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Identifying influential architectural design variables for early-stage building sustainability optimization

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ABSTRACT

Architectural design variables (ADVs) highly influence a building's sustainability performance. Thus, identifying which ADVs are most influential in a building's early stages is of great significance, especially when using computational building design optimization tools. Currently, sensitivity analysis based on computer simulations is the most commonly used means to identify which ADVs are the most influential in the early stages. However, we suggest that a stakeholder perspective should also be considered as stakeholders possess domain-specific knowledge and expertise as well as a contextual understanding that can greatly enhance the development and deployment of building design optimization tools. To explore the above, we combined a literature review with survey data from 24 architects and sustainability consultants in the Nordics. Surprisingly, we found that the influential ADVs in the literature do not always align with those of our surveyed stakeholders. For example, we found that the literature considers *building plan, window-to-wall-ratio (WWR),* and *wall material* as the most influential ADVs, which contrasts with *storey number, storey height, WWR, roof material* and *wall material* considered by stakeholders to be the most influential. We also found that the most influential ADVs differ across different sustainability optimization objectives, and that these also differ from the literature. Despite our limited survey sample, our study provides insights into influential ADVs and as such has implications for the development, use, and performance of computational building design optimization tools.

1. Introduction

As buildings play a significant role in the global sustainable transition due to their high environmental impact and their significant importance for human well-being and the economy [1–5], practitioners and researchers alike are looking for means to improve the sustainability of buildings. One means to achieve this is through optimizing a building for sustainability during the building design process. According to the Royal Institute of British Architects [6], the building design process consists of eight stages, from stage 0 - "Strategic definition" to stage 7 - "Building use". Many studies have noted that the early stages, i.e., stage 1 - "Preparation and briefing" and stage 2 - "Concept design" [1] are the most significant for optimization as the decisions made in these stages substantially impact the consecutive design stages and greatly influence the building's sustainability performance throughout its use on many levels [7,8]. For example, one study found that 70% of decisions related to a building's sustainability are made during the early stages [9], with these decisions leading to 80% of the building's environmental impact [10]. Furthermore, while only 15% of a building's life cycle costs are incurred in the early stages, the decisions taken during these stages greatly impact the remaining 85% of the building's lifecycle costs [11].

In the early stages, the first step in optimizing a building's design for sustainability entails clearly defining the sustainability objective [8]. Sustainability comprises many social, environmental, and economic aspects [12], and in recent years, sustainability objectives in the architecture, engineering, and construction (AEC) industry typically include various objectives such as reducing energy, enhancing daylight, or improving thermal comfort. Further, the objective may also depend on the climate context and local policies, e.g., enhancing daylight performance could be more important in Sweden than in Namibia.

Decisions related to the building's architectural design variables (ADVs) must be made during these early stages to achieve the defined sustainability objectives. ADVs are the physical design elements that describe the building's physical features, such as building shape, orientation, and materials. Common ADV categories include the composition of the opaque building envelope, such as wall thickness and

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material; the composition of the transparent building envelope, such as g-value and u-value of windows, shape and form; the type of mechanical systems; and the operation of the mechanical systems [13]. The ADV decisions made are critical for a building's sustainability. For example, selecting the right wall material can lead to approximately a 17% energy cost reduction [14] while adjusting window scenarios can improve the useful daylight illuminance by approximately 20% [15].

To facilitate sustainability optimization in the early stages, researchers and practitioners are developing various computational optimization tools to facilitate design choices and develop optimal solutions for a specific purpose [16], such as operational energy consumption [17], optimal daylight [18], reduced life cycle greenhouse gas (GHG) emissions [7]. Today there are multiple approaches to developing these tools. For example, some researchers have developed tools based on simulation engines such as Energy Plus [19], IES [20], and Daysim [21]. Using these tools, architects and consultants can achieve optimal design alternatives by running simulations varying the combination of different ADVs for a specific sustainability objective. However, these optimization tools are generally very time-consuming (Costa-carrapiço, Raslan, and Neila 2020). Further, they tend to be inefficient and ineffective for application in the early stages when users want to include a large number of ADVs.

More recently, researchers and practitioners are turning to artificial intelligence (AI) and machine learning (ML) as a means to improve the speed and efficiency of these optimization tools [22–28]. AI and ML are a collection of methods used to fit mathematical models from historical data and to make quick and accurate predictions [29]. However, while showing promise, these AI/ML-enabled tools are difficult to use in the early stages. On the one hand, they usually require detailed building information that can only be retrieved in the later stages of the building design process [30]. On the other, the more ADVs that are entered into the ML-based tool, the more complex and time-consuming its use becomes.

Including all ADVs in one optimization model not only exponentially increases the number of potential solutions but also the computational costs [31]. This appears to be a common issue for all current early-stage optimization tools [32]. Thus, one means to ensure the efficient and effective use of building design optimization tools is to identify which ADVs have the most influence on the chosen sustainability objective so that these can be selected as inputs.

Several ways to identify influential ADVs in early-stage optimization have been developed. Some studies have conducted a literature review [33], while some used case-based sensitivity analysis [34–36]. Others have also tried to use the ML-based feature selection method [37], in which feature selection is the process of selecting the ADVs that significantly influence the objective more than the other ADVs. Although the above methods are valid, these studies primarily investigated individual cases only in their specific contexts, thereby restricting their generalization to other contexts.

Furthermore, these studies only take a computational point of view and do not take a more holistic approach as the opinions of stakeholders have yet to be investigated. This is surprising for two reasons. First, researchers agree that the development of high-performance buildings is only successful when a project's stakeholders are involved [38], especially early in the design process [39]. Stakeholders are experts in the relevant fields, and they possess not only domain-specific knowledge and expertise but also a contextual understanding that can greatly enhance the development and effectiveness of optimization tools [40]. Their engagement could improve the optimization tools by providing actual practical experience. Second, some stakeholders are also the end users of the optimization tools, and extensive research in areas such as user-design and user-driven development [41–43] clearly shows the importance of integrating users in the development process for an effective product or service result. Further, previous research also shows that users should be engaged during the early stages to improve a building's final performance [44].

The stakeholder typically involved in early-stage building design tend to be architects and consultants. Architects consider both the building's aesthetic and functional aspects when creating the building plans, blueprints, and facades and often are responsible for making the final decisions regarding the building's design. Consultants, especially sustainability consultants, are generally not directly designing a building but rather providing sustainability insights into building projects. For example, their role can involve assessing the environmental impact of a building's different design alternatives and developing strategies to improve a building's sustainability. Of note is that consultants are usually more familiar with the optimization process than architects.

While the attitudes and preferences of architects and consultants regarding ADVs should be considered when developing early-stage optimization tools, to date there is limited information regarding which ADVs these stakeholders think are the most influential for various optimization objectives. This lack of understanding could lead to a discrepancy between the stakeholders' opinions and the outcomes of the optimization tools. For instance, these stakeholders might not want to use the optimization tools if they cannot find the ADVs they think are important to optimize. As a result, optimization tools could lack accuracy and contextuality, and stakeholders may either not deploy these tools, or they may not use them optimally. Thus, these tools may not be widely adopted across the AEC industry, and the opportunity to reap the benefits of optimization tools for designing sustainable buildings may not be fully achieved. As such, we argue that stakeholders should also be investigated, and their opinions incorporated in the selection of ADVs for optimization tools.

In response to the above, this paper aims to identify the most influential ADVs for early-stage sustainability optimization of building design. As there may be various objectives in early-stage optimization depending on the context, the ADVs that are considered influential can also vary depending on the specific objective. By incorporating stakeholder opinions, a more holistic approach to developing and implementing the tools can be achieved, helping to address the current limitations associated with optimization tools. To achieve our aim, we developed three research questions.

(1) Which early-stage ADVs are the most influential for different sustainability objectives *according to the literature*?
(2) Which early-stage ADVs are the most influential for different sustainability objectives *from a stakeholder perspective*?
(3) What discrepancies exist between the most influential ADVs in the literature and from a stakeholder perspective?

2. Method

To address our research questions, we chose to focus on residential buildings in the Nordic context. The Nordic countries are among the global sustainability leaders [45], and enabling a more sustainable building industry is critical to achieving sustainability goals [46]. Further, the Nordic residential sector has one of the highest resource requirements in the Nordic countries due to the harsh climate, and sustainable housing is thus key to the building industry's sustainability [47].

We collected data using two methods: a literature review and a stakeholder survey, in five steps (Fig. 1). First, we conducted a literature review to determine the most important objectives in sustainability optimization for residential buildings in the Nordics. Since the objectives can vary significantly depending on the geographical and climatic situation, we focused only on the most frequently mentioned objectives within the Nordic context. Second, we conducted a literature review to identify the most influential ADVs in the early stages in general, which were again the most frequently mentioned in the literature. Third, we analyzed the results and organized the sustainability objectives and ADVs into categories. Fourth, we conducted a survey with some follow-up interviews of 24 architects and consultants in Sweden and Norway to

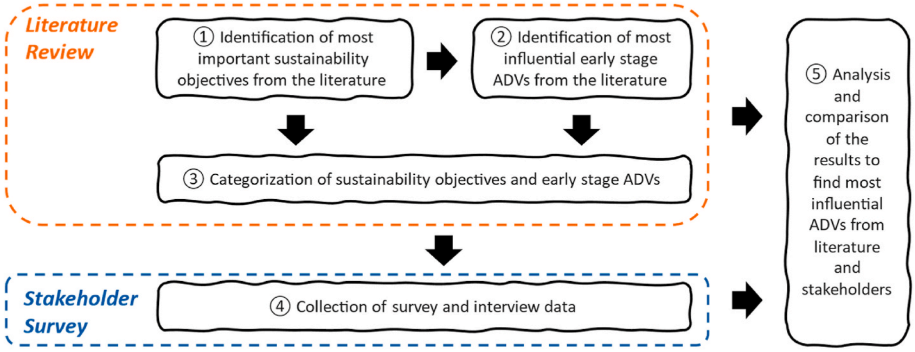

Fig. 1. Data collection and analysis.

gain insights into which ADVs they considered influential. Finally, we analyzed and compared the literature review results and survey responses to reveal the impact of each selected ADV on different optimization objectives from the perspective of the literature and stakeholders.

2.1. Literature review

We conducted our literature review using two academic search engines: (1) Web of Science, for its well-recognized database of academic publications and its advanced search functionality [29]; and (2) Scopus, for its reputation in the field of architectural research. We used the topic search (TS) function in Web of Science and the Title-Abstract-Keywords search function in Scopus. The flowchart of the review process and the keywords used are shown in Fig. 2. To obtain up-to-date information, we limited our search to the past ten years.

First, we searched for the sustainability objectives in the Nordic countries for residential buildings using the combination of keywords shown in Fig. 3. We found a total of 731 papers published in the last

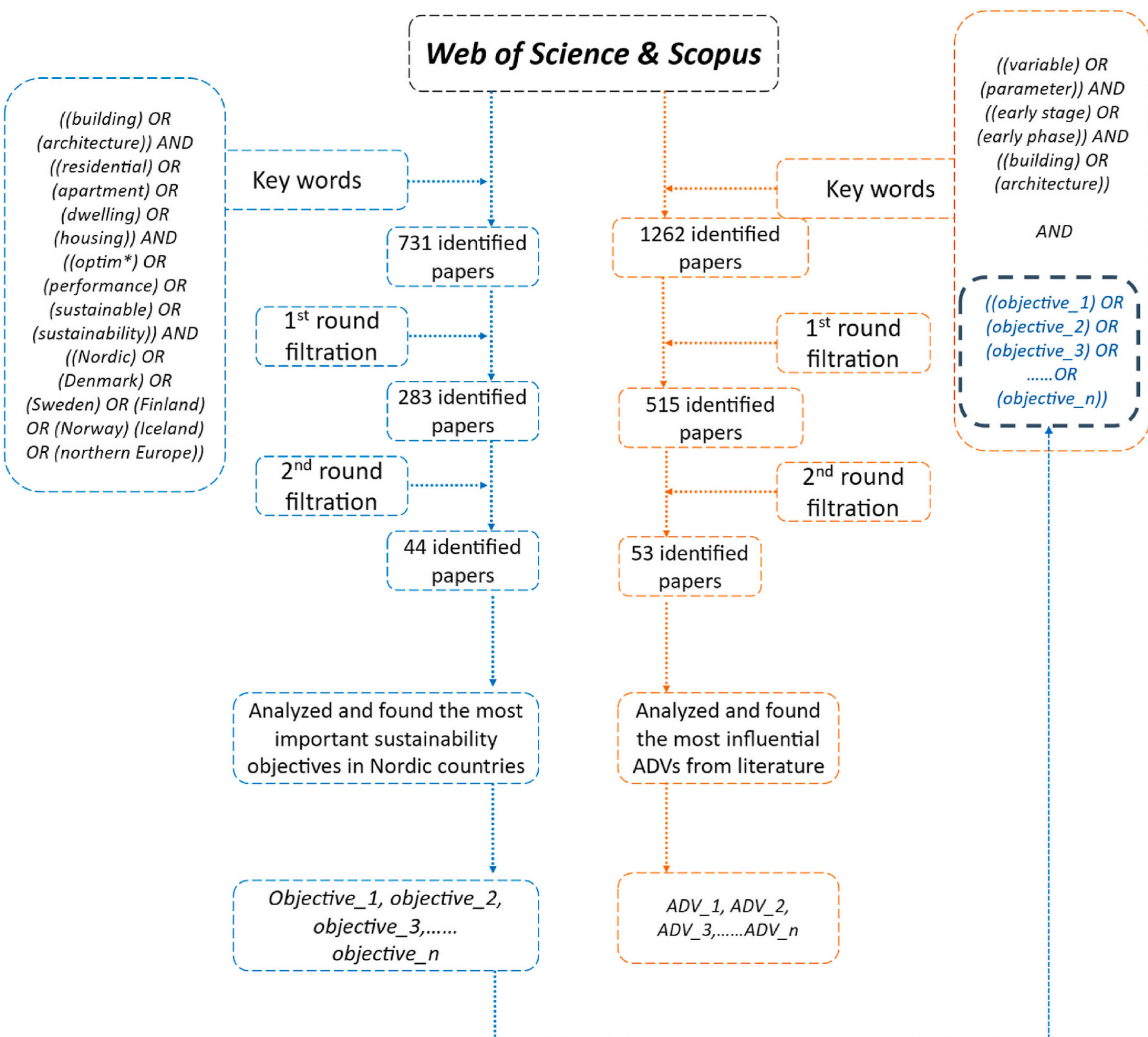

Fig. 2. Identification of the most important sustainability objectives and most influential ADVs.

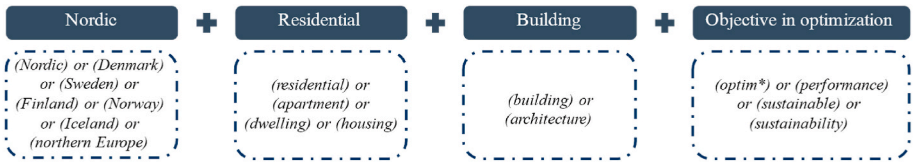

Fig. 3. Literature search keywords for the most important sustainability objectives in the Nordic countries for residential buildings.

decade. We filtered the preliminary results by adopting a two-round article selection to ensure the filtering quality. In the first round, we removed duplicate articles and articles from other disciplines that were out of context. For example, many studies were from computer science due to the search term "architecture", which can refer to software architecture, amongst others. After the first round of filtration, 283 papers remained. In the second round, we discarded articles that only dealt with certain technical parts of a building, e.g., HVAC system, energy storage system, as well as those that did not focus on newly constructed buildings, e.g., renovations, or historical buildings. After applying these criteria, only 44 papers remained for further analysis (Appendix A).

We applied the same strategy in the literature review to identify influential early-stage ADVs using the keywords in Fig. 4. Of note is that we included the important sustainability objectives determined in the previous literature review analysis as part of the search keywords. We excluded the Nordic keywords because the ADVs in the early stages should be similar across regions even though the sustainability objectives may vary depending on the climate and region. We found a total of 1262 papers published in the last decade. After the same two rounds of filtration as above, 53 papers were selected (Appendix B).

2.2. Categorization

Our analysis revealed that there was no unified set of terms for sustainability objectives and ADVs nor their application across the articles. As a result, we decided to conduct a thorough categorization as described below before continuing our analysis.

2.2.1. Categorization of sustainability objectives

We went through all the articles and synthesized all objectives into a set of common terms. We found that many articles referring to Life Cycle Assessment (LCA), which is widely used to quantify a building's environmental impact, tended to focus on *'energy'* or *'greenhouse gas emissions'* as the objective. Thus, we decided to adopt these two as overarching umbrella terms. Further, we found that both *'embodied carbon emissions'* and '*CO_2 emissions in construction*' were listed as objectives. As these both denote greenhouse gas (GHG) emissions, we collected these and all other related terms under the label of GHG emissions.

We also found that the same term was used to describe different objectives throughout a building's life cycle. For example, the term *'energy'* was used to describe the energy consumed in the construction stage, the energy consumed in the operational stage, and the energy consumed throughout the building's life cycle including both construction and operation, depending on the article's context. Thus, we referred to EN 15978 [48] to structure the terminology and differentiate among "embodied", "operational", and "life cycle" objectives. *Embodied* energy and *embodied* GHG emissions are associated with the material product and construction stages of a building (life cycle modules A1-A3, A4, and A5), while *operational* energy and *operational* GHG emissions are associated with operating a building in the use stage, e.g., electricity, gas, water (module B6). *Life cycle* energy and *life cycle* GHG emissions include both embodied and operational. Operational are the main contribution in most cases. Some studies also include the end-of-life (modules C1-4) in the embodied emissions, but as current legislation such as the Swedish climate declaration [49] only includes modules A1-A5, we exclude end-of-life here. A more detailed interpretation of a building's life cycle and which stages are included in the Nordic context based on EN 15978 [48] is provided in Appendix C.

The above analysis led to the creation of 11 categories of sustainability objectives (Table 1) with more information in Appendix A.

2.2.2. Categorization of early-stage ADVs

Turning to the categorization of ADVs, as mentioned we found no consistency among the ADVs as they were named and referred to differently across articles. For example, *'storey number', 'level', 'number of',* and *'stacking'* all refer to the number of storeys in a building. Moreover, it was difficult to single out one ADV without it influencing another. For instance, the meanings of "window-to-wall ratio (WWR)" and "window area" are different. However, one cannot be changed without also changing the other. As a result, we decided to follow

Table 1
Categorization of sustainability objectives.

Sustainability objective	Definition
Embodied energy	Energy consumption associated with a building's product stage and construction stage
Operational energy	Energy consumption associated with operating a building in its use stage, e.g., electricity, gas, water, other energy
Life cycle energy	Total energy consumption associated with a building's life cycle including product stage, construction stage, and use stage
Embodied GHG emissions	GHG emissions associated with a building's product stage and construction stage
Operational GHG emissions	GHG emissions associated with operating a building in its use stage, e.g., electricity, gas, water, other energy
Life cycle GHG emissions	GHG emissions associated with a building's life cycle including the product stage, construction stage, and use stage
Embodied cost	Costs associated with the product stage and construction stage
Operational cost	Costs associated with the use stage
Life cycle cost	Total costs associated with a building's life cycle including product stage, construction stage, and use stage
Daylight	Natural light indoors through windows and skylights
Thermal comfort	A person's state of mind in terms of whether they feel too hot or too cold

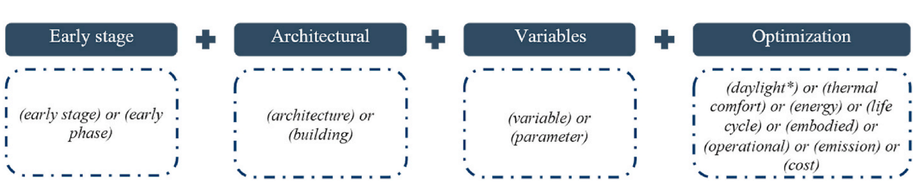

Fig. 4. Literature search keywords for the most influential ADVs in early-stage optimization.

previous studies [50] and categorized the ADVs into groups with minimum overlap. It is worth noting that we decided not to merge the four WWR ADVs into one ADV as we argue that the individual WWRs could influence various objectives differently. For example, increasing the WWR on the south side could significantly improve the solar gains in the Nordic context compared to increasing the WWR on the north side.

The above analysis led to the creation of 14 categories of early-stage ADVs (Table 2) with more information in Appendix B.

2.3. Stakeholder survey

In the next step, we surveyed two stakeholder groups: architects and sustainability consultants working in the Nordic countries. We targeted only sustainability consultants as they are the most familiar with the optimization objectives. We distributed the survey on LinkedIn and by email to three architecture firms in Sweden. The survey included 15 questions and took around 10 min to complete (Appendix D). In addition to questions on a respondent's professional background, work location, years of experience, and job description, the survey asked respondents to rate the influence of selected ADVs for selected sustainability objectives. Since not all stakeholders might have been familiar with the definitions of ADVs and sustainability objectives, we provided easy-to-understand terms in the survey. We also included an open-ended question asking respondents if there were any other variables that they thought were important. A follow-up interview of 5–15 min was initiated if the respondent's survey answers were not clear enough or if the respondent was willing to further explain their answers, in which the researcher encouraged a free-flowing discussion with the interviewee.

We collected 46 survey responses in total. However, only 24 responses were fully complete: 12 from architects and 12 from consultants (Appendix E). The respondents were primarily from Sweden and Norway, and relevant experience varied between 2 and 35 years. All responding architects had experience in residential building design, and the responding consultants all had experience in improving building sustainability. We further conducted six follow-up interviews including four with architects and two with consultants to gain a deeper understanding of the respondents' answers.

Table 2
Categories of early-stage ADVs.

Early-stage ADV	Definition
Window-to-wall ratio on north/south/west/east (WWR N, WWR_S, WWR_E, WWR_W)	Fraction of the exterior wall above grade that is covered by fenestration on the north/south/west/east façade, respectively
Window shape	A window's shape and dimension
Shading device	An integrated component of a window or facade protecting the interior space from direct sun, overheating, and glare
Window location	The specific placement of windows in a building, focusing on their specific positioning for architectural placement.
Wall material	Material used for external walls
Building plan	Vertical projection onto a horizontal plane cutting through the building, showing the size and arrangement of spaces
Building volume	The total volume of a building
Wall-to-floor ratio	Fraction of external wall area divided by gross internal floor area
Building orientation	Relationship of a building and positioning of its windows, rooflines, and other features to the building site
Roof material	Material used for the roof
Roof area	Surface area of the roof
Storey height	Height of each floor
Storey number	Number of floors

2.4. Analysis

In the final step, we analyzed the selected articles to identify the most influential ADVs by tallying the occurrence of each ADV in relation to the different sustainability objectives. We then analyzed the survey responses by calculating the mean rating of each ADV for each objective to find the most influential ADVs for that objective. We also checked the open-ended questions for potential additional ADVs. Finally, we conducted a comparative analysis to determine the discrepancy between the results from the literature and the stakeholder surveys.

3. Results

3.1. Literature review

3.1.1. Sustainability objectives in Nordic countries and early-stage ADVs

Table 3 summarizes our findings from our literature review. We find that *operational energy* is the most important objective for residential buildings in the Nordic context, appearing 31 times in the literature, far more than any other objective. The other frequently mentioned objectives are thermal comfort, daylight, life cycle cost, embodied greenhouse gas emissions, and life cycle greenhouse gas emissions. Table 3 only includes the sustainability objectives considered as frequently mentioned based on the literature review results in Appendix A.

Fig. 5 further summarizes our findings. We excluded the ADVs that appeared less than twice to avoid outliers, such as roof area and building volume. We found that *WWR, wall material,* and *building plans* are the most frequently mentioned and thus of greater influence in early-stage building sustainability optimization, while *storey height, storey number, shading device, building orientation, and roof material* are mentioned less frequently and thus considered to be less influential. Meanwhile, w*indow shape, window location,* and *roof type* are mentioned fewer than ten times and are therefore not considered influential.

3.1.2. Influential early-stage ADVs in relation to selected sustainability objectives

To rate the influence that early-stage ADVs had in relation to selected sustainability objectives, we created a rating for each ADV for each objective. The indicator equals the occurrence of an ADV for one objective divided by the total number of papers looking at this objective. For instance, the ADV *building plan* is mentioned 19 times in the 31 papers looking at the sustainability objective *operational energy*, so the rating for a *building plan* for *operational energy* is 19 divided by 31, which is 0.61. The higher the rating value is, the more influential the ADV is for the sustainability objective.

Fig. 6 provides a heatmap of the ADV ratings for the selected sustainability objectives. The values were converted into a color scale from blue (low influence) to red (high influence) to support the visual interpretation. We consider the ADVs appearing at least in half the papers as important, which means the more influential ADVs from the literature should have a rating higher than 0.5.

Fig. 6 shows that *WWR* (regardless of direction) has a high influence on all sustainability objectives and has an average high rating of 0.66. *WWR* is especially influential for *operational energy* with a high value of 0.81. *Wall material* is the second most influential ADV with an average rating of 0.54, and it has a high influence on all objectives except *embodied GHG emissions*. *Building plan* has an average rating of 0.47 and is influential for all objectives except *daylight* and *thermal comfort*.

Building orientation, storey number and storey height are considered influential only for *embodied GHG emissions* while *shading device* is considered influential only for *daylight* and *thermal comfort*. *Roof type* and *roof material* do not show a significant influence on any sustainability objectives in the literature.

Table 3
The most frequently mentioned early-stage ADVs and sustainability objectives in the literature.

Reference	Early-stage ADV														Sustainability objective					
	WWR_N	WWR_S	WWR_E	WWR_W	Window shape	Shading device	Window location	Wall material	Building plan	Building orientation	Roof material	Roof type	Storey number	Storey height	Operational energy	Daylight	Thermal comfort	Life cycle GHG emissions	Embodied GHG emissions	Life cycle cost
[51]	✓	✓	✓	✓				✓									✓	✓		✓
[9]	✓	✓	✓	✓				✓	✓						✓			✓		✓
[52]	✓	✓	✓	✓				✓			✓				✓					
[53]	✓	✓	✓	✓	✓		✓	✓	✓				✓	✓	✓					
[54]	✓	✓	✓	✓				✓			✓				✓					
[55]	✓	✓	✓	✓				✓	✓						✓			✓		
[18]					✓	✓			✓						✓	✓				
[56]	✓	✓	✓	✓				✓	✓	✓	✓				✓					✓
[57]	✓	✓	✓	✓		✓		✓	✓				✓	✓				✓		✓
[58]	✓	✓	✓	✓					✓	✓		✓			✓					
[59]	✓	✓	✓	✓				✓		✓	✓				✓					
[60]	✓	✓	✓	✓					✓				✓	✓					✓	
[34]	✓	✓	✓	✓					✓	✓		✓		✓						
[61]	✓	✓	✓	✓		✓			✓						✓	✓				
[62]					✓	✓				✓						✓	✓			
[63]	✓	✓	✓	✓	✓			✓					✓		✓					
[64]	✓	✓	✓	✓		✓		✓						✓	✓	✓				
[8]	✓	✓	✓	✓				✓	✓		✓			✓	✓	✓				
[65]	✓	✓	✓	✓				✓	✓		✓			✓	✓					
[66]	✓	✓	✓	✓		✓		✓		✓					✓					
[67]						✓		✓		✓	✓							✓	✓	
[68]	✓	✓	✓	✓			✓		✓						✓					
[69]		✓				✓			✓					✓					✓	
[11]					✓			✓	✓	✓			✓	✓				✓	✓	
[70]	✓	✓	✓	✓		✓				✓					✓	✓				
[35]					✓					✓					✓					
[71]					✓		✓		✓		✓				✓					
[72]								✓								✓	✓			
[73]								✓										✓	✓	
[74]								✓										✓		
[75]									✓			✓			✓	✓				✓
[76]	✓	✓	✓	✓	✓				✓	✓				✓		✓				
[25]	✓	✓	✓	✓				✓	✓				✓	✓	✓					
[77]	✓	✓	✓	✓					✓	✓					✓					
[78]	✓	✓	✓	✓				✓							✓			✓		
[79]					✓	✓		✓								✓	✓			✓
[80]	✓	✓	✓	✓		✓			✓				✓	✓	✓		✓			
[81]	✓	✓	✓	✓		✓		✓			✓				✓	✓	✓			
[82]	✓	✓	✓	✓		✓		✓	✓				✓	✓	✓					
[83]					✓	✓	✓								✓	✓				
[84]	✓	✓	✓	✓				✓	✓	✓			✓	✓				✓	✓	
[85]						✓	✓	✓			✓					✓				
[86]	✓	✓	✓	✓				✓	✓	✓	✓				✓					
[87]	✓	✓	✓	✓				✓	✓		✓		✓						✓	
[88]	✓	✓	✓	✓					✓				✓	✓					✓	
[89]													✓						✓	
[90]	✓	✓	✓	✓						✓					✓		✓			✓
[91]	✓	✓	✓	✓						✓			✓						✓	
[92]	✓	✓	✓	✓					✓	✓					✓			✓	✓	✓
[93]	✓	✓	✓	✓		✓			✓	✓								✓		
[94]						✓				✓								✓		
[95]	✓	✓	✓	✓						✓			✓	✓					✓	
[96]	✓	✓	✓	✓		✓				✓					✓			✓		
Total	37	38	37	37	10	18	5	28	28	21	12	3	14	16	31	13	7	14	12	8

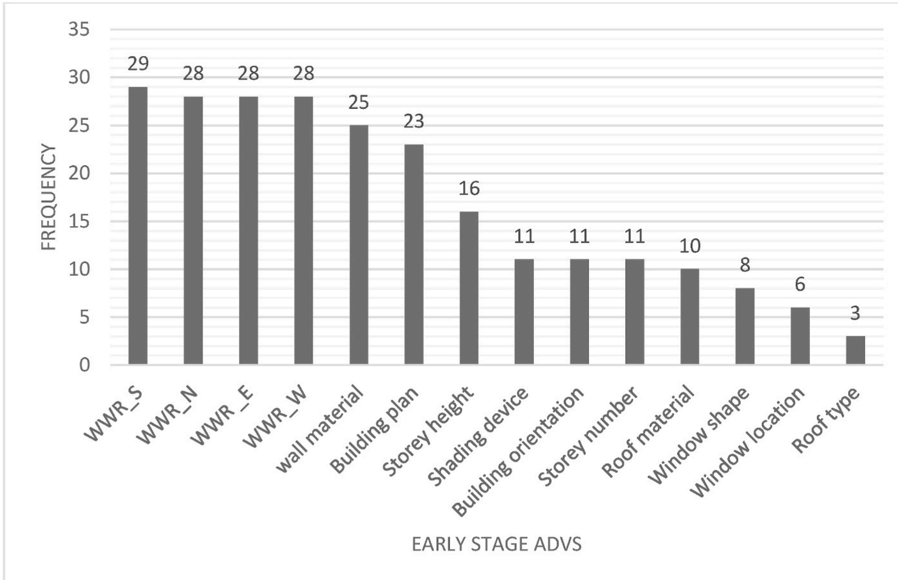

Fig. 5. Most frequently mentioned early-stage ADVs.

Fig. 6. Rating of ADV influence on selected sustainability objectives.

3.2. Stakeholder survey results

Fig. 7 provides the average rating that the surveyed architects and sustainability consultants provided for the influence that each ADV has on each sustainability objective, and we consider the ADVs with an average rating higher than 3 as influential as the scale was from 1 to 5.

The three ADVs that stakeholders rated to be the most influential on the objectives are *wall material* (architects 3.6, consultants 3.7), *window-to-wall ratio - south (*architects 3.5, consultants 3.7), and *shading device* (architects 3.3, consultants 3.5). Stakeholders rated *wall material* as having a very high influence on all objectives except *daylight,* while *building plan, building orientation,* and *WWR* have a significant influence on *operational energy*, *daylight*, and *thermal comfort*. *Window shape* received the second lowest rating on average for all objectives (2.7 from both stakeholder groups), while *window location* received the lowest rating (architects 2.4, consultants 2.5).

Further, *daylight* is the objective most influenced by the ADVs, as seven ADVs were given a rating higher than 4.0 by architects and 3.7 by consultants. *Daylight* is followed by *operational energy* and *thermal comfort*, while *embodied GHG emissions, life cycle GHG emissions*, and *life cycle cost* were all given low ratings.

While the two stakeholder groups gave similar ratings across the ADVs, sustainability consultants tended to give higher ratings than the architects. The only ADV with a high discrepancy is *roof type*. Architects rated this ADV with values lower than 3 for all objectives, while consultants rated it higher, especially for *operational energy, embodied GHG emissions* and *life cycle cost*.

The survey also contained one open-ended question: “Is there any other variable that you think might influence the objectives mentioned before? Please state the variable, the objective, and the level of importance here.” We received two answers from architects and three from consultants (see Table 4).

Thus, two ADVs not found in our literature review were considered important by some respondents: *interior structural materials* and *urban context*. Interior structural materials can influence optimization objectives to a great extent and can be considered an important ADV. However, these materials are generally decided after the early stages of a design process. Further, the urban context is usually already selected and not under the designers’ control. As such, it does not fit the ADV definition, which is the physical design elements that describe the

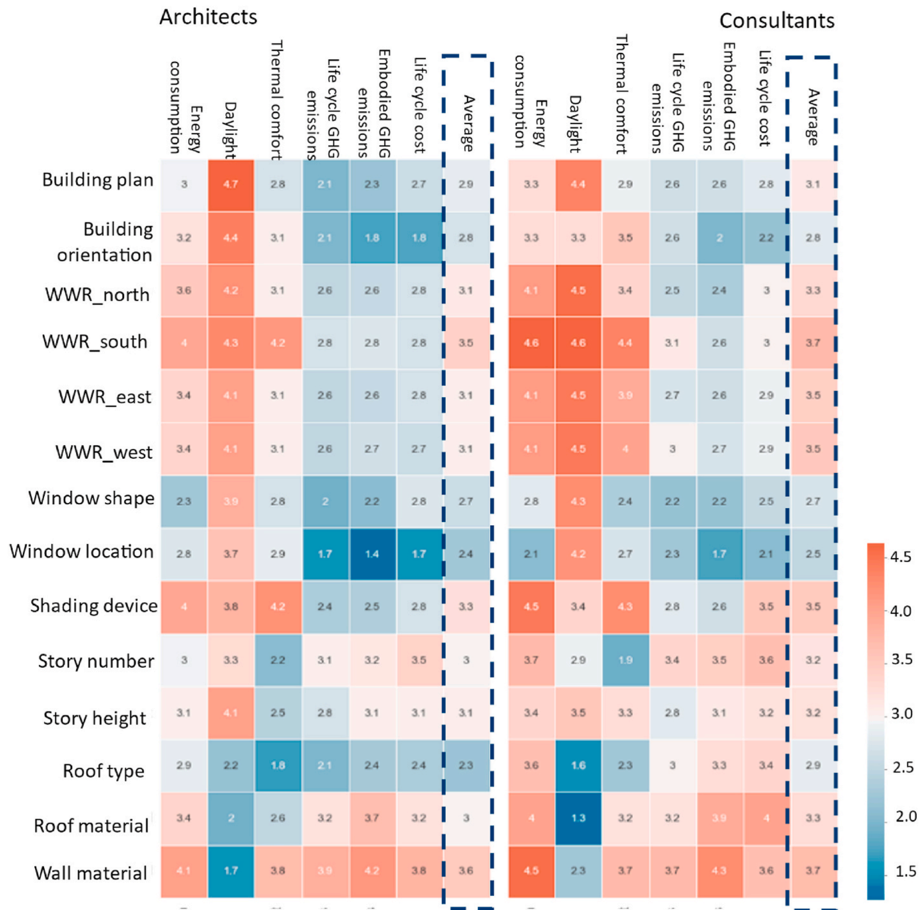

Fig. 7. Mean rating of ADV influence on selected sustainability objectives by architects and sustainability consultants.

Table 4
Open-ended question answers.

Respondent	Answer
A4	Slabs and foundations have a big influence on *embodied GHG emissions* and *LCC*. Well, the whole loadbearing structure, but I assume that is included in "building roof" and "building wall".
A9	Floor and ceiling materials (interior surfaces) on Operational Energy:1; Daylight: 2 Thermal Comfort: 2 Life cycle GHG Emissions: 3 Embodied GHG emissions: 4 LCC: 4
C5	Urban density has quite an impact on Daylight (5) and thermal comfort (4) and can have a significant impact on Operational energy (3) and the LCA/LCC (4) aspects as well.
C8	Surrounding buildings
C10	Material of floors and slab (affects thermal and by reflectance affects daylight)

building's physical features. Although these two variables are important to consider, they do not fit the scope of this study.

3.3. *Comparison of influential ADVs between the literature and the stakeholder perspective*

Fig. 8 summarizes the influence of ADVs under different sustainability objectives from the literature by showing the fraction of different ADV occurrences divided by the number of papers (left) and from stakeholders by indicating the average rating from all 24 participants (right). In general, in terms of objectives, the literature and stakeholders are more consistent in identifying the influential ADVs for operational energy and daylight. In terms of the ADVs, they are more consistent regarding the influence of WWR, shading device, and wall material. WWR_S is rated as the most influential ADV by both, followed by WWR on the other sides and wall material. Storey number, storey height, shading device, and roof material are considered influential by the stakeholders, while the literature does not consider them influential.

(1) Operational energy

WWR, building plan and *wall material* are considered influential by both literature and stakeholders, while the stakeholders' opinion on the influence of *WWR_S* is stronger than in the literature and yet the influence of *building plan* is weaker than in the literature. *Building orientation, shading device, storey number, storey height, roof type* and *roof material* are influential according to stakeholders but not in the literature.

(2) Daylight

The influential ADVs are in general similar, but the extent of influence varies considerably. Although *WWR* and *shading device* are influential for *daylight*, stakeholders consider *WWR* to be much more influential and *shading device* less influential than in the literature.

Building plan, building orientation, window shape, window location and *storey height* are influential from a stakeholder's perspective but receive a lower rating in the literature. *Wall material* is considered influential in the literature, but it lacks recognition among stakeholders.

(3) Thermal comfort

Fig. 8 shows that the influential ADVs for *thermal comfort* are in general similar with few exceptions. Both the literature and stakeholders agree on the high influence of *WWR, shading device* and *wall material*,

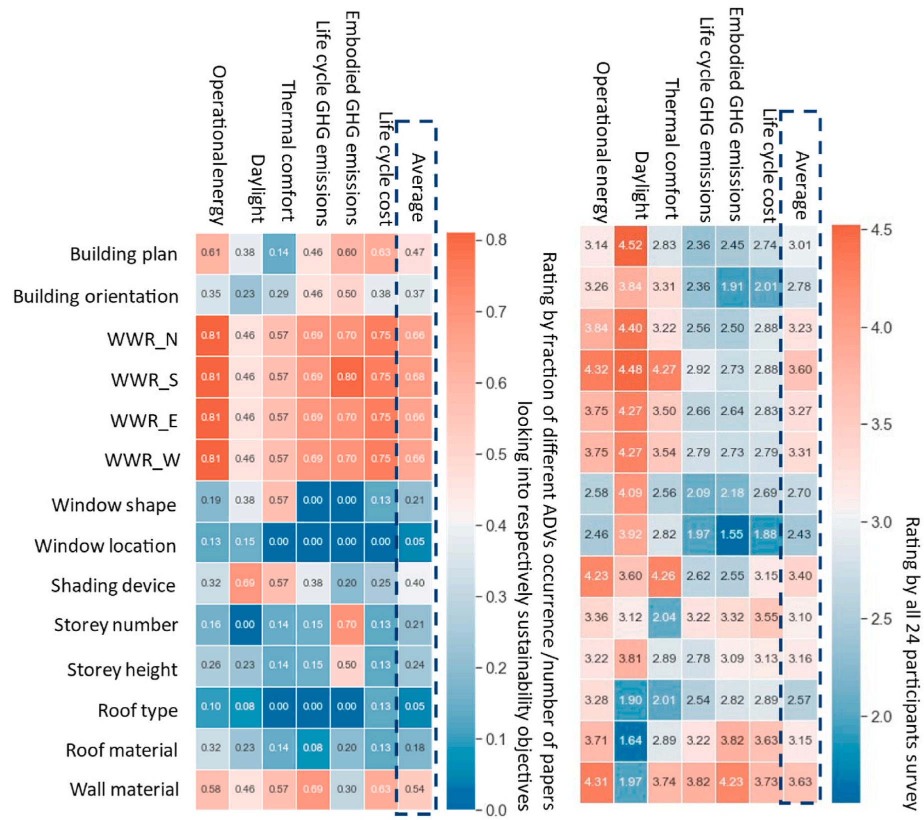

Fig. 8. Comparison of ADV influence on selected sustainability objectives between the literature and stakeholders.

while stakeholders' opinion on the influence of *WWR_S* is stronger than in the literature and *WWR_N* is weaker. Stakeholders also consider *building orientation* as an influential ADV for *thermal comfort* while the literature does not.

(4) Life cycle GHG emissions

There is no consistency between the literature and stakeholders on the influential ADVs for *life cycle GHG emissions*. Although *wall material* is influential, the literature considers *WWR, building orientation* and *building plan* as influential ADVs, while stakeholders do not agree. Stakeholders consider *storey number* and *roof material* as influential ADVs while the literature does not.

(5) Embodied GHG emissions

The influential ADVs for *embodied GHG emissions* also lack consistency. The literature considers *building plan, building orientation, WWR, storey number,* and *storey height* as influential ADVs, while stakeholders consider *storey number, storey height, roof material* and *wall material* as influential.

(6) Life cycle cost

The influential ADVs for *life cycle cost* also lack consistency as the literature considers *building plan, WWR,* and *wall material* as important ADVs, and stakeholders consider *shading device, storey number, storey height, roof material,* and *wall material* as influential.

In summary, for *operational energy, daylight, and thermal comfort*, the literature and stakeholders in general agree with a few exceptions. However, for *life cycle GHG emissions, embodied GHG emissions, and life cycle cost,* the influential ADVs lack consistency.

4. Discussion

4.1. Discrepancy between the literature and stakeholders

Through our analysis, we found clear similarities and discrepancies in the influential early-stage ADVs for different sustainability objectives between the literature and stakeholders (Table 5). That the influential ADVs are not always aligned between the literature and stakeholders

Table 5
Influential ADVs for selected sustainability objectives.

Objective	Important ADVs from		
	Both literature and stakeholders	Literature	Stakeholders
Operational energy	WWR, wall material	building plan	building orientation, shading device, storey number, storey height, roof type, roof material
Daylight	WWR, shading device	wall material	building plan, building orientation, window shape, window location, storey height
Thermal comfort	WWR, shading device, wall material,	–	building orientation
Life cycle GHG emissions	wall material	building plan, building orientation	storey number, roof material
Embodied GHG emissions	storey number	building plan, building orientation, WWR, storey height	storey height, roof material, wall material
Life cycle cost	wall material	building plan, WWR	shading device, storey number, storey height, roof material

can be explained by multiple reasons. First, most studies identified the influential ADVs by running simulations, yet, it is well known that simulation results can differ from reality [97,98]. For example, input weather data may lack accuracy, the simplified modeling assumption may not fully capture the intricacies of real-world conditions, occupants' behaviors may be unclear, and equipment performance in real-world conditions may differ from that in a simulation. Further, simulation results are normally very specific to a certain case and context. Many studies state that their results are valid only for their particular situation and are therefore not generalizable [84,99].

Second, architects and consultants may lack sufficient professional knowledge about certain sustainability objectives. For instance, Section 3.3 indicates that the rating and consistency between the literature and stakeholders regarding *daylight, operational energy,* and *thermal comfort* are higher, while stakeholders rate *embodied GHG emissions, life cycle GHG emissions,* and *life cycle cost* lower. To better understand this discrepancy, we interviewed six survey respondents. The respondents suggested that the reason could be that the industry has been working with *energy, daylight,* and *thermal comfort* for a longer time than with *embodied GHG emissions, life cycle GHG emissions,* and *life cycle cost,* which are still often considered novel aspects. As stakeholders are more familiar with the former objectives, they may be more comfortable in giving higher ratings.

Finally, stakeholders may feel reluctant to change a certain ADV in the early stages as this might make them consider it to be less influential. For instance, *building plan* in most cases is more influential in the literature than for stakeholders. According to our six interviews, while stakeholders rated ADVs based on their previous project experiences in most cases, some respondents also admitted that they tended to give higher ratings to the ADVs because they were more willing to change in the design process. Thus, part of the reason that *building plan* is not as influential for stakeholders may be that they may be reluctant to change it to improve the building's performance.

4.2. Implications for developers and stakeholders

Our findings show that the field lacks a more holistic approach to the development of building sustainability optimization tools, in which the opinions of stakeholders are also taken into consideration. Not only do we find in our literature review that previous studies fail to address stakeholder opinions, but we also find through our comparison analysis that the influential ADVs differ across the literature and stakeholders. This is especially the case when the sustainability objectives are *embodied GHG emissions*, *life cycle GHG emissions*, and *life cycle cost*.

By communicating the results of our study to industry, architects could become more conscious of how to improve sustainability when designing buildings, while consultants could better understand optimization tools. Even architects who refuse to use digital tools in design could have a better idea of how their design decisions could affect a building's sustainability performance.

Further, it is well known that the industry lags far behind academia in the implementation of building sustainability optimization tools in practice [98,100]. Indeed, many well-developed building sustainability optimization tools fail to be widely used by industry [101–103]. One reason for this could be that the developers of optimization tools are not aware of stakeholder opinions. Although stakeholder opinions might not be entirely accurate, they should, however, also be considered as stakeholders are both experts and in some cases, even the end users of the tools. Our results could thus be used more specifically as inputs for developers creating early-stage building sustainability optimization tools. For instance, if developers desire to create a daylight prediction model, they should not only consider the influential ADVs from the literature, such as *WWR, shading device,* and *wall material,* but they should also include the influential ADVs provided by the stakeholders, such as *building plan, building orientation, window shape, window location,* and *storey height*.

Finally, developers should continuously evaluate what end users consider as important in building sustainability optimization, as this is a crucial step in user-centered tool development. Tools that integrate what the end users consider as influential can help users to more effectively utilize them, thereby ensuring their long-term use. If not considered and integrated, the risk could be, for example, that optimization tools could fail to be more widely implemented in the industry, thereby unnecessarily leading to an increased negative impact of the ACE industry on sustainability. Thus, our findings promote taking a more holistic approach to optimization tool development.

4.3. Limitations and future research

It is worth noting that although we focused only on the Nordic countries for the sustainability objectives, we did not limit the literature review to identify influential ADVs for those objectives to the Nordics. Not only did many articles not specify the geographical region, but if we had focused only on the Nordics, there would not have been a sufficient number of papers for analysis. We argue, however, that although different regions and climates focus on different sustainability objectives, the influential ADVs for the same objective do not necessarily change across the regions. To further analyze this assumption, we took *operational energy* as an example to investigate if the influential ADVs for the same objective vary based on climate. Our result showed that the influential ADVs do not vary across different climate contexts (Appendix F). Therefore, it was reasonable to include the literature beyond the Nordics when identifying influential ADVs. Future research should investigate the sustainability objectives for other regions beyond the Nordics as well as determine which ADVs are most influential and how these results differ across geographical regions. In the same vein, we limited our study to investigating only residential buildings, thus a similar study should be conducted for other building types such as commercial buildings and industrial installations.

As most papers in our literature review investigated *operational energy*, research identifying important early-stage ADVs for other sustainability objectives is very limited. Future research could investigate the importance of early-stage ADVs for other objectives, such as *thermal comfort*, *embodied GHG emissions, life cycle GHG emissions,* and *life cycle cost* from a simulation point to see if the results still lack consistency with stakeholder opinions.

While we used surveys as the main method to gain stakeholder insights, surveys with closed-ended questions may have a lower validity rate. Further, our study involved only 12 architects and 12 consultants. To check the validity of our results, we took answers from ten randomly chosen respondents for each stakeholder category to calculate the comparative results (Appendix G). The difference between the mean rating for 20 respondents and that for 24 respondents is small: 98% of the difference in average rating is from 0 to 0.2, with most results around 0.05. The small difference in the rating between 20 respondents and 24 respondents indicates that an increase in the number of respondents would most likely not lead to a different result.

Another limitation is that 22 survey respondents worked in Sweden, which may have led to a biased result. However, even though most respondents are physically located in Sweden, the companies employing them all have projects throughout the Nordic countries. Therefore, it can be assumed that the respondents have experience in projects located across Nordic countries. However, future studies should encourage a larger and more diverse survey pool.

5. Conclusions

Defining the most influential ADVs for sustainability objectives is a crucial step in developing building sustainability optimization tools. To address this, our study combined a literature review with a survey of 24 architects and building sustainability consultants in the Nordics. We found that while many studies identified the influential ADVs from a simulation point of view, we did not find any studies that considered the stakeholder perspective. Stakeholders, including architects and consultants, are not only experts but also the end users of optimization tools. Further, our comparison analysis showed that there was a discrepancy between the findings in our literature review and our stakeholder survey. The reasons behind this can include the gap between simulation results and reality, a lack of sustainability knowledge across stakeholders, and an inconsistency in the most frequently used ADVs by stakeholders in practice and academia. Thus, researchers and developers who work in early-stage building optimization could use the results from our study as initial input in their work.

In conclusion, our study provides support for a more holistic development of computational building sustainability optimization tools. On the one hand, our results could help to improve the development of building sustainability optimization tools, and on the other hand help architects, sustainability consultants, and other stakeholders to improve their ability to design more sustainable buildings, both of which can significantly contribute to decreasing the ACE industry's impact on sustainability in the long run. For future development, the number of participants in stakeholder interaction part could be scaled up, the same method could be applied to different regions to compare the results.

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CRediT authorship contribution statement

Xinyue Wang: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robin Teigland:** Writing – review & editing, Supervision. **Alexander Hollberg:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alexander Hollberg reports financial support was provided by Swedish Research Council Formas.

Data availability

Data will be made available on request.

Appendix A. Categories of sustainability objectives for early-stage optimization in the Nordics from the literature review

Objective category	Frequency of occurrence	Description	Different objective names	References
Embodied greenhouse gas emissions	7	Greenhouse gas emissions associated with both the material production and construction processes of a building.	Low carbon footprint in construction	[104]
			Low carbon in construction	[105]
			Environmental impact on material	[106]
			Environmental embodied impacts	[107]
			Embodied and construction stage greenhouse gas emissions	[108]
			Embodied emissions in materials	[109]
			Embodied greenhouse gas emissions	[110]
Operational greenhouse gas emissions	5	Greenhouse gas emissions associated with operating a building in the use stage.	Low carbon footprint in use	[104]
			Low carbon in heating	[105]
			Environmental impact on energy	[106]
			CO2 emissions	[111]
			Carbon emissions	[112]
			Operation emissions	[109]
Life cycle greenhouse gas emissions	6	Total greenhouse gas emissions associated with the building's life cycle including raw material extraction, material production, transports, construction, building operation and maintenance, and disposal at end of life.	Carbon footprint	[113]
			Life cycle greenhouse gas emissions	[114]
			GWP	[115]
			CO2 emissions	[116]
			CO2 in LCA	[117]
			Carbon emissions in LCA	[118]
Embodied energy	3	Energy consumed is associated with the material and construction stages of the building.	Embodied energy	[119–121]
Operational energy	23	Energy consumed is associated with operating a building in the use stage, e.g., electricity, gas, water, and other energy used in the building.	Annual heating energy consumption	[122]
			Energy used for heating and air-conditioning	[104]
			Energy consumption	[123–125]
			Energy demand	[112,126–129]
			Energy	[130–133]
			Operational energy	[119–121,134]
			Consumption of energy	[116]
			operating energy consumption	[107]
			Energy use	[135]
			Primary energy	[111]
Life cycle energy	5	Energy consumed is associated with the material, construction and use stages of the building.	Life cycle energy	[107,121,136,137]
			Life cycle primary energy	[138]
Construction cost	1	Costs of the construction stage.	Construction cost	[116]
Operational cost	1	Costs in use stage.	Operational cost	[116]
Life cycle cost	8	The total cost associated with building design and construction, building operation and maintenance, in addition to costs associated with building disposal at the	The cost is defined by the sum of the present value of the investment cost for the building's materials and components as well as the operational costs for the operational energy	[119]

(continued on next page)

(*continued*)

Objective category	Frequency of occurrence	Description	Different objective names	References
		end of life. External costs, for example, environmental costs are excluded.	LCC	[116,118,128, 137,139,140]
			Total cost	[141]
Daylight	8	Natural light indoors by using windows and skylights.	Natural light indoors	[105]
			Sunlight	[142]
			Daylight distribution	[120]
			Visual comfort	[106]
			Daylight	[143,144]
			Interior daylight	[145]
Thermal comfort	9	A person's state of mind in terms of whether they feel too hot or too cold.	Thermal comfort	[116,125,132, 133,144, 146–148]
			PMV value	[122]

Appendix B. Categories of ADVs for early-stage optimization in the Nordics resulting from the literature review

Category	Description	Different variable names	Reference
Window-to-wall ratio on north/ west/east (WWR_N, WWR_E, WWR_W)	Fraction of the above grade wall area that is covered by fenestration on the north/west/east facade.	Window-to-wall ratio	[8,9,25,26,34,51–61,63–66,70, 76–78,80,82,85–87,90–93,95, 96]
		Glazing area percentage	[68]
		Glazing ratio	[88]
Window-to-wall ratio south (WWR_S)	Fraction of the above-grade wall area that is covered by fenestration on the south facade.	Window-to-wall ratio south	[8,9,25,34,51–61,63–66,70, 76–78,80,82,85–87,90–93,95, 96,149]
		Glazing area percentage	[68]
		fenestration ratio on the southern façade	[69]
		Glazing ratio	[88]
Window shape	Shape and dimensions of the window.	Glazing shape	[11]
		Window length	[18]
		Window size	[35,62,71,79,85]
		Width-to-height window ratio	[63]
		Window width and height	[76,83]
Shading device	Integrated component of a window and facade protecting space from direct sun, overheating, and glare; and providing increased daylight levels, desired privacy, or an outside view.	Shading length	[69]
		Louvre length	[18]
		Type of solar protection	[57]
		Shading device	[61,64,66,67,70,85,93,96]
		Shading factor	[79]
		Shade depth	[80]
		Overhang depth	[82,83]
		Shading ratio	[62]
		Shading area	[94]
Window location	Location of windows.	Window location	[71,85]
		Glazing area distribution	[68]
		Window position in the facade	[83]
Wall material	The material used on the external wall.	Envelope composition	[51]
		Building envelope	[11]
		Exterior wall	[9,55]
		External wall R-value	[54]
		Wall type	[52,56,64,67]
		Wall U-value	[8,25,53,59,63,65,66,80,82]
		Wall material	[57,72,73,78,86,87]
		Façade material	[74]
Building plan	Drawing to scale, showing the view from above contains information on sizes, boundaries and dimensions.	Building length, width, height	[8,9,18,25,34,53,55,57,60,65, 68,69,77,86]
		Plan shape	[11,56,93]
		Building shape	[52]
		Aspect ratio	[80,82]
		Building plan	[58,76,87,88]
		Plan	[61,71,75]
		Shape coefficient	[92]
Building volume	The total volume of the building.	Building volume	[60]
Wall-to-floor ratio	Fraction of dividing external wall area by gross internal floor area.	Wall-to-floor ratio	[60]

(*continued on next page*)

(*continued*)

Category	Description	Different variable names	Reference
Building orientation	Relationship of building site situation and positioning of windows, rooflines, and other features.	Building orientation	[11,34,35,56,58,59,62,66,67,70,76,77,80,86,90–93,95,96]
Roof material	The material used on the roof.	Roof type	[52,56,67]
		Roof R-value	[54]
		Roof U value	[8,59,65]
		Roof material	[71,86]
Roof type	Style of roof (e.g., flat, inclined).	Roofing style	[58]
		Roof type	[34,75]
Roof area	Value of area of the roof.	Roof area	[58,82]
Storey height	Height of each floor.	Story height	[11,25,53,63]
		Floor height	[57,60,80,82,95]
		Room height	[76,83]
		Level height	[88]
Storey number	Number of floors.	Story number	[8,11,25,53,75,89]
		Level	[69,88]
		Number of floors	[57,60,64,65,80,82,87,91,95]
		Stacking	[34]

Appendix C. A summary of the typical interpretation of life cycle modules based on EN 15978 in the Nordic context

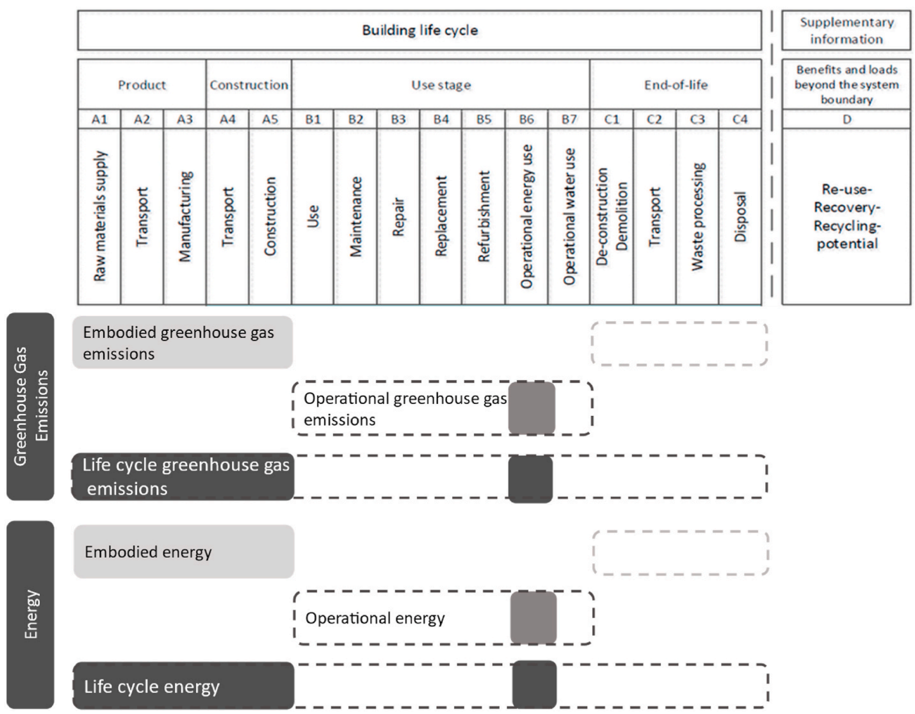

Fig. 9. A summary of the typical interpretation of life cycle modules based on EN 15978 in the Nordic context.

Some studies also include the end-of-life (module C1-4) in the embodied emissions, but as the current legislation such as the Swedish climate declaration only includes modules A1-A5, we exclude end-of-life, here.

Appendix D. Survey

Architectural design variables' impact on different objectives

Hello architects and consultants!

My name is Xinyue Wang; I am currently a PhD candidate at Chalmers University of Technology studying computational sustainable building. This is a survey related to my current project: architectural design variables assessment. The information you filled here will only be used in this specific project.

1. Please state your occupation here.

2. Please state your year of experience here.

3. Please state the country you currently work in.

4. Please describe briefly about your work content here, including what type of building do you normally work with.

Imagine you are designing a residential building located in Gothenburg, Sweden. Please rate the importance of different objective and the impact of different architectural design variables (ADVs) under various objectives based on your experience.

Some explanation:
Energy refers to ALL the energy used to operate a building. In a residential building, energy consumption will include electricity, gas, water, and any other energy used to live in it.
Daylighting refers to natural light indoors by using windows and skylights.
Life cycle cost refers to the total cost associated with building design and construction, building operation and maintenance, in addition to the costs associated with building disposal at the end of its life cycle. External costs, for example environmental costs are excluded.
Life cycle GHG (greenhouse gas) emissions refers to the total greenhouse gas emissions associated with building's life cycle including raw material extraction, material production, transports, construction, building operation and maintenance, and disposal at the end of its life cycle.
Embodied GHG (greenhouse gas) Emissions are the greenhouse gas emissions associated with material production and construction processes of a building.
Thermal comfort describes a person's state of mind in terms of whether they feel too hot or too cold.

1. Please rate the impact of different architectural design variables (ADVs) to various objectives here
You can rate the importance of each variable on a scale of 1 to 5.
1 means the variable has nearly no impact on the objective.
5 means the variable has extremely significant impact on the objective.

OBJECTIVES / ADVS	Energy consumption	Daylighting	Thermal comfort	Life cycle GHG emissions	Embodied GHG Emissions	Life cycle cost
Building plan						
Building orientation						
Window to wall ratio (north)						
Window to wall ratio (south)						
Window to wall ratio (east)						
Window to wall ratio (west)						
Window shape						
Window location						
Shading device						
Number of storey						
Height of storey						
Roof type						
Roof material						
Wall material						

2. Is there any other variable that you think might have influence on the objectives mentioned before? Please state the variable, the objective, and the level of importance here.

Fig. 10. Survey.

Appendix E. Information about all respondents

Table 8
Information about all respondents

Index	occupation	Work location	Year of experience	Main work description
A1	Architect	Sweden	3	Early stages design projects
A2	Architect	Sweden	7	New production and renovation of residential buildings
A3	Architect	Sweden	9	Housing, urban design
A4	Architect	Sweden	9	Design and planning of multi-residential buildings AND coordinator Miljöbyggnad
A5	Architect	Sweden	7	Planning of housing and offices, early stage till built
A6	Architect	Sweden	35	Private sector housing& and offices
A7	Architect	Sweden	10	Dwellings, Offices
A8	Architect	Sweden	10	residential, office, hospitals
A9	Architect	Norway	22	Residential, office, schools
A10	Architect	Sweden	5	Residential, commercial, office
A11	Architect	Sweden	22	Computational design development lead for architectural design projects at all scales.
A12	Architect	Sweden	2	Hotel, housing, event, office
C1	Consultant	Sweden	25	Newly constructed commercial buildings
C2	Consultant	Sweden	4	Mainly work with sustainability strategy, but I have worked with simulation tools, parametric design, reducing climate impact and building performance.
C3	Consultant	Norway	2	I deal with the analysis and documentation of building energy use and indoor climate in terms of thermal and visual conditions. I also work with LCA and LCC on buildings
C4	Consultant	Sweden	4	Housing
C5	Consultant	Sweden	5	I do daylight and solar heat gain calculations for both residential and office buildings. Mostly to check for building codes and building certifications.
C6	Consultant	Sweden	8	All kinds of buildings, mostly new construction but even some renovations and existing buildings. Everything from sustainability certification over energy optimization to all types of calculations and simulations
C7	Consultant	Sweden	4	Residential, Offices, schools
C8	Consultant	Sweden	10	Building performance design of multi-family buildings, schools, and offices.
C9	Consultant	Sweden	4	Building performance calculations on pretty much any type of building, but often residential and office ones
C10	Consultant	Sweden	9	Analysis and simulation of building models for daylight, solar gains and comfort performance
C11	Consultant	Sweden	2	LCA, Energy, Daylight analysis + sustainability strategies. All kinds of buildings
C12	Consultant	Sweden	25	Newly constructed commercial buildings

Appendix F. Influential ADVs for operational energy under different climates

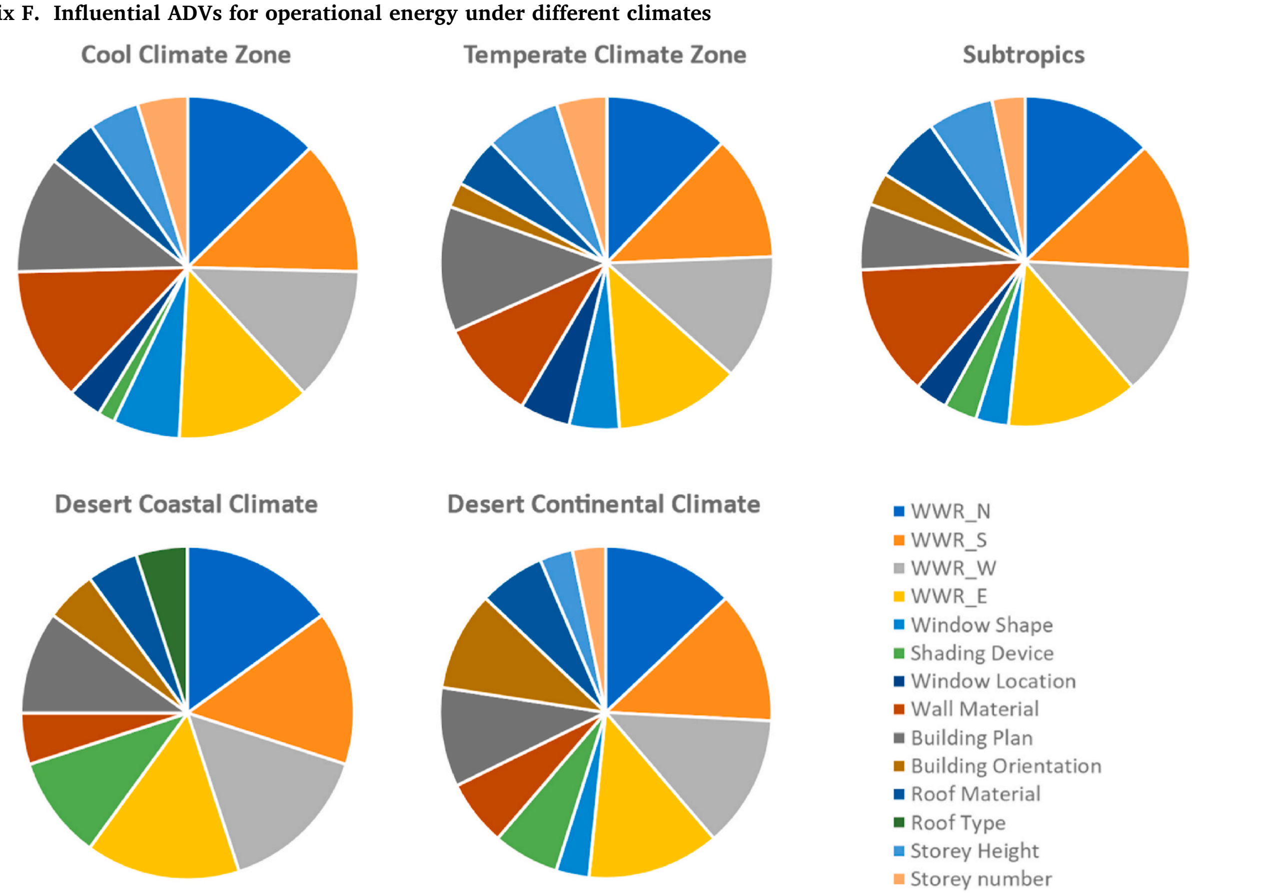

Fig. 11. Influential ADVs for operational energy under different climates.

Appendix G. Average rating with all 24 respondents and random 20 respondents

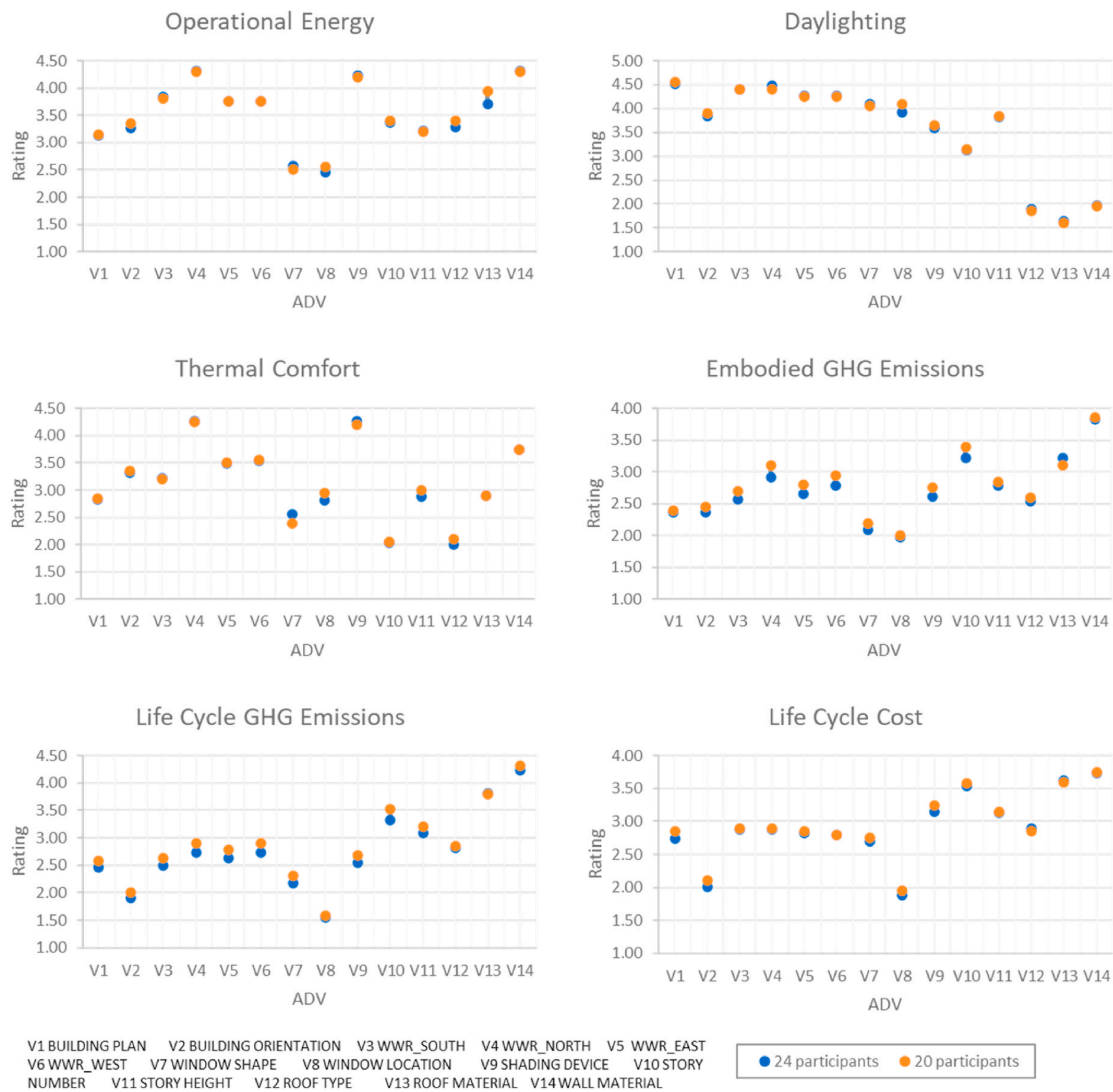

Fig. 12. Average rating with all 24 respondents and random 20 respondents.

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