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A hierarchical reference-based know-why model for design support of sustainable building envelopes

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A B S T R A C T

In current complex building designs, sustainability assessments are often performed after project completion, with limited impact on building performance which results in missed goals in terms of quality, cost, and time. We address this problem by proposing a hierarchical reference-based know-why model to answer the research question "what is a suitable decision support model to successfully integrate the sustainability requirements in the early design phase of buildings?". The model presents a process that incorporates a life-cycle perspective and calculates design alternatives based on a defined reference and the DGNB building certification system. The results show that criteria synergies and trade-offs can be identified, leading to improved design by engineers and better building performance. Our findings pave the way for full integration of the model into building information modeling, combined with artificial intelligence. This can help manage the complexity of the sustainable design process on the path to carbon-neutral buildings.

1. Introduction

Greenhouse gas emissions and the associated global warming caused by humankind has been changing life on our planet. Pollution, deforestation, overusing fossil fuels and other changes all have been triggering climate change which necessitates swift response and taking proper measures in all economic sectors to reduce the negative impact on the environment. Objectives from all sustainability dimensions are now increasingly entering the policy realm [1,2]. According to Rockström [3], four out of seven planetary boundaries have already been exceeded. In addition to the areas of biodiversity loss, nitrogen cycle and land use, the limit exceedances also concern climate change [4].

One of the sectors that is largely responsible for these negative environmental trends is the construction sector [5–7]. The construction sector consumes 40 to 75% of the total value of materials mined worldwide [8]. In addition to the enormous amount of extracted materials, the construction sector is also responsible for consuming 25% of the global water [9]. In terms of emissions, the construction sector is accountable for emitting 39% of global greenhouse gas emissions [10]. With the 2030 Climate Target Plan, the European Union aims to reduce greenhouse gases by 55% compared to the amount in 1990. To achieve this, greenhouse gas emissions in the construction sector must decrease by 80 to 90%, and building-related energy consumption must decrease by 14% [11]. Based on these alarming numbers, sustainability assessment of buildings is becoming increasingly important.

In the context of reducing the environmental impact of buildings and increasing the building quality, the design phase of buildings is crucial due to the maximum flexibility in terms of considering and implementing sustainability aspects [12,13]. However, it is not practicable to design based on repetitive procedures and processes because of the unique features of each building. Additionally, the design process is emphasized by sustainability requirements due to the overall complexity inherent to each building, given by structural, static, and building physics constraints.

Back in 2008, ISO 15392 established a uniform understanding of sustainability for the construction sector [14]. Progressive work at the European level has created harmonized standards and numerous normative and voluntary instruments to promote the implementation of sustainable construction [15]. The European framework of CEN/TC 350 states that in addition to the three sustainability dimensions, i.e., environmental dimension, economic dimension, and social dimension [16], also the functional and technical qualities of buildings must be taken into account in sustainability assessments [17–20]. In order to be able to evaluate these multitude aspects in terms of sustainability, numerous

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building certification systems have been established on the market over the last two decades. Many of these building certification systems consequently include complete sets of criteria for sustainability assessment, although with different concentration.

The problem thereby lies in the circumstance that sustainability assessments are often carried out after project completion, where there is limited possibility to influence the building performance and the sustainability assessment result within building certification systems. In order to perform a sustainability assessment in the design phase of buildings, the criteria as well as their interdependencies must be considered. In this regard, various systemic approaches in relation to sustainability criteria interactions in the construction sector are discussed in [21–26]. However, due to excessively complicated interdependencies among factors, the application of systems thinking methods in the design phase of buildings is not straightforward [27].

In this context, Building Information Modeling (BIM) as one of the main streams of the Industry 4.0 era is also at the center of the transformation of the planning process. The implementation of sustainability aspects in BIM has become increasingly important in research in recent years [28,29]. Particularly in the design phase, BIM already has offered the possibility to implement, in addition to 3D modeling, the time scheduling (4D), the cost estimation (5D) as well as aspects of sustainability assessment (6D) [28,30]. Design tasks that can be integrated in BIM include energy performance analyses, CO_2 emission analysis, solar and light simulation, thermal comfort analysis and waste management [29,31]. Due to the growing impacts of climate change, implementation options for Life Cycle Assessment (LCA) in BIM are being promoted [32–34]. In addition to the ecological assessment of buildings, the economic assessment of buildings is also being integrated into BIM by means of the Life Cycle Costing (LCC) method [35,36]. Initial approaches that address the problem of systemic interactions of different sustainability requirements are already analyzing different building designs and their interdependencies in terms of different sustainability criteria, e.g., LCA and LCC [37,38].

Nevertheless, the implementation of tools or methods for a holistic building design in the design phase is indispensable. If a parameter is changed in a system with four or more interacting parameters, its effects on the system cannot be perceived manually [39]. Due to this, the way of thinking in simple logical contexts often leads to overlooking medium or long-term effects on the immediate environment. Future generations are endangered, when the objectives of sustainable development cannot be reached [40]. In order to deal with complex systems and the associated inherent dynamics of the systems, a networked way of thinking is necessary [41].

The implementation of sustainable buildings is a multidimensional concept that is gaining relevance in all areas of society [42]. Barbier [43] states that sustainable development involves the simultaneous maximization of environmental, economic, and social goals. However, as Munda [44] has shown, it is generally not possible to maximize different goals simultaneously. Therefore, a compromise between the different objectives must be found, which can be achieved by applying a proper Multiple Criteria Decision Making (MCDM) method. MCDM methods have been largely used in the construction industry in a variety of practical topics and contexts. These include, for example, the selection of construction materials [45,46], the selection of construction equipment [47–49] and risks of construction projects [50]. In this context, MCDM methods were also addressed in relation to the evaluation of green construction suppliers in designing processes of construction supply chains [51]. Within the environmental topics, MCDM methods have been applied, for example, in waste management, energy management [52], wastewater treatment, water quality, or air quality. For a review of MCDM methods applied in the (sustainable) construction industry, see the review articles by [55,57]. Other examples include transportation and logistics in general [7,53,54], but also transportation and logistics considering environmental issues [56,58].

The goal of the article is to support the consideration of sustainability aspects in the early design phase of buildings by developing a suitable decision support model. In this study, we take advantage of a MCDM method named hierarchical decision modeling (HDM) and combine it with the principles of the know-why method which is a systems thinking methodology. The proposed hybrid model (i.e., hierarchical reference-based know-why model) incorporates the advantages of a classic MCDM approach in dealing with complex set of goals, alternatives and criteria and a systemic approach to handle the relationships between them.

The rest of this article is organized as follows. In Section 2, materials and methods which are employed in our research are discussed. In Section 3, the proposed hierarchical reference-based know-why model is explained. Results are presented in Section 4 and findings are discussed in discussion section (i.e., Section 5), followed by the conclusions, limitations, and future research directions in Section 6.

2. Materials and methods

2.1. Research framework

With the aim to develop a decision model based on given sustainability requirements and considering the systemic interactions, a research question is developed as: *what is a suitable decision support model to successfully integrate the sustainability requirements in the early design phase of buildings?*. To answer the research question, three approaches have been applied in our proposed model including (i) building certification systems, (ii) MCDM methods and (iii) systems thinking approaches. In contrast to BIM, the hierarchical reference-based know-why model is characterized by the unique selling point that it can be filled with qualitative or semi-quantitative data, thus reducing the time-consuming data acquisition in the early design phase of sustainable buildings. As shown in Fig. 1, the hierarchical reference-based know-why model lies in the intersection of these three approaches and docks with the method of BIM, as it could also be fully integrated into BIM in future research.

2.2. Building certification systems

Frameworks for assessing buildings in terms of sustainability have been established since the last decade of the 20th century [59,60] leading up to 600 assessment methods now available [61]. The range of sustainability issues that are addressed by these methods is diverse and ranges from a single topic, such as energy efficiency, to a broad spectrum of topics that belong to all three pillars of sustainability. Building certification systems are considered objective and contain clear comparative tools for a holistic sustainability assessment of a building. Moreover, they are developed and structured in a way that results of the building assessment are transparent and are followed by a certificate suitable for the use in the building market. The sustainability criteria are, however, assigned and weighted differently in various systems [62]. Because of the huge amount of sustainability criteria in building certification systems, the majority of users and planners lack knowledge about their effects on the certification result and therefore on the quality of the building. For this reason, the systemic interactions among the criteria of building certification are frequently underestimated [63–66] and stakeholders need a building management tool based on sustainability criteria [67].

From the comparison of several building certification systems, we can state that the DGNB criteria set is an advanced certification system of the so-called 2nd generation [23] and in line with the CEN/TC 350 requirements [17–20]. Due to this and due to the certification of the case study according to the building certification system DGNB, it was applied for further model development [68].

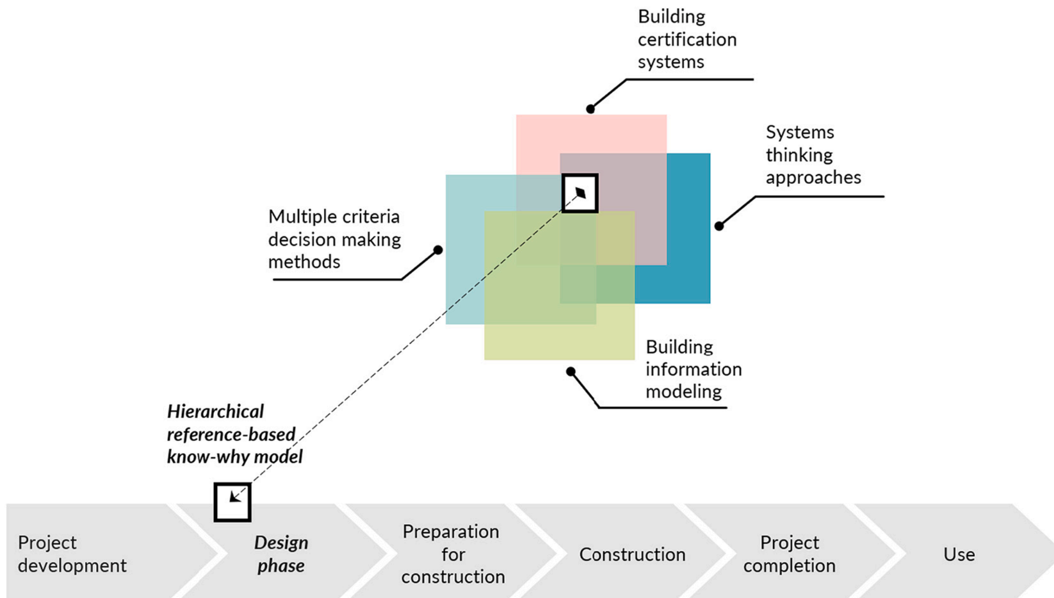

Fig. 1. Research framework.

2.3. Hierarchical decision modeling (HDM)

HDM was introduced by Chen and Kocaoglu [69] as an MCDM method. HDM helps decompose problems into hierarchical levels in order to deal with multiple decision layers which are common in complex decision-making problems [70]. HDM represents the problem in a hierarchical structure by providing a visual understanding for decision makers to understand which criteria or sub-criteria can influence the objective or mission [71]. A mission-objective-goal-strategy-action model (MOGSA) including five decision levels was also proposed as the classic structure in the literature [72]. However, the structure can vary based on specific requirements in each use case [71]. For instance, a three-level HDM (mission, perspectives, factors) is depicted in Fig. 2.

HDM has been applied in various decision-making contexts such as technology transfer in the energy sector [56], laptop purchase problem [73], stadium site selection [74], solar photovoltaic technologies [75] or health technology assessment [76].

The mathematical background of a three-level HDM (mission, perspectives, and factors) as shown in Fig. 2 is presented in Eq. (1) [54,56].

$$V_{n,j} = \sum_{n=1}^{N} \sum_{j=1}^{M} w_n C_{n,j} \tag{1}$$

where,

$V_{n,j}$ = relative value of the jth factor under the nth perspective.

w_n = relative priority of the nth perspective.

$C_{n,j}$ = relative contribution of the jth factor under the nth perspective.

2.4. Know-why model

Systems thinking has become increasingly important in recent years. Various systemic approaches in relation to sustainability criteria interactions in the construction industry are discussed in [25,77–79].

While Zavadskas et al. [66] emphasizes the importance for building management tools based on sustainability criteria for stakeholders in the design phase of buildings in general, Neumann [27] go in more detail and argue that the reason why it has been quite complicated and tedious to analyze these individual cause-effect relationships so far seems to be mainly because the tools and methods needed to do so have been far too complicated, why a further development of simple tools, but also tools for qualitative assessment is necessary.

Qualitative modeling, in contrast to quantitative modeling, requires no specific data, formulas or parameters and does not lead to exact scenarios, which in many cases are not accepted as accurate anyway. Above all, the only rough, qualitative description of interrelationships is much faster. Such a rough weighting of the interrelationships also stands up to scientific criteria. For many challenges of the present and future, we would not be able to fall back on data from the past - therefore, the only remaining option is an investigation based on abductive-logical conclusions, i.e., a consideration of the consequences of an assumption that is valid until it can be refuted. Errors can still occur, if illogical connections are made or decisive factors are not considered at all.

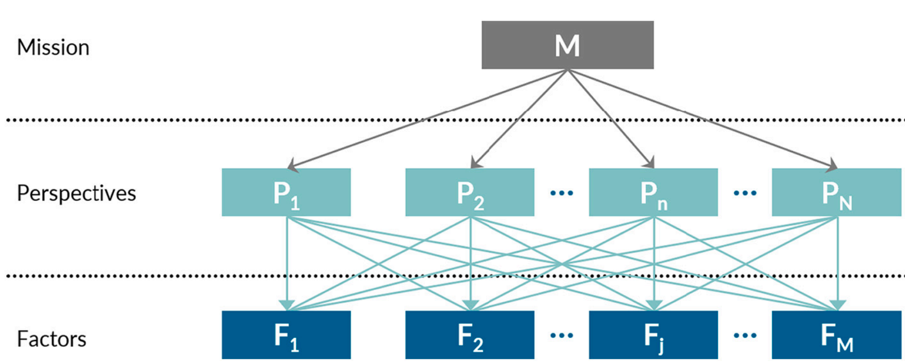

Fig. 2. Three-level HDM.

A method that supports the qualitative (but also quantitative) modeling of complex systems is the know-why method. The know-why method offers a highly practical approach to addressing the complex challenges of business, politics, and personal life. The know-why method simply asks you to consider the evolutionary pattern of success by answering the four know-why questions in the course of qualitative or quantitative modeling [27,80]. These four questions are (i) what leads directly to more of it right now?; (ii) what leads directly to less of it right now?; (iii) what might lead directly to more of it in the future?; and (iv) what might directly hinder it in the future?.

These four questions are modified for the proposed hierarchical reference-based know-why model based on the defined reference alternative as follows:

(i) what leads directly to more of it right now compared to the reference alternative?
(ii) what leads directly to less of it right now compared to the reference alternative?
(iii) what might lead directly to more of it in the future compared to the reference alternative?
(iv) what might directly hinder it in the future compared to the reference alternative?

This modification leads planners to being able to answer the know-why questions for alternatives (building envelopes) in the early designing phase based on their experience compared to an already known and unchanging alternative (reference building envelope).

The modification of the know-why questions as well as its application was tested in a research project during the design of building envelopes and used for the development of a sustainable design process (see supplementary materials). Therefore, the term "design" is not only understood as the design of the whole building, but also the design of individual building elements.

3. Hierarchical reference-based know-why model

A combination of building certification systems (in our case DGNB) and HDM can help facilitate the understanding of complex systems by breaking it down to individual interrelated levels. Thus, a hierarchical reference-based know-why model can help identify the most appropriate alternatives based on the building certification system, the hierarchical structure, and by incorporating individual preferences compared to a reference alternative. The proposed model is comprised of the following steps:

Step 1: Identify criteria, sub-criteria, alternatives and the reference alternative.

The façade-relevant certification criteria were identified along with sub-criteria, alternatives and the reference alternative.

Step 1.1. Relevant certification criteria for buildings envelopes.

A total of 17 expert workshops were held with the aim of identifying the influencing certification criteria for assessing different building envelopes. The overall goal of the workshops was to determine the influence of different building envelopes on the façade-relevant certification criteria and therefore, on the certification results. In each of these workshops, it was ensured that at least 6 experts with different professional backgrounds (i.e., structural engineers, thermal engineers, industrial engineers, economic engineers, and sustainability assessment experts) participated in order to guarantee the interdisciplinary constellation.

In the first series of workshops, the façade-relevant certification criteria were identified. For this purpose, the certification criteria of the DGNB building certification system were used to identify criteria which were "façade-relevant" or criteria for which the building envelope had an influence on the sustainability assessment at the building level. In the sense of a "top-down" approach, based on the DGNB building certification system, the certification criteria were broken down to the building component level. The analysis has shown that the building component "building envelope" influences a total of 22 out of 38 criteria. In order to be able to depict the influence of building envelopes on the life cycle phases in more detail, the criteria "building life cycle assessment" (ENV1.1) and "life cycle cost" (ECO1.1) were subdivided into three further equally weighted criteria. The criteria ENV1.1 and ECO1.1 address LCA and LCC. These two methods cover and evaluate the entire life cycle of a considered building, a considered building component or a considered building product. In order to evaluate the alternatives in more depth, these two criteria were divided into the production phase (ENV1.1a and ECO1.1a), the use phase (ENV1.1b and ECO1.1b) and the end-of-life phase (ENV1.1c and ECO1.1c). Thus, the 22 identified façade-relevant criteria resulted in 26 criteria, which were used for the expert evaluation. Based on the identified façade-relevant criteria, the sub-criteria were based on the DGNB building certification system (see the appendix).

Step 1.2. Reference alternative.

In the second workshop series the reference alternative was chosen, and other building envelope alternatives were designed. The reference alternative was the case study "Karmeliterhof" (an office building situated in Graz, Austria), which served as the assessment basis for the other alternatives (Table 1).

The six-story office building was designed as a solid construction. Non-load-bearing walls and parapets were made of brick or double-shell plasterboard. The building envelope was composed of a 16 cm thick thermal insulation composite system. The roof construction was made of a warm roof with a roof covering in fiber cement. The transparent exterior components were made from double glazing. The floor covering composed mainly of industrial parquet, the kitchenettes and sanitary facilities on the individual floors had a ceramic floor covering. The floors of the technical rooms in the cellar had an epoxy coating. Glass walls were also constructed as non-load-bearing dividing walls. The proportion of window area in the building was around 26%. The building was heated via a district heating connection. The heat was emitted by radiators and convectors - with the exception of the entrance hall on the first floor - where heating walls and floor heating are installed. Ventilation of the sanitary facilities was mechanical. There was no controlled ventilation of the office areas. Hot water was supplied centrally for the first floor, while the upper floors were supplied decentrally via undersink storage tanks. The same for the kitchenettes and sanitary facilities on each floor. The shower in the cellar was centrally supplied. The building also had a multifunctional room, which was equipped with air conditioning.

Step 1.3. Development of alternatives.

In total, 13 further alternatives were designed with different properties, in which, in addition to the construction structure, the energy generation with solar and/or photovoltaic, the heating and/or cooling possibilities of the building envelope typologies and combination of these were considered. The designed building envelope alternatives are shown in Table 2.

Step 2: Decompose the problem into a hierarchy.

The problem can be decomposed into a few levels in order to make the problem more comprehensible as such a four-level HDM is proposed

Table 1
Case study parameter Karmeliterhof in Graz, Austria (reference alternative).

Characteristics	Measured value
Building type	Office building
Gross floor area	2300 m^2
Stories	5 + 1
Outer wall construction	Reinforced concrete, brick wall, thermal insulation system
Energy efficiency class	B (39 kW/m^2*a)
Surface-volume ratio	0.21 [m-1]
Heat generation	District heating
LEK value	33 [−]
Average U-Value	0.565 [W/ m^2*K]

Table 2
Description of building envelope typologies.

Alternatives	Building envelope typology	Construction	Energy generation	Conditioning
R01	ETICS[1]	Massive wall construction with window bands Plaster – Brick (25 cm) – EPS[2] (16 cm) - Plaster	–	–
A01	ETICS[1]	Massive wall construction with window bands Plaster – Brick (17 cm) – EPS[2] (16 cm) - Plaster	–	–
A02	M&T[3]	Curtain wall (Skeleton construction)	–	–
A03	M&T[3]	Curtain wall (Skeleton construction)	No element-integrated energy generation (façade collectors)	–
A04	M&T[3]	Curtain wall (Skeleton construction)	Energy generation (photovoltaic modules)	–
A05	M&T[3]	Curtain wall (Skeleton construction)	–	Room conditioning (heating and cooling system – building element activation)
A06	M&T[3]	Curtain wall (Skeleton construction)	No element-integrated energy generation (façade collectors)	Room conditioning (heating and cooling system – building element activation)
A07	M&T[3]	Curtain wall (Skeleton construction)	Energy generation (photovoltaic modules)	Room conditioning (heating and cooling system – building element activation)
A08	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	–	–
A09	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Element-integrated energy generation (no glass plate)	–
A10	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Energy generation (glued photovoltaic panel)	–
A11	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	–	Room conditioning (heating and cooling system – SP panel
A12	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Element-integrated energy generation (no glass plate)	Room conditioning (heating and cooling system – SP panel
A13	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Energy generation (glued photovoltaic panel)	Room conditioning (heating and cooling system – SP panel

[1] External thermal insulation composite system.
[2] Expanded polystyrene.
[3] Mullion and transom.
[4] Sandwich panel.
[5] Polyurethane.

in this study (objective, criteria, sub-criteria, alternatives). Table 3 lists the hierarchical characteristics of the reference-based know-why model.

The proposed model reflects the structure of a four-level HDM (objective, criteria, sub-criteria, and alternatives). It is possible to take individual stakeholders' preferences into account to obtain weights of sub-criteria. For a comparative presentation of results, two scenarios were defined. Scenario A reflects the weighting of the DGNB building certification system. This means that the weighting of the building certification system remains unchanged and thus the alternatives are ranked based on the probability of achieving the highest certification result to the lowest certification result.

Scenario B represents a randomly selected scenario, where the individual criteria were specified based on an individual stakeholder. In this scenario, alternatives are ranked to alternatives that best meet the individual stakeholder's preferences.

One advantage of the model is that an alternative ranking is possible for each level - i.e., for each model element. The hierarchical referenced-based know-why model can place each model's element in the center of the model. Consequently, decision support can be provided for each model's element. Fig. 3 shows the schematic structure of the hierarchical referenced-based know-why model.

Step 3: Construct an assessment matrix using know-why rating.

The contribution of each alternative (j) under each sub-criterion (n) was analyzed individually by each expert (k) on a scale of −2 to +2 ($C_{n,j}^{k}$). Within the expert evaluation, each alternative for the reference alternative was rated as neutral, i.e., with 0.

With the results of the conducted workshops, an assessment matrix was created. This matrix is composed of 14 columns (13 building envelope typologies plus one reference alternative) and 26 rows (22 identified façade-relevant certification sub-criteria plus breakdowns of the two sub-criteria ENV1.1 and ECO1.1). The further workshops were used to evaluate the influence of the defined alternatives on the façade-relevant certification sub-criteria.

Each evaluation of the impact of an alternative on a certification sub-

Table 3
Structure of the hierarchical reference-based know-why model.

Level	General structure of the hierarchical decision-making model	Structure of the model	Explanation
Level 1	Objective	Sustainable building envelope	The overall objective is to design the most sustainable building envelope to increase the probability of a high building certification result already in the design phase
Level 2	Criteria	6 DGNB quality sections	Level 2 contains the six DGNB quality section environmental quality, economic quality, sociocultural and functional quality, technical quality, process quality and site quality.
Level 3	Sub-criteria	38 DGNB sustainability criteria	The six DGNB quality sections are separated by 38 sustainability criteria. These sustainability criteria represent sub-areas of the superordinate quality section and thus simplify the measurability of the sections.
Level 4	Alternatives	Different building envelope typologies	The alternatives present different building envelope typologies. The alternatives differ in the chosen construction method, the used building materials, and the installed technical building equipment. The alternatives are designed and evaluated in expert workshops.

criterion was done individually by each expert on a scale of −2 to +2 prior to the workshop. Within the expert evaluation, each façade-relevant certification sub-criteria for the reference alternative were rated as neutral, i.e., with 0. Table 4 shows the linguistic meaning of the evaluation scale.

Step 4: Aggregate opinions of experts.

In order to obtain the aggregation of experts' opinions in terms of the provided ratings in the previous step, Eq. (2) is utilized. Then, consensus procedure was applied to get the aggregated value as a whole number by rounding up/down.

$$S_{n,j} = \frac{C_{n,j}^{k}}{K} \forall k = 1,\dots,K; j = 1,\dots,M; n = 1,\dots,N \tag{2}$$

where, $S_{n,\ j}$ = aggregated opinion of experts for the contribution of j^{th} alternative under n^{th} sub-criterion $C_{n,\ j}^{k}$ = relative contribution of the j^{th} alternative under n^{th} sub-criterion by k^{th} expert K = total number of experts.

The review of all data was carried out in the course of the expert workshops. This procedure ensured that no errors were incorporated into the hierarchical reference-based know-why model during the assessment and the aggregation of the data.

Step 5: Compute weights of sub-criteria (W_n): under scenarios A and B.

Next to the weighting for the six DGNB quality sections and their 38 sustainability criteria based on the DGNB building certification system, it is possible to set individual stakeholder preferences for the sub-criteria in the model. Two scenarios (i.e., A and B) are defined. Scenario A that is DGNB criteria weighting unchanged. Scenario B is DGNB criteria weighting changed based on individual stakeholder preferences.

We can look at the DGNB based weighting (scenario A), meaning that the given DGNB weighting is multiplied by 1 (100%) and therefore not changed. Or the DGNB weighting can be changed via the individual preferences, then the DGNB sub-criteria weighting is e.g., multiplied by 0%, 33%, 66% or 100%.

The mathematical adaption to calculate weights of each sub-criterion (W_n) including individual stakeholder preferences as shown in Table 5 is presented in Eq. (3). $W_{n,\ l}$ can be computed considering weights presented in the Appendix by multiplying weights in Tables 8–9 (Appendix)

$$W_n = p_n^A p_n^B W_{n,l} \forall n = 1,\dots,N; \forall l = 1,\dots,L \tag{3}$$

where,

$W_{n,\ l}$ = relative weight of the n^{th} sub-criterion under the l^{th} criterion.

p_n^A = relative priority of the n^{th} sub-criterion (scenario A).

p_n^B = individual stakeholder preferences-relative priority of the n^{th} sub-criterion (scenario B).

Meaning that each sub-criterion can be multiplied by other values in scenario B (Table 6). The weighting of the applied DGNB building certification system (scheme: office and administration buildings) is provided in the appendix.

Step 6: Calculate final value of alternatives.

At this step, the final value of each alternative (V_j) is calculated using Eq. (4).

$$V_j = \frac{\sum_{n=1}^{N} W_n S_{n,j}}{N} \forall j = 1,\dots,M \tag{4}$$

where,

W_n = relative weight of the n^{th} sub-criterion obtained in previous step.

N = total number of sub-criteria.

4. Results

In this section, output possibilities of the hierarchical reference-based know-why model are presented. The developed model can pursue two main scenarios: (A) building certification system-compliant planning and (B) individual stakeholder preferences-compliant planning. Combinations of the output possibilities in the know-why model are feasible.

4.1. Evaluation matrix of alternatives

The results of the model are based on the expert evaluation (6 experts) as explained in step 4 in Section 3. These were compared with the reference alternative and evaluated by using the suggested rating scale. The reference alternative was given a score of zero for all 26 sub-criteria. With respect to the criterion being evaluated, better alternatives compared to the reference alternative were given a score of +1 or + 2 and worse alternatives compared to the reference alternative were given a score of −1 or − 2. Alternatives that have the same impact as the reference alternative were evaluated as zero. Table 7 shows the evaluation matrix for the 26 criteria and the 13 alternatives.

4.2. Building certification system-compliant planning (scenario a)

The know-why model can center each element of the model and thus provide a decision support for any element within the model. Fig. 4 shows the results of the model element of level 1, i.e., the question of the most sustainable building envelope including all six DGNB quality sections. The results are based on the specified weightings from the DGNB building certification system and the expert assessments. The value of each alternative (V_j) of the x-axis are calculated using the calculation methods within the hierarchical decision model and know-why model and is calculated using Eq. (4). In linguistic terms, a positive value

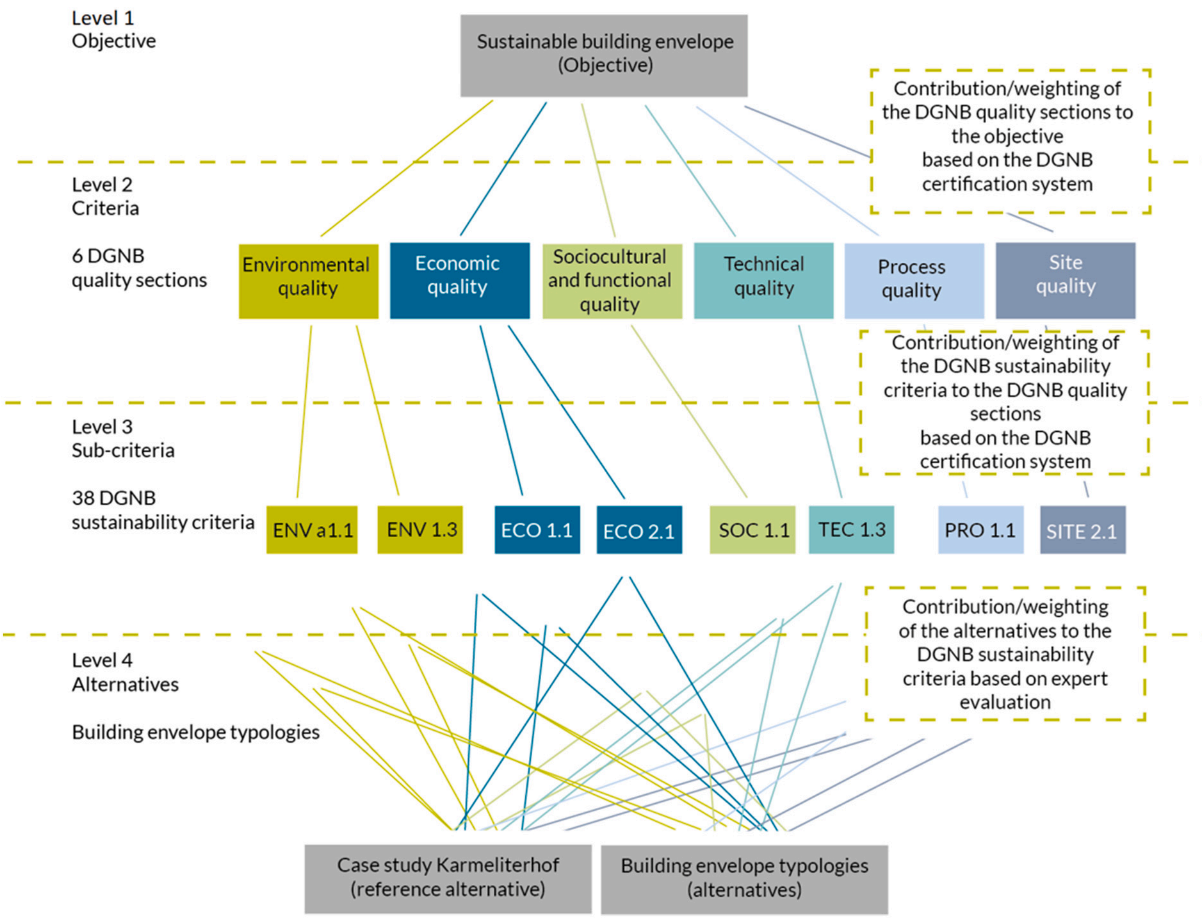

Fig. 3. Structure of the hierarchical reference-based know-why model.

Table 4
The rating scale.

Score	Linguistic meaning
−2	The impact of the assessed building envelope typology has a "high" potential for trade-offs within the observed certification sub-criterion compared to the impact on the reference alternative.
−1	The impact of the assessed building envelope typology has a "medium" potential for trade-offs within the observed certification sub-criterion compared to the impact on the reference alternative.
0	The impact of the assessed building envelope typology has the same impact on the observed certification sub-criterion as the reference alternative.
+1	The impact of the assessed building envelope typology has a "medium" potential for synergies within the observed certification sub-criterion compared to the impact on the reference alternative.
+2	The impact of the assessed building envelope typology has a "high" potential for synergies within the observed certification sub-criterion compared to the impact on the reference alternative.

Table 5
Weights determination scale by individual stakeholder preferences (scenario B) [81].

Score	Linguistic meaning
0%	Not at all important
33%	Moderately important
66%	Important
100%	Highly important

means that this alternative is relatively better than the reference alternative. Conversely, a negative value means that this alternative is relatively worse than the reference alternative.

The best certification result can be achieved with the execution of the designed building envelope A12. A12 is a sandwich panel made of aluminium sheets and PU foam filling. In addition, the sandwich panel has an element-integrated energy generation without an additional glass plate. Heating and cooling functions are performed by the integrated technology in the panel. Detailed constructional details of this building envelope can be found in [82–84]. The building envelope with the worst certification result is alternative A03. This building envelope represents a mullion and transom façade. The curtain wall is constructed as skeleton construction. On the outside, façade collectors were installed for thermal energy generation. In this context, alternative A01, which represents the minimum standard according to Austrian construction guidelines (OIB guidelines), achieves a higher certification result than alternative A03, meaning that the minimum standard is not the worst construction in each case. However, alternative A01 is still relatively worse than the reference alternative. The load-bearing structure of the minimum standard consists of brick with bonded EPS thermal insulation. The surfaces on the outside and inside are plastered with lime plaster. The building envelope has no integrated technical systems and therefore has no energy generation function and no heating and cooling function.

In addition to the visualization from the holistic point of view (level 1), the individual quality sections of the DGNB building certification system can also be presented. Fig. 5 shows the results for the best alternatives for each DGNB quality section (scenario A).

The quality section "site" is not influenced by the building envelope and is therefore not shown. For the quality sections environmental quality, sociocultural and functional quality, technical quality and process quality the building envelope typology A12 is also the one that best meets the sustainability criteria within each quality section. In the

Table 6
Sub-criteria weighting under two scenarios A and B.

No	Sub-criteria	Description	Scenario A (p_n^A)	Scenario B (p_n^B)
1	ENV[1]1.1	Building life cycle assessment	100%	100%
2	ENV1.2	Local environmental impact	100%	33%
3	ECO[2]1.1	Life cycle cost	100%	100%
4	ECO2.1	Flexibility and adaptability	100%	0%
5	SOC[3]1.1	Thermal comfort	100%	100%
6	SOC1.2	Indoor air quality	100%	66%
7	SOC1.3	Acoustic comfort	100%	33%
8	SOC1.4	Visual comfort	100%	0%
9	SOC1.5	User control	100%	66%
10	SOC1.7	Safety and security	100%	33%
11	TEC[4]1.2	Sound insulation	100%	100%
12	TEC1.3	Quality of the building envelope	100%	66%
13	TEC1.4	User and integration of building technology	100%	33%
14	TEC1.5	Ease of cleaning building components	100%	33%
15	TEC1.6	Ease of recovery and recycling	100%	0%
16	PRO[5]1.1	Comprehensive project brief	100%	66%
17	PRO1.4	Sustainability aspects in tender phase	100%	100%
18	PRO1.5	Documentation for sustainable management	100%	33%
19	PRO2.2	Quality assurance of the construction	100%	66%
20	PRO2.3	Systematic commissioning	100%	100%
21	PRO2.4	User communication	100%	66%
22	PRO2.5	FM-compliant planning	100%	66%

[1] Environmental quality.
[2] Economic quality.
[3] Sociocultural and functional quality.
[4] Technical quality.
[5] Process quality.

economic quality, however, it is alternative A13. Alternative A13 is a sandwich panel made of aluminium sheets and PU foam. In contrast to A12, however, the energy generation takes place via a bonded photovoltaic panel.

In conclusion the worst building envelope alternatives differ greatly in the respective quality sections. In the environmental quality and in the sociocultural and functional quality the worst building envelope is alternative A04, in the economic quality section and in the technical quality section the worst becomes alternative A06 and in the process quality section alternative A01 has the worst value.

4.3. Individual stakeholder preferences-compliant planning (scenario B)

The results shown in Section 4.2 can also be calculated for arbitrary scenarios with different individual stakeholder preferences. Fig. 6 shows the ranking of building envelopes from a holistic perspective (level 1) based on the criteria weighting of scenario B.

The building envelope that best meets individual stakeholder preferences is alternative A12. Alternative A03 is the building envelope that fails to meet individual preferences the most. The alternatives for the different model elements can also be ranked and presented for scenarios with individual stakeholder preferences. In scenario B the building envelope typology A12 is the best ranked alternative for the environmental quality section, the sociocultural and functional quality sections, and the process quality section. For the economic quality section, the best alternative is A13. For the technical quality section, the reference case is

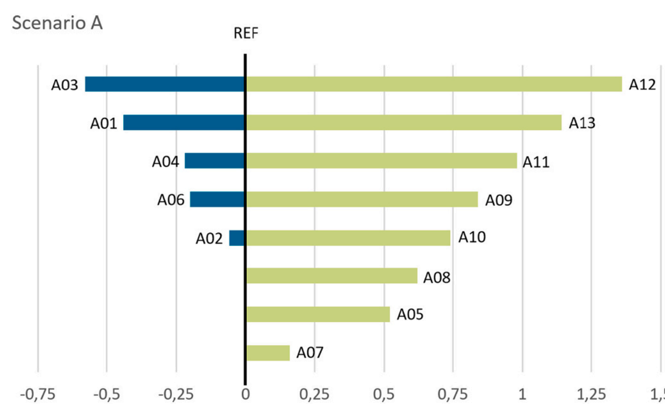

Fig. 4. Best alternatives for building certification system-compliant planning (scenario A).

Table 7
Assessment matrix based on expert judgment.

Sub-criteria	REF	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13
ENV1.1a	0	0	−1	−2	−2	−1	−2	−2	0	1	0	1	1	0
ENV1.1b	0	−1	−1	0	0	1	1	1	1	1	1	1	2	2
ENV1.1c	0	0	1	1	0	1	1	0	2	1	0	2	2	1
ENV1.2	0	−1	0	−1	−1	0	−1	−1	0	−1	−1	0	−1	−1
ECO1.1a	0	1	−1	−2	−1	−1	−2	−2	1	1	1	1	2	2
ECO1.1b	0	−1	−1	0	1	−1	−1	0	1	1	2	−1	0	1
ECO1.1c	0	0	1	1	1	2	1	1	2	2	1	2	2	2
ECO2.1	0	0	1	0	1	1	0	1	1	2	2	2	2	2
SOC1.1	0	−1	−2	−1	−2	1	2	1	−1	0	−1	1	2	1
SOC1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOC1.3	0	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
SOC1.4	0	0	1	−1	0	1	−1	0	1	1	1	1	1	1
SOC1.5	0	0	0	0	0	1	1	1	0	0	0	2	2	2
SOC1.7	0	0	−1	−2	−1	−1	−2	−2	−1	−1	−1	−1	−1	−1
TEC1.2	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
TEC1.3	0	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
TEC1.4	0	0	0	0	0	1	1	1	0	0	1	1	2	1
TEC1.5	0	0	2	1	1	2	1	1	2	2	2	2	2	2
TEC1.6	0	1	1	0	1	0	−1	1	2	2	2	2	2	1
PRO1.1	0	−1	1	1	1	1	2	2	1	1	1	1	2	2
PRO1.4	0	−2	0	0	0	1	2	2	1	1	1	1	2	2
PRO1.5	0	−2	1	0	0	1	1	1	1	1	1	1	2	2
PRO2.2	0	−2	0	0	0	0	0	0	0	1	0	1	2	0
PRO2.3	0	0	0	−1	0	−1	−2	−1	0	−1	0	−1	−2	−1
PRO2.4	0	0	0	0	0	−1	−2	−1	0	0	0	−1	−1	−1
PRO2.5	0	−1	1	1	0	2	2	1	1	1	1	2	2	2

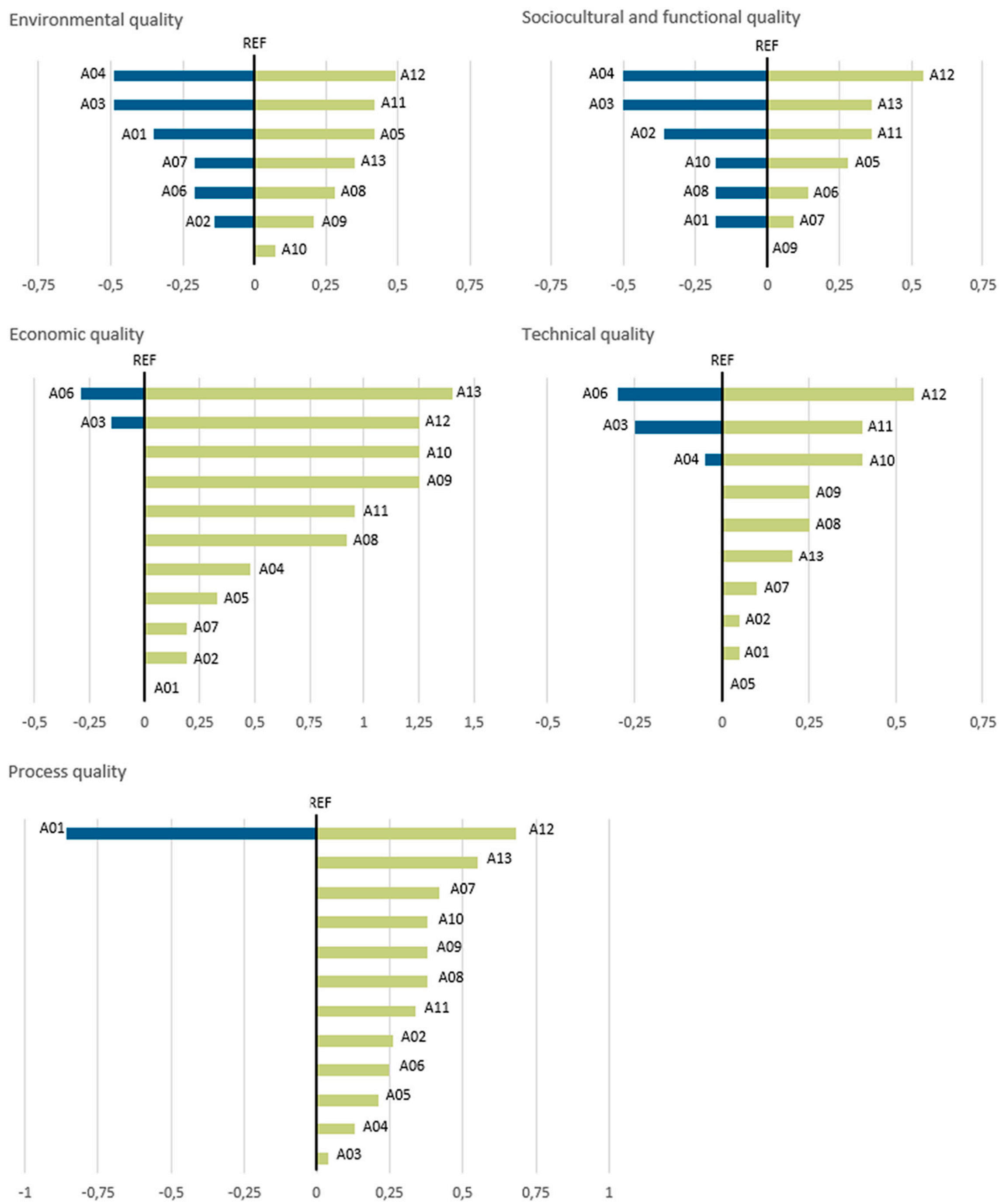

Fig. 5. Best alternatives for the DGNB quality sections (scenario A).

the best alternative to satisfy the stakeholder requirements. In addition to the visualization from the holistic point of view (level 1), the individual quality sections of the DGNB building certification system can also be presented. Fig. 7 shows the results for the best alternatives for each DGNB quality section (scenario B).

5. Discussion

This paper demonstrates the suitability of know-why questions in hierarchical decision making for sustainability improvement processes by combining the DGNB building certification system with a multiple-criteria decision-making method and a systems thinking approach.

The construction sector is an industry that highly interacts with environmental, economic and social dimensions. The concept of sustainability states that there should be a dynamic balance between these dimensions. In this context, the design phase of buildings is the phase in which the greatest influence can be exerted on the building quality and also on the fulfillment of sustainability aspects [85–87]. This early phase is characterized by a high variability of design parameters, often with trade-offs, and subsequently forms an enormous design freedom for planners [88].

Our analytical thinking, which has been shaped for generations, hinders us from taking into account these numerous aspects and, in particular, their interactions and effects in the design phase, which requires the implementation of systemic approaches. This current designing approach leads to striving for area-oriented or goal-oriented

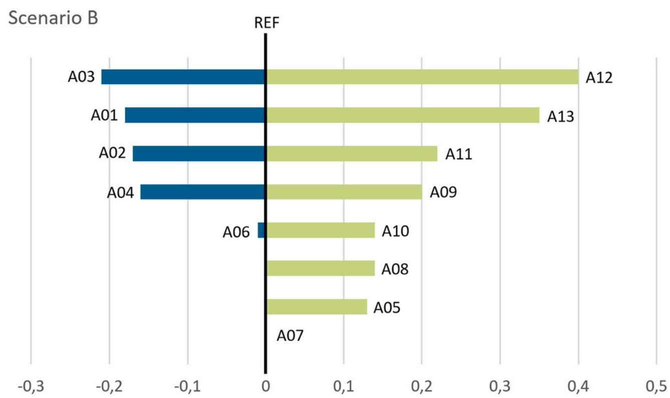

Fig. 6. Best alternatives for stakeholder preferences-compliant planning (scenario B).

designs, forgetting that the sum of the parts is greater than the whole. To counteract these undesirable developments, we propose an early application of the hierarchical reference-based know-why model in the design phase of buildings.

The literature shows that systems thinking in the field of construction industry has been gaining interest in recent years. Different systemic approaches related to interactions between sustainability criteria requirements in buildings are described in [21,23,26,41,65,67,79]. Compared to existing work in the literature, the hierarchical reference-based know-why model takes the next step toward implementing sustainable construction. By mapping the DGNB building certification system as a hierarchical structure and implementing the four know-why questions to evaluate design alternatives, synergies, and trade-offs among set of sustainability requirements can be highlighted.

Unlike the focus of BIM research, which increasingly seeks to extend 3D modeling to include different sustainability aspects [32–34,89,90], the hierarchical reference-based know-why model provides a way to semi-quantitatively assess different design variants and contrast their

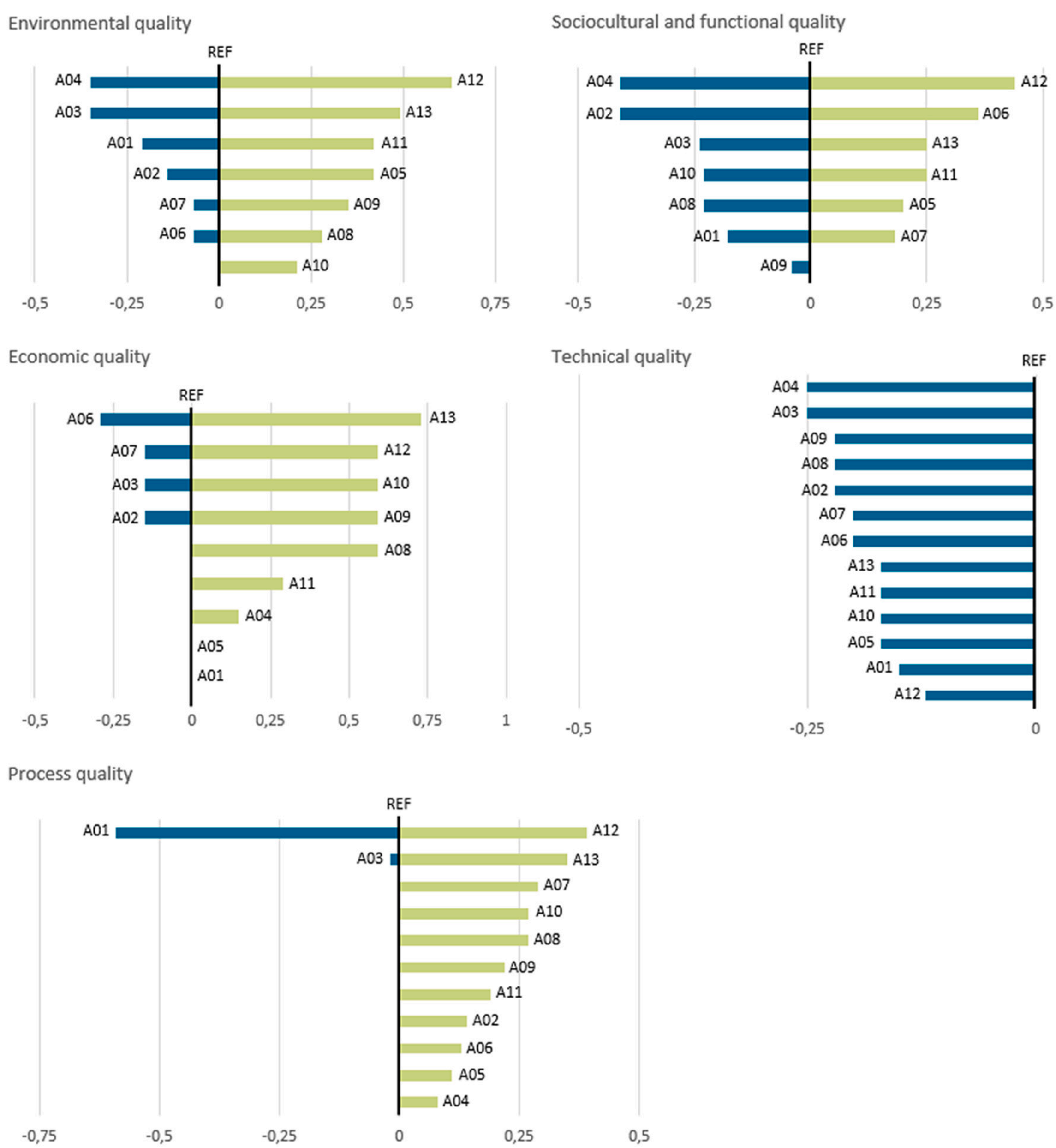

Fig. 7. Best alternatives for the DGNB quality sections (scenario B).

impact on required sustainability goals.

A full implementation of the hierarchical reference-based know-why model in BIM is theoretically possible and not excluded. In this context, interfaces between building certification systems and BIM have already been developed, thus also enabling the evaluation of individual sustainability criteria in BIM [91–94]. However, there is currently no possibility to fully automate all criteria of a building certification system including their interactions as well as the input of individual stakeholder preferences in the BIM design process.

One of the purposes of the hierarchical reference-based know-why model is to support thinking in contexts and thus to ensure that planners are able to holistically consider all requirements for buildings. However, the aim is not to predict an exact value for the contribution of the alternatives, but rather to show, from a more holistic perspective, a positive or negative trend induced by certain design alternatives compared to a well-known reference case and their importance in contributing to the overall project goals.

For the development of the hierarchical reference-based know-why model, the DGNB building certification system was used. It is not the focus of this article to discuss the advantages and disadvantages of different building certification systems. The DGNB certification system was chosen because it is a frequently used performance-based building certification system in Austria, Germany and Switzerland. The DGNB scheme "new building – office" was defined as the scheme, since the reference alternative was a new office building situated in Austria. For building envelopes of other building types, the criteria as well as the criteria weighting may differ depending on the scheme. Modifications to the hierarchical reference-based know-why model for the application to other building elements must be undertaken in the criteria selection process to include the relevant criteria for other building elements. Furthermore, the hierarchical reference-based know-why model in its current form can only be used for the assessment of the building envelope, since 22 of 38 DGNB criteria have been identified as façade -relevant. For the assessment of other building components, the relevant criteria have to be identified and modeled before applying the hierarchical reference-based know-why model. In this context, the model not only can be applied to different building components but also can be applied to a building as a whole. For this purpose, all 38 DGNB criteria must be inserted in the model. In contrast to the current version of the model, the alternatives then no longer represent the building envelopes, but the whole building. Furthermore, a reference building must be defined instead of a reference building envelope. Planners can then use the four know-why questions to evaluate whole buildings in comparison to the defined reference alternative. The presentation of synergies and trade-offs is analogous to the current visualization.

In practice, it may be the case that the "best" design alternative cannot be implemented due to the unique characteristics of buildings. In this case, the focus can be placed on the other proposed alternatives in order to increase the probability of achieving the objectives. In addition to the reference alternative, the current model contains 12 further alternatives that can be used by the planner as a template during the design phase. The aim of the model is not to provide a single building envelope, but to show the advantages and disadvantages of the different alternatives for different DGNB quality sections or criteria. This does not restrict the design freedom of planners, but rather shows possible design variants that can lead to the desired certification result.

An additional re-evaluation in a later planning phase does not have to be carried out. However, the application of the hierarchical reference-based know-why model can also be useful in later design phases since planning variants at a later point in time are more likely to correspond to the construction variant. These design alternatives usually contain detailed information and can therefore be inserted and evaluated in the model in the same way as other alternatives. In addition, a re-evaluation can also be used to perform a target-actual comparison between the design variant in the early planning phase and the design variant in a later planning phase. With these findings, planners can be made aware of the implementation of sustainable building and benefit from this knowledge in future projects.

For the building envelopes currently included in the model, the best certification result is achieved with a sandwich panel construction, consisting of aluminium sheets and polyurethane foam filling with a glued photovoltaic mat on the outer side and an integrated cooling possibility through fluid-filled channels on the inner side. This building envelope typology was designed and developed in a research project at Graz University of Technology, Austria [95][. During the development of the building envelope, an integrated design process was carried out based on the DGNB building certification system. Based on the accompanying sustainability assessment of the building envelope during the design process, iterative changes were made to the structural design, which ultimately ensured the best possible certification result. Details on the construction of the building envelope as well as on the integral and sustainable design process can be found in the supplementary materials. Furthermore, it is also shown that there are building envelopes that achieve a worse certification result than a building envelope that is executed according to the minimum Austrian construction guideline (OIB minimum standards). The results also reveal that in the individual DGNB quality sections or criteria, different building envelopes represent the best alternative. It is worth mentioning that the hierarchical reference-based know-why model can be extended to any additional building envelope. For this purpose, the added alternative must be compared to the reference case by using the presented evaluation scale.

In addition to the goal of achieving the best certification result, the goal was also to make it easier for stakeholders to be involved in the design process. For this purpose, an input mask for individual stakeholder preferences was added to the model. By entering the individual preferences, building envelope typologies can be visualized which fulfill these preferences best or worst. This representation is intended to enable an early basis for discussion between planners and stakeholders in order to think together in the desired direction right from the beginning.

6. Conclusions

The building sector currently contributes to nearly 36% of direct and indirect European Union's greenhouse gas emissions and 40% of energy consumption. With the 2030 Climate Target Plan, the European Union aims to reduce greenhouse gas emissions by 55% compared to 1990. Consequently, greenhouse gas emissions in the building sector must decrease by 80 to 90%, and building-related energy consumption must also be reduced by 14%. Additionally, achieving the undertaken international, national, or regional climate goals or sustainable development driven agendas such as Agenda 2030, requires that the construction sector continues to evolve toward a net zero carbon-built environment. This transition will not be plausible through merely technological innovations, such as material development, development of energy-efficient technologies, or even the increase of sustainable building standards, but additional developments are necessary in the design process. For this reason, building certification systems have been established in recent decades to promote sustainable construction. However, increased sustainability requirements increase the complexity of the design process and lead to more and more interactions among planning practices. In the design phase, the lack of recognition of these interactions often leads to the overlooking of emerging trade-offs among planning practices and thus to project constraints in terms of cost, time, and quality.

To make this complexity manageable, a systemic approach is necessary. It must be possible to apply this approach in the course of the design phase without major additional effort. Furthermore, an interdisciplinary development of the planning practices as well as a transparent communication of the contents and results must be feasible. We address this problem by answering the research question "what is a suitable decision support model to successfully integrate the sustainability requirements in the early design phase of buildings?"

For this purpose, we proposed a simplified design support tool, called the hierarchical reference-based know-why model, to enable holistic design based on sustainability aspects. For the development of the model, we used the principles of HDM and the know-why method. The know-why method offers a highly practical approach to addressing the complex challenges of business, politics, and personal life by answering the four know-why questions in the course of qualitative or quantitative modeling.

The early identification of the effects of different building or building envelope alternatives will ensure the possibility of the desired building certification level, but also will satisfy the individual preferences of stakeholders at an early stage. In addition to these contributions, the application of the model also reduces the vulnerability to failures due to possible design errors. In our view, these overwhelming advantages are offset only by the additional time and cost required in the design phase. In the current Austrian Fee Scales for Architects and Engineers (HOAI) such expenses are already partially taken into account under the term "special services for the implementation of sustainability aspects". The required process steps for the effective practical application of a planning tool like the hierarchical reference-based know-why model must be classified in the HOAI in order to define and allocate a payment concept for the additional efforts involved.

The application of the proposed model indicated that different design variants in the form of alternatives can be implemented in a very short period of time. The planner can orientate herself on these suggested alternatives and additionally carry out detailed analyses for individual DGNB quality sections or criteria. Another advantage of the model is that it can be easily and quickly extended to generate a data pool of alternatives. Depending on the desired focus, these data pools can include entire building alternatives, but also different building elements, such as the building envelopes as in this article. For this extension of the data pool, the expert evaluation needs to be performed for new alternatives. This evaluation is performed as described depending on the defined reference alternative. It can be carried out by the responsible planner on her own, based on the experience of past projects, but also by several people from the planning team in the project meetings.

The proposed model is based on the DGNB building certification system and therefore only provides valid results for this certification system. Based on the reference case, we have shown which building envelope typologies achieve the best certification result. The application of the model was tested in the scope of a research project at the Graz University of Technology. Within this project the alternatives were designed by experts and compared to the reference case. The proposed model presents procedural work, including a life-cycle perspective. The model demonstrates value for building designers, planners, and engineers for the early design phase of buildings to improve design processes and to provide an innovative approach to address systemic interactions of planning practices.

In future studies, other similar methods can be compared with our hierarchical reference-based know-why model to increase the validity of the proposed method. Thus, we suppose triangulation can be suitable to enhance the validity of experts' judgements by applying other similar methods such as best-worst method (BWM) to improve the credibility and reliability of the findings. Furthermore, the proposed model has not been applied in various practical settings which can be undertaken in future research. Ultimately, full integration of the model into building information modeling, combined with artificial intelligence, can help manage the complexity of the design process and further advance the procurement of sustainable buildings on the path to carbon-neutral buildings.

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CRediT authorship contribution statement

Marco Scherz: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Endrit Hoxha:** Validation. **Helmuth Kreiner:** Conceptualization, Methodology, Validation, Supervision, Project administration, Funding acquisition. **Alexander Passer:** Supervision, Funding acquisition. **Amin Vafadarnikjoo:** Methodology, Validation, Visualization.

Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2022.104276.

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