving (local/national) cultural heritage.
Environmental value	3	SAVE (Kulturarvstyrelsen 2011)	As a part of the SAVE method, the environmental quality is often given considerable weight, along with the two criteria mentioned above. However, it is considered that the general area of the hospital can seem untidy without smooth integration, hence the weighting was reduced.
Originality	2	SAVE (Kulturarvstyrelsen 2011)	As part of the SAVE method, originality is often given a lower weight than the above criteria. As most of the buildings today need ongoing renovation, maintenance and improvement to reach the expected durability, the originality of the design might always be tampered a bit.
Condition	3	SAVE (Kulturarvstyrelsen 2011)	As a part of the SAVE method, condition is often given medium weight. Appearance and condition have an influence on the further service life of the building, hence the middle weighting.
Floor area	1	(measured)	The floor area is weighted low, as it is not seen as a decisive factor. Furthermore, the normalization/span of size is considerable, so large that it can dominate the entire MCDM-analysis. This particular issue is addressed further in the discussion section.
LCA—Embodied energy	4	IMPACT 2002+ (Humbert et al. 2012)	LCAs and the impact potentials obtained through this assessment framework are stimulating greater interest within the building industry. In addition, scarce resources are a paramount concern of various construction stakeholders, while embodied energy is seen as important in evaluating the existing building's impacts.
LCA—Embodied carbon	4	IMPACT 2002+ (Humbert et al. 2012)	As LCAs and the associated impact potentials are gaining in interest, and since embodied energy and environmental energy are not necessarily correlated, it is considered important to evaluate the existing building's main impacts.
Remaining lifetime	5	SBi Standard (SBi = Danish Building Research Institute) (Aagaard et al. 2013)	The buildings in the compound are all constructed of different materials and were built in different decades. It is considered important when the buildings' natural end of life is reached. The lifetime of the main construction material was used in this assessment.

carbon covers the intended reflection of the embodied GHG burden. Hence, both the energy and the GHG measures of environmental impact are taken into account showing how much impact was stored in or has already been emitted by the buildings.

To align the embodied emissions for all buildings, the emissions were 'normalized' according to floor area, hence the final impact potentials assessed in the macro-scale case study were expressed in m^2. To assess which buildings to demolish or refurbish according to their environmental impact, the buildings with the lowest impact per square meter were found to have been the most environmentally efficient, and hence they were more liable for possible demolition. Conversely the buildings that are most likely to be preserved might be those with the highest impact per square meter, as these impacts are not well utilized, and is considered to be a waste to demolish these buildings now and downcycle the materials.

2.4.2 Micro-scale case study

These scenarios are evaluated across four criteria: Physical, Performance, Environmental and Architectural. The *Physical* criteria assessed were floor area, remaining service life span, taking into account the building materials' estimated remaining service life (Aagaard et al. 2013; Møller et al. 2012) and the construction period (i.e., age). *Performance* is assessed using the estimated energy consumption, annual overheating and the amount of daylight (indoor climate). The *Environmental* criteria were included by assessing the recycling rate and embodied environmental impacts in the materials. The *Architectural* criteria were once again assessed through the SAVE concept, and the social context of the surroundings was assessed as an architectural feature. Similarly, to the previous macro-scale case study, each criterion is given a certain weight according to its importance. An overview of the weighting and assessment tools used for each criterion is presented in Table 2.

The environmental parameters for the micro-scale case study were assessed as *embodied carbon*. This assessment also included impacts from renovation actions, both additions and disposals. Transportation to the construction site was ignored, hence it is assumed that 95–98% of the impacts are accounted for by leaving out transportation. The assessed process is handled as a 'black box'[1] process (see illustration in Figure 4).

An additional evaluation of the recycling rate was made based on carbon embodied in the building materials in the existing building compared to the amount of embodied carbon preserved when renovated (see illustration in Figure 5). The evaluation includes embodied carbon-dioxide equivalents (CO_2-eqv.) from the production of materials, but the final assessed criterion, the recycling rate, is expressed in percentages. The higher the recycling rate, the higher the score in the MCDM assessment.

2.5 Visualization

The potential ability to visualize the TOPSIS results through mapping was an important point of focus in the two case studies, as this supports the argumentation and explanations and enables transparency in the decision-making. By mapping the various criteria and the overall results obtained via the MCDM modelling, a visual presentation is obtained for potential use in various respects, such as project decision documentation.

1. A method for obtaining insights into an overall processual behaviour considering only input-output, as the internal workings and mechanisms are often very time-consuming.

TABLE 2. Overview of weighting and tools applied for the micro case.

Criteria	Weight	Tool	Explanation
Energy consumption	4	BE15 (Statens Byggeforsknings Institut n.d.)	Energy consumption is an important factor. Building operation is a large consumer and should preferably be reduced for the security of our environment as well.
Overheating	3	BE15 (Statens Byggeforsknings Institut n.d.)	It is deemed important to have a comfortable thermal indoor environment to ensure user satisfaction.
Daylight	4	VELUX Daylight Visualizer (VELUX n.d.)	Daylight is an important quality in a building and in working environments. Good daylight also minimizes the use of artificial lighting and hence minimizes energy consumption.
Floor area	2	(measured)	The floor area is not considered an important factor in this project, where the focus has been more on functionality and quality. However, it is often an important factor and could in other cases be given a higher weight.
Environmental impact of materials	2	ReCiPe 1.08 (Hierarchist) (Goedkoop et al. 2013b)	Environmental impacts have been given a rather low weight. This is an important factor but due to large uncertainties in the calculations the weight has been reduced.
Recycling rate	4	ReCiPe 1.08 (Hierarchist) (Goedkoop et al. 2013b)	The rate of recycling is given a high weight, as the preservation of resources has become more and more important for the environment and minimizes extraction of raw materials.
Remaining lifetime	3	SBi standards. (Aagaard et al. 2013)	Remaining service life in years is quite important, and a very low timeframe can be avoided if utilising existing materials.
Architectural quality	3	SAVE method. (Kulturarvstyrelsen 2011)	Architectural quality in our surroundings is very important for the preservation of buildings. In this project, however, there are some uncertainties, as a fictional scenario is included. Therefore, a weight of 3 is given.
Interaction with surrounding site	4		Interactions with the surrounding site are considered important in this case especially, as the quality of the area and its concept is important for the city and the site's development.

FIGURE 4. Refurbishment process ('black box' process). Environmental impacts are the sum of the new impacts added (through production of new products) to the building together with the impacts from the disposal (of the removed/replaced products). Thus, only obtaining insights into the overall processual behaviour considering only input-output, as the internal workings and mechanisms are not known.

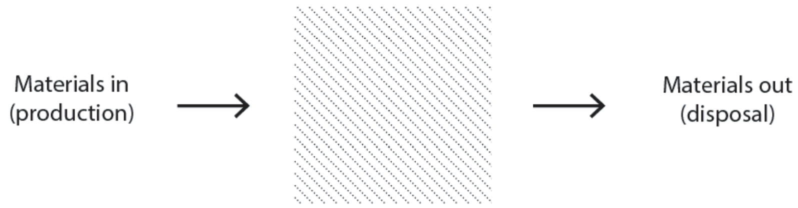
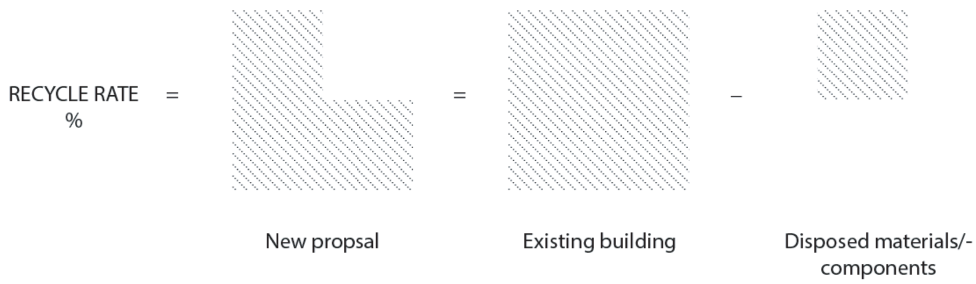


FIGURE 5. Recycling rate: Embodied carbon (contained in the remained materials) in the new proposal compared to the Embodied Carbon content of the existing building.



3. RESULTS

3.1 Macro-scale case study

On the macro scale, all the buildings on the site are included in the MCDM analysis. The purpose of this analysis is to rank all buildings in the hospital compound according to their preservation values. The MCDM process yields a ranking of how close each building is to the ideal solution. In this case the buildings closest to the ideal solution are more likely to be preserved than the buildings at the other end of the ranking spectrum.

Figure 6 presents an example of the mappings of rankings used to visualize the TOPSIS results on the macro scale. The mapping illustrates the entire urban area that was assessed and marks the relative closeness to the ideal solution of all the assessed buildings and other structures. When all the criteria covered in the MCDM of the macro-scale case study had been evaluated, it was found that the buildings marked in the lightest colour were those that were to be preserved, whereas the darker ones were more likely to be recommended for demolition based on the assessment criteria.

FIGURE 6. Ranking map showing mapping of the relative closeness to the ideal solutions of all buildings at OUH.

3.1.1 Visualization

For each criterion shown in Table 1, the *performance* of the buildings was visualized in mappings in order to facilitate the communication and transparency of the results. Figure 7 shows how the buildings throughout the urban compound perform in terms of their relative ranking, e.g., the mapping of the floor area, shows the dark-coloured building with the largest floor area of > 40,000 m^2, while the light-coloured buildings have a floor area of between 0–1000 m^2. See additional explanation on the criteria performance visualization in Table 3.

TABLE 3. Explanation of mappings shown in Figure 7.

Architectural value	Mapping the architectural quality of the buildings at OUH according to the SAVE method. The lighter the colour, the better the performance rating.
Cultural historical value	Mapping of the cultural-historical quality of the buildings at OUH according to the SAVE-method. The lighter the colour, the better the performance rating.
Environmental value	Mapping of the Environmental Quality of the buildings/OUH site according to the SAVE-method. The lighter the colour, the better the performance rating.
Originality	Mapping the Originality of the buildings at OUH according to the SAVE method. The lighter the colour, the better the performance rating.

TABLE 3. *(Cont.)*

Condition	Mapping of the Condition of the buildings at OUH according to the SAVE-method. The lighter the colour, the better the performance rating.
Floor area	Mapping the total area above ground of the buildings at OUH. The lighter the colour, the smaller the floor area.
LCA—Embodied energy	Mapping the Embodied Energy per square meter, in MJ, of all buildings at OUH. The lighter the colour, the lower the impact.
LCA—Embodied carbon	Mapping the Global Warming Potential per square meter, in CO_2 equivalents to air, of all buildings at OUH. The lighter the colour, the lower the impact.
Remaining lifetime	Mapping the expected expiration time of the buildings at OUH. Yellow: 5 years; Orange: 35–45 years. Purple: 55–65 years; Grey: 75–85 years; Brown: 'unlimited'.

FIGURE 7. Visualization through mapping of the evaluation criteria for the macro-scale case study, as presented in Table 1.

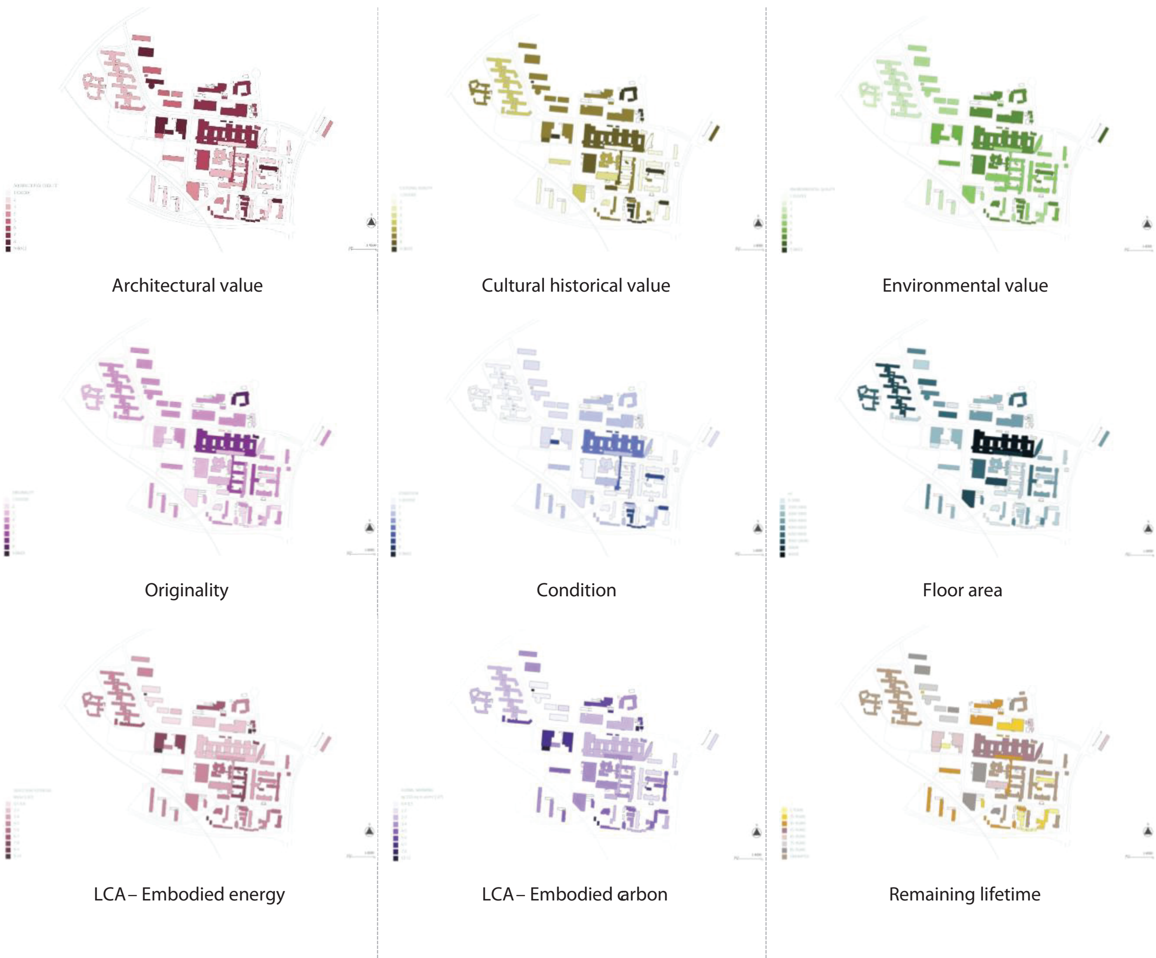
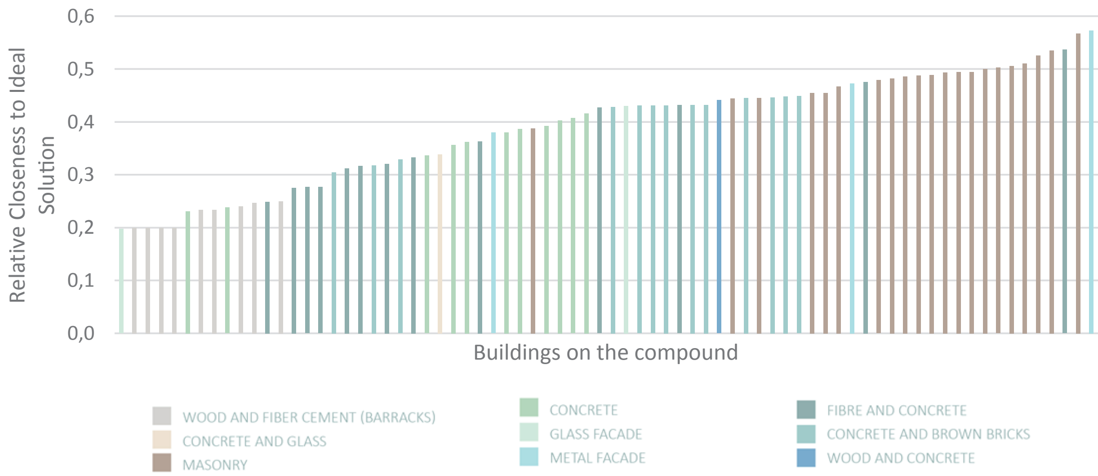


FIGURE 8. Distribution of the MCDM results from the macro-scale case study: values on relative closeness to the ideal solution. The better (closer to 1) the score the more preferable the solution.



Using the results of the MCDM calculation, a pattern was established for the different building types in the compound (see Figure 8). Small, temporary barracks were found to be far from an ideal solution, hence they were placed in the group of buildings proposed to be demolished. At the other extreme, and closer to the ideal solution, were old brick structures which were in good condition and represented great architectural- and cultural historic value.

3.2 Micro-scale case study

In the micro-scale case study, the issue is slightly different from that in the macro-scale case study. Here, the decisions to be made are about the fates of the individual buildings which was tested through an example of one of the buildings, with four different suggested scenarios. The MCDM will subsequently calculate which scenario is the most preferable for each building. Each scenario is evaluated according to several criteria. The scenarios considered are the following: demolish and construct a new building; maintenance; minor renovation, including actions to reduce the building's energy consumption; and larger renovation projects to transform the building while reusing the original structure.

3.2.1 Visualization

Since four refurbishment strategies were assessed, a visualization representing the extent of the designs was made (see Figure 9 to Figure 12).

A direct comparison of the scenarios within each criterion was conducted as illustrated in Figure 13, followed by assessment through MCDM to obtain a *single score* result indicating an overall assessment taking into account all included criteria.

The results of the MCDM analysis of the scenarios for a single building provided a ranking of the scenarios and indicated which scenarios were more desirable. This is shown in Figure 14. The least preferable solutions were those with minor renovations, illustrated in Figure 10 and Figure 11. As illustrated in Figure 14, there was no significant variation between the two scenarios. The best solution was that involving a transformation and the preservation of the original construction, as shown in Figure 12.

FIGURE 9. Demolish and build new. It is assumed that the existing building is demolished and a new standard office building is constructed. Mentioned as scenario 1 later on.

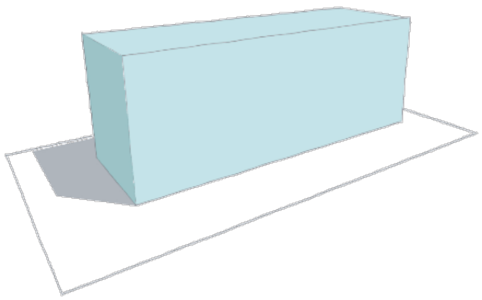


FIGURE 10. Maintenance. In this case only necessary elements are renewed. These elements include windows, roofing felt and Eternit coverage on the 7th floor with installations. No maintenance of installation systems is considered and therefore is not taken into account. Mentioned as scenario 2 later on.

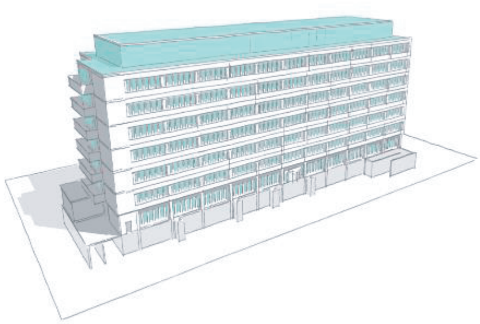


FIGURE 11. Maintenance and façade optimization. All elements of scenario 2 are renewed, and then additional insulation is added to the external walls and around external concrete columns, which results in a slight reduction in the width of new windows. Again, no measures on technical installations are considered. Mentioned as scenario 3 later on.

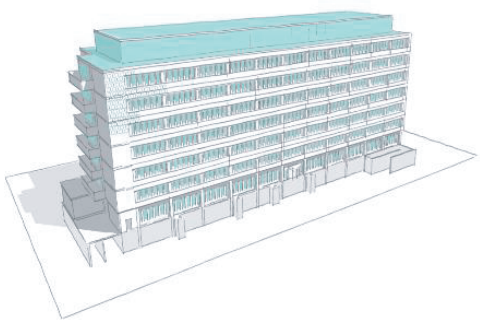


FIGURE 12. Major renovation. In this case larger parts of the building are removed. A new design for the building is drawn up, giving the building a new interior composition and function, with studios and exhibition rooms for entrepreneurs. The basic maintenance from scenarios 2 and 3 is still implemented. As in scenario 2 and 3 no actions are considered for the technical installations. Mentioned as scenario 4 later on.

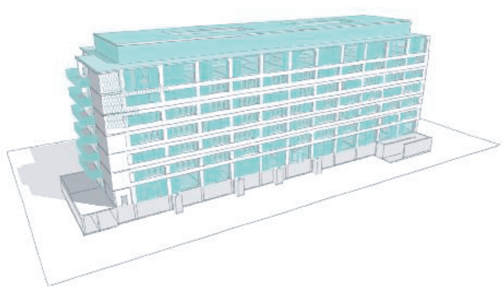


FIGURE 13. Direct/relative comparison of the scenarios (x-axis) within each MCDM criterion (relative comparison on y-axis. Each diagram represents one criterion). Actions taken in the different scenarios are illustrated and explained shortly in Figure 9 to Figure 12.

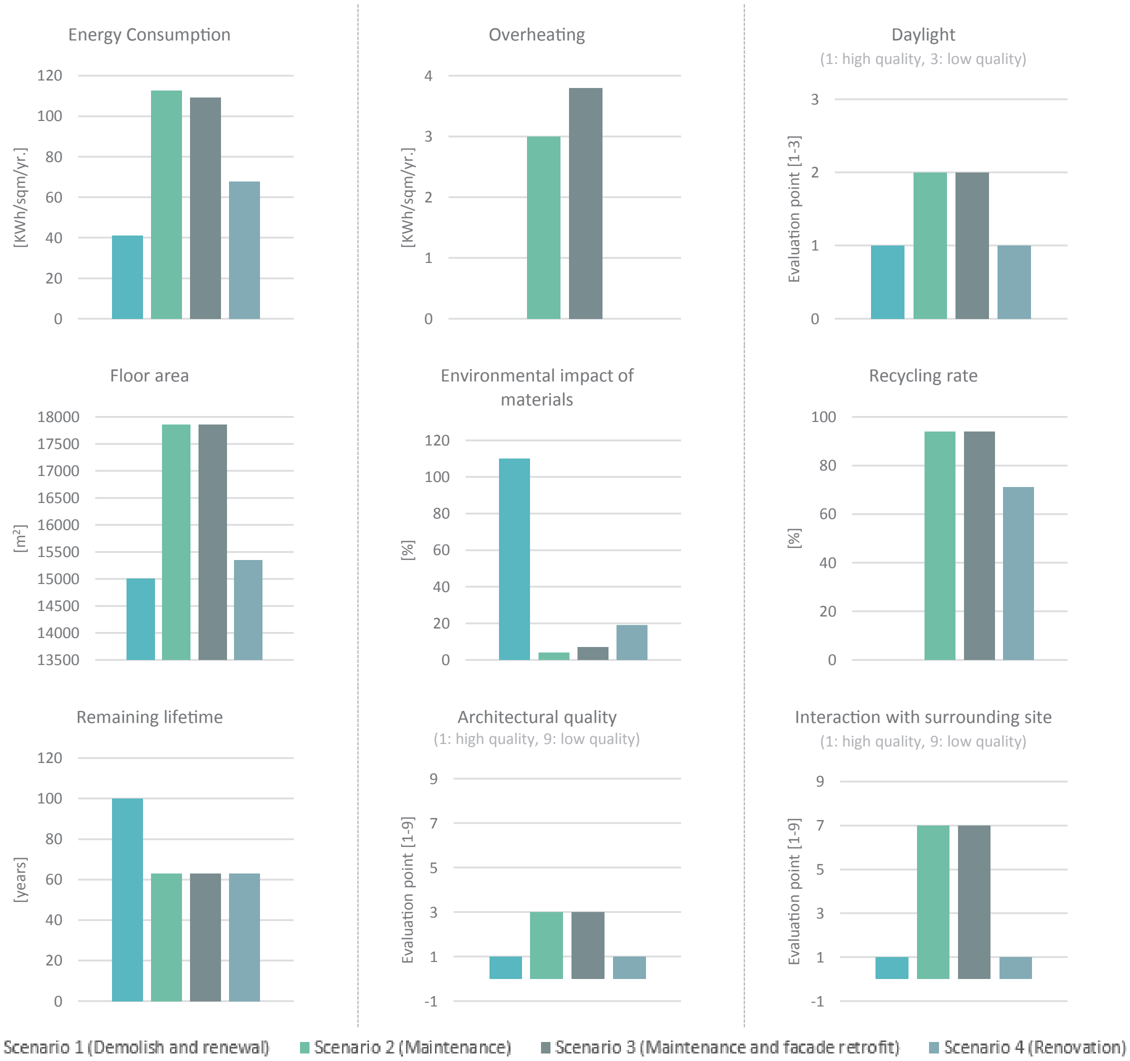
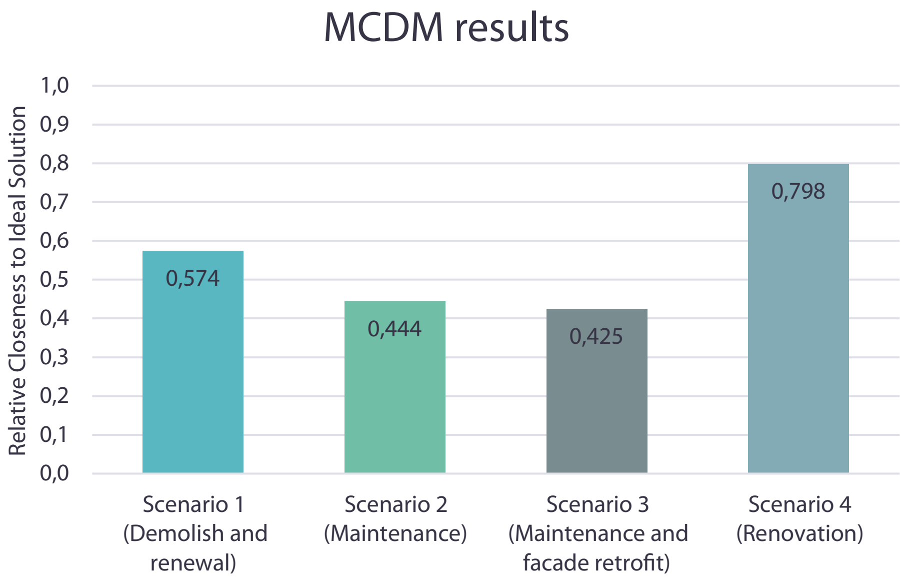


FIGURE 14. MCDM results of micro case study: values for relative closeness to the ideal solution. The better the score the more preferable the solution/the closer to the ideal solution.



4. DISCUSSION

The decision support tool presented was able to include all the desired parameters and proved flexible across project scales. Nevertheless, the more parameters included, the more time was needed for the decision-making process. The process itself is time-consuming as it forces an opinion/result/data for each criterion for each alternative. Hence the decision-making process requires considerable time in order to obtain a thorough and usable analysis, mainly due to the amounts of data needed. However, the results will be much more thorough as all arguments/criteria for each alternative is included and accounted for consciously, compared to when not applying the method. In relation to large-impact decisions such as large-scale demolition or refurbishment, it is considered worth prioritizing spending the necessary time on the MCDM process and calculation tool in order to make the right decision, satisfying the overall project group, instead of risking a wrong and non-transparent outcome potentially with great consequences.

The weighting is itself a decision-making process and is hence very important to take into account. It carries the risk that it may considerably affect the results. It is important to apply objective weightings if an objective result is desired, as the tool cannot do this on its own. Objectivity in terms of weighting can be reached by involving a variety of stakeholders. As the (weighting) inputs have human origins, the assessment cannot become fully objective or normative, but works as guidelines and sets a direction. On the other hand, a certain project group might have certain wishes and interests for their construction project and the weightings might not be considered objective generally, but as long as they represent the general objective opinions of the project group (and the project group is aware of this) the results will indicate the opinions and arguments of the project group.

The MCDM calculation delivers a value for the relative proximity to the ideal solution. This value does not tell us anything in itself, but it is useful for comparing different solutions in a multitude of dimensions.

4.1 Strengths of the method

The use of mathematical systematics forces participants to be specific in their opinions, and everybody involved should have the chance to react to the weighting of the various criteria covered. This eases communication, as the process becomes transparent. Qualitative values such as cultural heritage will not be as easily overruled in a TOPSIS model because the weighting against quantitative issues is explicit.

The tool helps maintain an overview of a complex and multifaceted situation. It facilitates keeping track of conflicting factors and allows obvious patterns and dependencies to become manifest and be visualized.

Further, the tool is easily adapted to any project group and with different interests/goals as long as the weights and criteria are considered and handled with careful considerations and awareness as the results are directly calculated from these.

The tool allows sustainability factors to be included and with the same weight as all other parameters. Cultural heritage depends on the cultural orientation of the decision-maker giving it excessive weight, meaning, for example, that sustainability might be overruled in a conventional non-transparent and implicit decision-making process.

Furthermore, TOPSIS allows stakeholders to be aware and explicit about how they define sustainability. For instance, stakeholders may include environmental impacts, whether as impacts induced by future actions and/or as preservation of the embodied energy and carbon in the existing building. Perhaps both criteria are important and might vary depending on the question asked. The tool does not help decide on these issues, but it allows decision mapping and the inclusion of various parameters.

Ideas for further applications include, for example, architectural competitions for both judges and competitors, as the decision-making tool is transparent and could help competitors to profile themselves in a meaningful way. The method is thus flexible, and not only implementable for final project assessment/evaluation but could also work as a starting point for discussions (within a project group) on what is important in a project, what should be investigated/analysed and what should be prioritized.

4.2 Limitations of the method

The tool obviously cannot include important unconscious factors like the brain can, which has both advantages (i.e., everything relevant must be entered) and disadvantages. Everything relevant has to be entered into the calculation. In addition, a subjective opinion can be ignored and thus not dominate the decision making (unless it is so desired of course).

4.3 Sensitivity of the method

A sensitivity analysis as such has not been performed for the case studies, as the sensitivities will be dependent on the criteria implemented in the specific project. It was however found, in the presented case studies, that the changes in results, caused by changes in the weighting, depends on the span within the criteria among the different alternatives.

An example on the sensitivity of the case study on macro scale, is the floorage of the buildings. The buildings were found to have floorage spanning from 100m^2 to 10,000m^2. It was found that, when using a high or average weight (of 5 or 3), building with a floor area of 10,000 m^2 dominated the results. This means that when a criterion has such a large impact, its weighting will have a crucial and exaggerated impact on the results and might even affect the calculation in such a way that all the other criteria seem to have no importance at all.

In order to reduce the dominance of the floorage, the weighting was thus changed to the lowest (1).

In other criteria where the spread was smaller, e.g., Architectural value, which were rated from 1–9, a change in weighting would not cause a big change in the MCDM results.

Whilst the above patterns were found, it was not deemed necessary to perform sensitivity analysis, as the application of the method is subjective—a/the weighting therefor depends on which criteria the project group prioritizes and find important.

As the 'results' presented in the article are case studies used to illustrate the use/applicability of the MCDM method, it is found irrelevant to discuss 'robustness' or sensitivity of the specific results.

For the case studies, assessed by the particular project group (here, the authors) the results are seen as correct as they reflect the general opinions, criteria and priorities of the authors. However, if the project group consisted of other people, the results may have looked different, reflecting their opinions, criteria and priorities.

It may be debatable, however the general opinion is that the bigger a project group, the more objective the results, as more people have been included in the decisions making. The method and calculations would however still be the same, using mathematical formulas to find the optimum, according to a set of priorities chosen by the project group.

4.4 Further potential

All inputs to the TOPSIS tool are added manually. It has great potential for automation in, for example, a Building Information Modelling (BIM) context, which would make the process less costly and even more operational. BIM integration could be done by setting up a fixed set of criteria which could be repetitive and quantitative. A plug-in for MDCM criteria extraction could be developed, enabling a quick data output on e.g., cost, floorage, LCA, IEQ, energy consumption etc. (depending on other BIM plug-ins already developed). By extracting the quantitative measures for a design proposal from BIM, they could then be matched with qualitative values through the MCDM method.

However, a BIM optimization of the MCDM method would not be applicable for all types of projects. In the case studies presented, it might be more suitable for the micro-scale case study (as project proposals are modelled in BIM), whereas the macro-scale case study would not be as suitable, as a modelling of the entire urban area is not necessarily done and needed.

Some work has already been investigating the integration of MDCM tool within BIM. (Chen and Pan 2016) evaluated implementing MCDM (using fuzzy Preference Ranking Organization METHod for Enrichment Evaluation—PROMETHEE) into BIM for selections of Low-Carbon building (LCB) measures.

Also (Jalaei et al. 2015) investigated the integration of MCDM and BIM, looking into how Entropy-TOPSIS can be used to develop a Decision Support System (DSS) which should help a design team in deciding a optimal solution between several conceptual designs proposals.

In the analysis of the case studies, other criteria that could have been included are cost and finance, fire protection, eco-toxicity, CPTED (Crime Prevention Through Environmental Design) (ICA n.d.) and social sustainability criteria. The choice of criteria should be decided by the stakeholders/project group in each project, since the relevance varies and again depends on the questions asked.

If an objective set of weights are desired, an extensive study should be carried out. In addition, criteria of any MCDM analysis should be structured through a hierarchy which was not considered in this study.

The hierarchy should be established, for instance, with three main criteria of sustainability; environment, economy and social, where each main criterion consists of a number of detailed/sub criteria. An example could be (as illustrated in Figure 15); Environment might contain embodied energy, embodied carbon, recycle rate, etc., whereas the Social criterion contains architectural qualities as well as e.g., indoor environmental qualities (lighting, air quality etc.). Finally, Economy may consist of cost and energy consumption. The weights will then be applied for each set of criteria-group, which again is sub-weighted within these criteria groups—e.g., Environmental sustainability has been weighted with 50% of the total in the main criteria and the sub-criteria within has been weighted 45%, 45% and 10% respectively of the 50% weighting.

Thus recycling rate should not be compared to degrees of overheating as the comparison and judgement between such two detailed criteria is complex. Using this hierarchy method could further have enabled the weighting to be smoothed out in the current case study, considering the 'issue' found with the dominant floor area.

Even though a screening of established MCDM methods was performed, from which TOPSIS was chosen as optimum method, an explicit 'validation' could be interesting to perform, to map the strength and weaknesses of the methods for decision support applying project criteria in the Built Environment. Using the same case study throughout such a comparative review, would enable a direct comparison of usability.

FIGURE 15. Example of additional hierarchy, applying main criteria and sub-criteria weighting.

5. CONCLUSION

In both the macro- and micro-scale case studies, the TOPSIS tool was found to be applicable and proved to be operational in the design and planning process. The tool is applicable for decision support in prioritizing different renovation scenarios, such as whether to demolish or refurbish. And if refurbishment is chosen, how to refurbish?

The results of the chosen case studies, provided by the tool, gave simple and transparent indications of the solutions which proved the most preferable according to the method presented. The MCDM tool eases and facilitates the decision-making process by making it transparent and communicable while keeping numerical track of all the arguments used. It was demonstrated that it is possible to communicate the results of the TOPSIS process by means of visual mappings, further enhancing the communication of the results.

While the method presented is well documented by literature, the implementation and use of it as decisions-support in building projects with multiple stakeholders is innovative. It enables a group of people/stakeholders to sum up several criteria/qualities to one aggregated score, considering both soft values and knock-out performance criteria, along with enabling an evaluation of both qualitative and quantitative values within the same analysis.

The TOPSIS process allows stakeholders and others involved in a project to understand and follow the motivation of the scores. However, as the method might imply a more time-consuming decision-making process (at least for the decision-makers), it is important to consider the time/cost factor in relation to the importance and relevance of the method application. In other words, if the consequence of applying the method is small, the time used in decision-making should be small and vice versa. Finally, as the tool cannot make the actual decision itself, the results should be included in the decision-making process as guidelines or as a way to validate/illuminate a decision that has other origins.

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