Critical perspectives on life cycle building performance assessment tool reviews

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Review article

Critical perspectives on life cycle building performance assessment tool reviews

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ABSTRACT

Despite the environmental, social, and economic benefits of integrating quantitative analysis in early architectural design stages, tools developed for this purpose see little use in practice. This meta-review provides an overview of eighty-seven tool reviews in the field of life cycle building performance assessment to identify best practices and remaining gaps. It is found that most previous reviews emphasise technological advancement rather than tool integration in practice, by failing to apply the perspective of tool users in design processes. It is further found that the reviews mostly lack consistent methodologies. To bridge these gaps, it is proposed that future tool evaluation studies define a clear target user and investigate tools based on how they perform in real-world design processes. A tool characterisation framework based on the approaches in previous reviews is proposed to facilitate such investigations.

1. Introduction

Buildings have a great social and environmental impact, including effects on human wellbeing [1], large amounts of material extraction [2], and carbon emissions [3]. The actors in the design process have the opportunity to reduce the negative impacts of the construction sector by consciously selecting and developing well-performing design alternatives [4]. The consideration of these impacts is increasingly being perceived as the responsibility of architects active in early design stages [5]. However, quantitative methods such as life cycle assessment (LCA) [6], and building performance analysis (BPA) [7], are more commonly used by specialists in late design stages for certification and regulation purposes [8]. If these methods were instead employed by architects and other stakeholders in early design stages, large benefits could be had through avoiding the development of suboptimal design alternatives [6]. In this study, this combination of LCA and BPA is referred to as life cycle building performance assessment.

The early architectural design stages [9], intermittently referred to as conceptual or schematic design stage [10], corresponds to the "preparation and brief" and "concept design" stages defined by the Royal Institute of British Architects (RIBA) (see Fig. 1). As seen in the figure, the benefit of using analysis results to make design changes is the greatest at the lowest cost in these design stages [9]. However, there are challenges to integrating life cycle building performance assessment in these stages, including the uncertainty inherent as the design proposal changes rapidly, and the limited resources and information available [6]. This motivates emphasising these design stages in research, firstly because the use of analysis tools in later design stages is well established [7], and because, as also indicated in Fig. 1, tools aimed at the early design stages often need to cater to the needs of architects with limited technical expertise as opposed to engineers or specialists with expertise in using advanced analysis tools [11].

The software industry has responded to the need for methods applicable in early design stages through the development of a number of simplified computational assessment tools for BPA [12] and LCA [13]. However, studies in the practice show that the uptake of these tools among architects is still limited in various national contexts like the US [14], the UK [15], and Australia [5]. Instead, assessments are, if at all, done through in-house scripts or rule-of-thumb approaches [15]. One possible explanation for this discrepancy between the research and development communities and the day-to-day architectural design practice is that the development efforts do not sufficiently take into account the complex and iterative ("messy" [16]) reality of the architectural design process and effectively meet its needs.

Fig. 2 shows possible perspectives during software development processes. During a traditional, techno-centric tool development process, requirements for the tool front-end and back-end are developed based on perceived user needs. If instead a user-centric approach is applied, the user is actively engaged in the conversation about tool requirements [17]. However, as shown in Fig. 2, tool developers have largely emphasised the technology side of tools and to some extent considered a user perspective, while largely overlooking the wider practice perspective including the design team, client, regulations, and so on [16]. This study investigates if the existing literature evaluating tools can inspire the application of such a practice perspective.

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Abbreviations

BEPS	building energy performance simulation
BIM	building information modeling
BPA	building performance analysis
CAD	computer-aided design
CFD	computational fluid dynamics
LCA	life cycle assessment
RIBA	the Royal Institute of British Architects

The purpose of software evaluation studies (tool reviews) is typically to support tool developers in identifying the needs of potential tool users by drawing inspiration from and identifying gaps among tools on the market [18]. Alternatively, the purpose is to support potential users in selecting tools by comparing their capabilities [19]. The software evaluation process is usually carried out through the development and employment of specifically tailored, more-or-less explicit characterisation frameworks.

Within the wider field of software development, there are several studies discussing how to characterise software tools. For example, van der Linden et al. [20] propose an evaluation framework for software families. Jadhav and Sonar [19] provide a generic methodology for software evaluation which can be used as a starting point for a specific characterisation framework for life cycle building performance assessment tools. Fumagalli et al. [21] design a framework for selecting simulation software under the assumption that the demand for a specific product has been identified during an industrial manufacturing process.

There are also some previous studies which make an effort to provide systematic characterisation frameworks for tools specifically within life cycle building performance assessment and adjacent fields. Based on a literature review, Attia et al. [23] present criteria for what they call "architect-friendly" building performance simulation tools. They list (1) usability and information management of interface, (2) integration of intelligent design knowledge base, (3) interoperability of building modeling, and (4) accuracy and ability to simulate complex elements. Attia et al. [24] further add (5) integration in the building design process to this list.

Weytjens and Verbeeck [25] provide another conceptual framework for "architect-friendliness" based on interviews and a survey: (1) data-input, (2) output, (3) interface, (4) usability in design process, and (5) general criteria. Wallhagen et al. [26] introduce a framework for the evaluation of building environmental assessment tools: (1) structure, (2) content, (3) aggregation, and (4) scope. Østergård et al. [27] develop a conceptual holistic simulation framework through a literature and tool review, including (1) knowledge database, (2) baseline model, (3) sampling, (4) simulations, (5) statistical analysis, and (6) visualisation.

Based on interviews, Purup and Petersen [28] provide a framework for understanding architects' design activities and their relationships to potential integration of BPA. They identify thirty-one design activities, separated into (1) research activities, (2) modeling activities, (3) analysis activities, and (4) meeting activities. Hollberg et al. [29] categorise different goals for LCA studies which could potentially be extended to cover all analysis-based design support: (1) Identification of hotspots, (2) comparison of design options, (3) correlation, uncertainty, and sensitivity analysis, (4) benchmarking, (5) spatial distribution, and (6) temporal distribution.

While these studies all present different aspects and perspectives of design integrated analysis tools, to the knowledge of the authors, no previous studies have attempted the systematic retrieval of characterisation criteria from published tool reviews in the field of life cycle building performance, or comprehensively discussed the usefulness of these criteria in investigating the applicability of life cycle building performance tools in early-stage architectural practice. Further, in previous research, the studies often provide limited justification as to why the specific characterisation framework employed is the most well-suited to meet the specific study aims, and typically fail to provide clear definitions of the characterisation criteria used which leaves their meaning open to the interpretation of the evaluator [19]. Judging by the discrepancy between the volume of tool development efforts and the limited tool uptake in practice, the available tool reviews with the goal of supporting tool development appear to overlook some aspects of practice integration. These gaps motivate the application of a meta-review methodology which scrutinises dominating assumptions within the research on life cycle building performance assessment tools [30], by comparing the approaches and findings in previous comprehensive tool reviews as opposed to primary analyses presenting novel tools [31].

The main contribution of this research is such a critical assessment of the methods applied in previous tool reviews, by means of a meta-review methodology. The outcome of the meta-review is a proposed systematic approach to carrying out tool reviews which consider the needs of the wider practice beyond technological and tool user perspectives. The findings are aimed to support both researchers investigating the state-of-the-art in terms of tools available on the market, and software developers who need a consistent method of organising software requirements. Fig. 3(a) summarises the identified gap by visualising the prevalent tool development process — there is a disconnect between practice needs and the criteria used to evaluate tools which causes the development of software requirement not anchored in practice, and consequently a limited tool uptake. Fig. 3(b) instead shows the intended outcome of this research, a practice-oriented tool development process — tools are evaluated based on practice needs, allowing the definition of software requirements which enable an improved tool uptake.

2. Methodology

This study is a meta-review of literature evaluating tools for life cycle building performance assessment and from related fields. The meta-review is different from the comprehensive review, which investigates literature presenting primary analyses conducted within a research field, identifying agreements or conflicts regarding specific research questions. Contrastingly, the literature investigated during a meta-review consists of review articles within a wider research area, allowing an observation of the prevailing research streams and trending methodologies [31]. Meta-reviews are useful to integrate the findings of a large collection of studies and compare methodologies [32]. They have, for instance, been applied to harmonise LCA approaches [33] and to combine user-centric software development methodologies [34]. Meta-reviews are useful to analyse the assumptions dominating a research area, to clarify the constructs present in the literature through the definition of conceptual frameworks, and to define a research agenda based on different assumptions or a more holistic understanding of the involved constructs [30]. This motivates the application of a meta-review methodology in this study, aiming to detect whether a practice-centric perspective is missing in the available literature reviewing tools.

The meta-review was conducted in three stages. After literature was collected, first, the aim of each article was investigated. Second, the literature was scrutinised in order to identify characterisation criteria previously used to assess tools. Third, three critical perspectives (a user, design process, and practice perspective) were applied in order to identify gaps related to previous tool review methodologies. An overview of the three-stage meta-review methodology is provided in Fig. 4.

The literature was primarily collected through a snowballing literature search [35]. Literature in English, Swedish, or German, providing a systematic presentation, comparison, and/or review of two or more

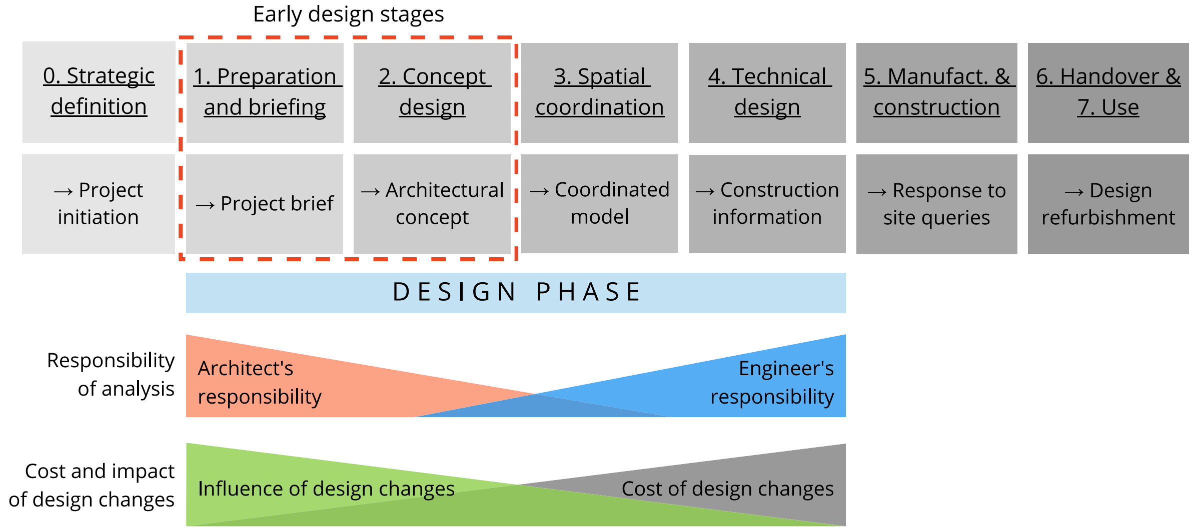


Fig. 1. Design stages as defined by RIBA [22], a schematic representation of the shifting responsibilities of architects and engineers during the design phase [11], and of the cost and influence of design changes in different stages [9].

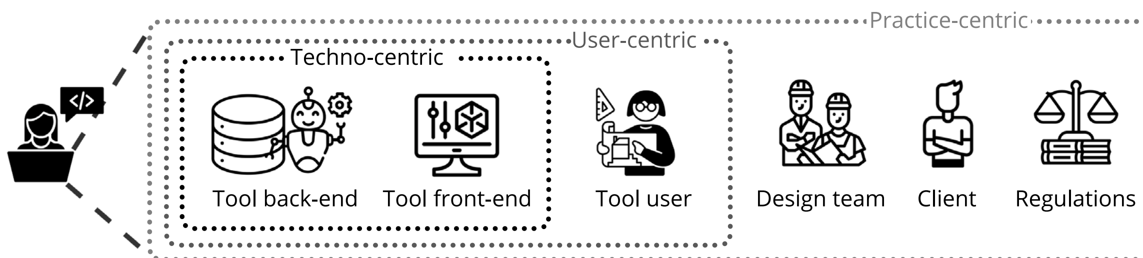


Fig. 2. Possible perspectives during software development.

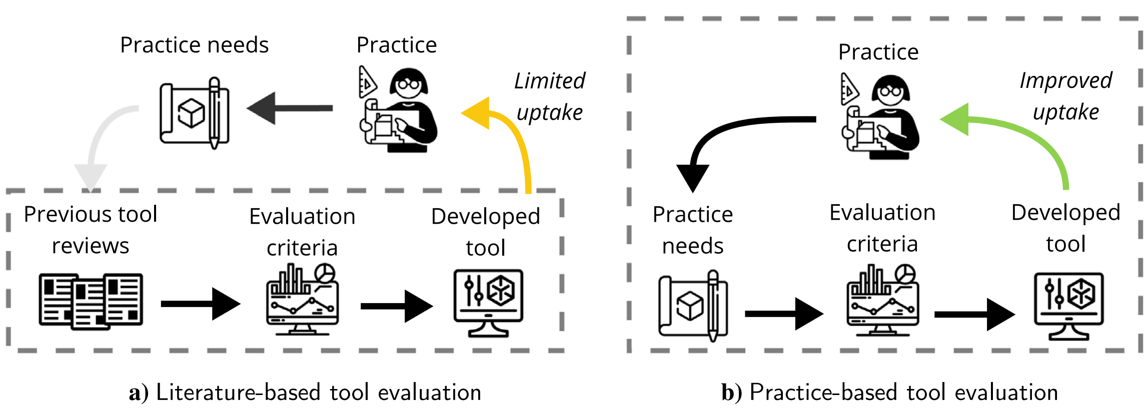


Fig. 3. Developing software requirements based in literature versus based in practice.

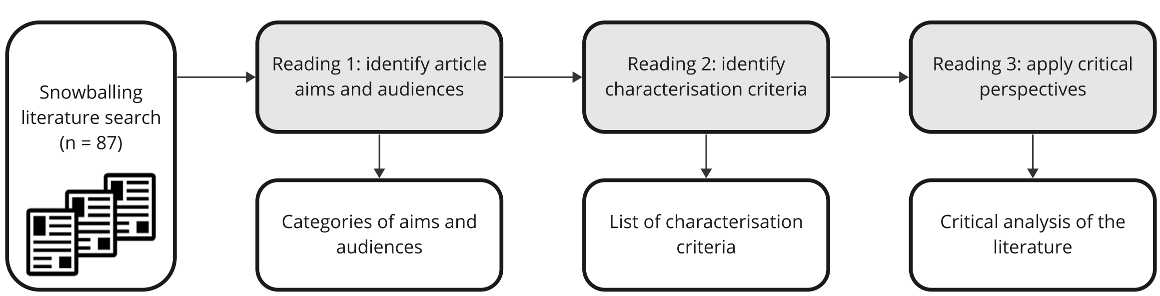


Fig. 4. Overview of meta-review methodology.

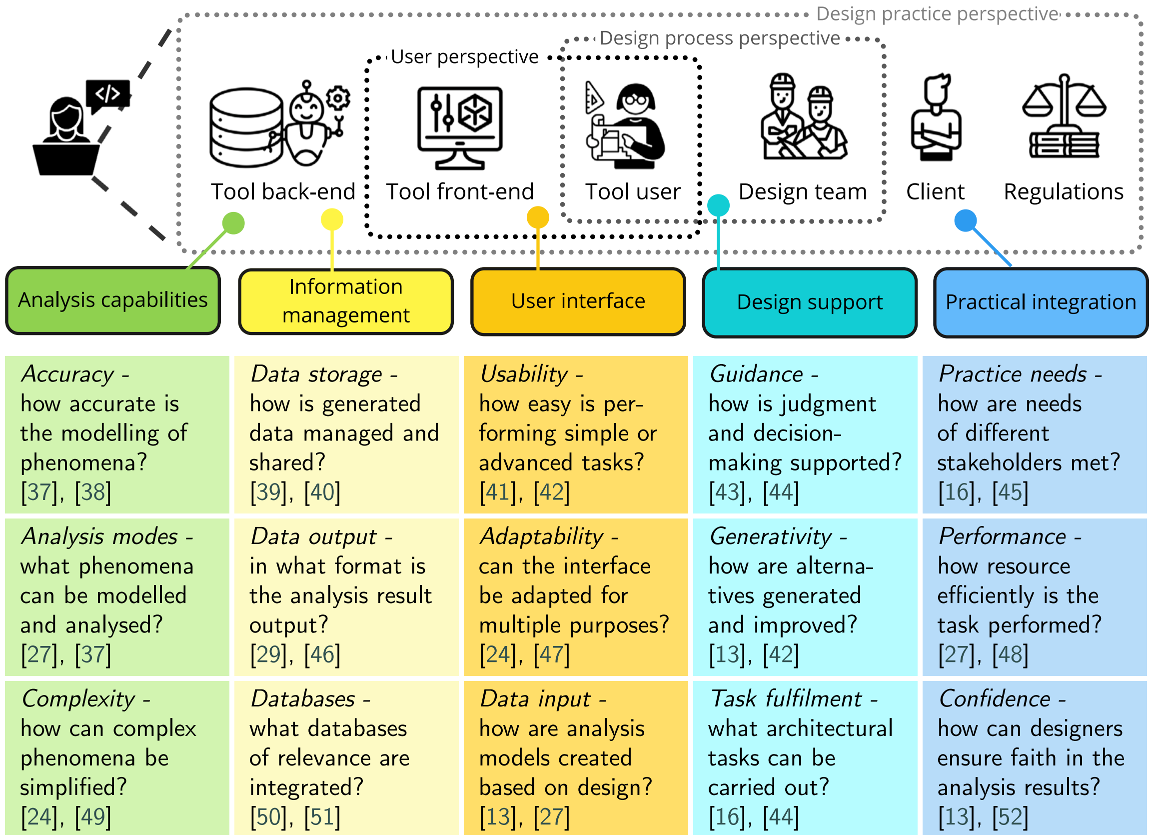


Fig. 5. Perspectives applied in the critical meta-review, and links to the developed characterisation criteria.

tools or workflows combining tools is considered. Tools in this instance may refer to digital tools, such as stand-alone software, computer-aided design (CAD) software plug-ins, or spreadsheet based calculation models [36]. Alternatively, it may refer to analogue guidance tools for designers such as checklists, result templates, or certification systems [26]. Reviews of tools aimed both to support new construction and refurbishment are considered, research on novel analysis methods and reviews of such methods, however, are considered out of scope. Tool reviews in the fields of LCA, BPA, and adjacent fields including structural analysis, architectural design, and energy systems, published 1998 or later, are considered. Eighty-seven articles were identified during this process. The literature reviewed was collected through a snowballing approach which may have left some relevant articles with few citations out of the search. As the literature collected is limited to articles which specifically review tools, studies which do not have this express purpose are not covered. Hence, the knowledge gaps identified can only be said to be relevant for the genre of tool reviews and adjacent studies.

A first systematic reading of the literature was performed in order to establish the aim of each publication. Once this information had been established for each publication, an aggregation of the aims into categories was performed. The results of this categorisation are presented in Table 1. The definitions of aims, the characterisation criteria collected, and the critical perspectives applied, were qualitatively defined and investigated within this study. A replicating study may thus devise a different categorisation than the one presented.

A second systematic reading of the literature was performed in order to identify characterisation criteria. Characterisation criteria refers to criteria used in the reviews to quantitatively or qualitatively describe, the features, capabilities, and traits of tools, among other aspects. The criteria were retrieved firstly from the methodology section, secondly from the results and analysis section, and thirdly from the discussion section of each paper. Once the full set of criteria from all literature had been identified, overlapping criteria were combined, after which the criteria were aggregated into categories. The categorisation was inspired by the organisation of tool characterisation criteria into five categories established by Attia et al. [24]. The following five categories were defined: (1) user interface (how does the user interact with the analysis?); (2) information management (how is data related to the analysis stored and presented?); (3) analysis capabilities (what phenomena can be analysed?); (4) design support (how does the workflow support design judgment and decision making?); and (5) practical integration (how can design practices adopt the tool into their existing workflows and toolkits?). An overview of the categories and what they entail is presented in Fig. 5. The references indicated next to each of the fifteen subcategories provide examples of how these criteria can be evaluated.

Finally, a third systematic reading of the literature was performed, organised according to the identified characterisation criteria and established categories, in order to critically examine if and how tool criteria were related to the practice uptake of tools in the literature, and where gaps and potential research directions could be detected.

The gaps and research directions identified were organised according to three perspectives on tool integration in practice, shown in Fig. 5. Firstly, a user perspective, considering questions which relate to the single user or group of users interacting with the tools and their needs. Secondly, a design process perspective, which treats the inclusion of tools in integrated, multidisciplinary design processes and the usefulness of tools as design support. Finally, a design practice perspective, which treats the practical needs and motivations for design practices to adopt tools. These perspectives represent how a software developer could organise software requirements related to how tools are embedded in the practice by potential users, allowing the development of tools which better conform to practice needs.

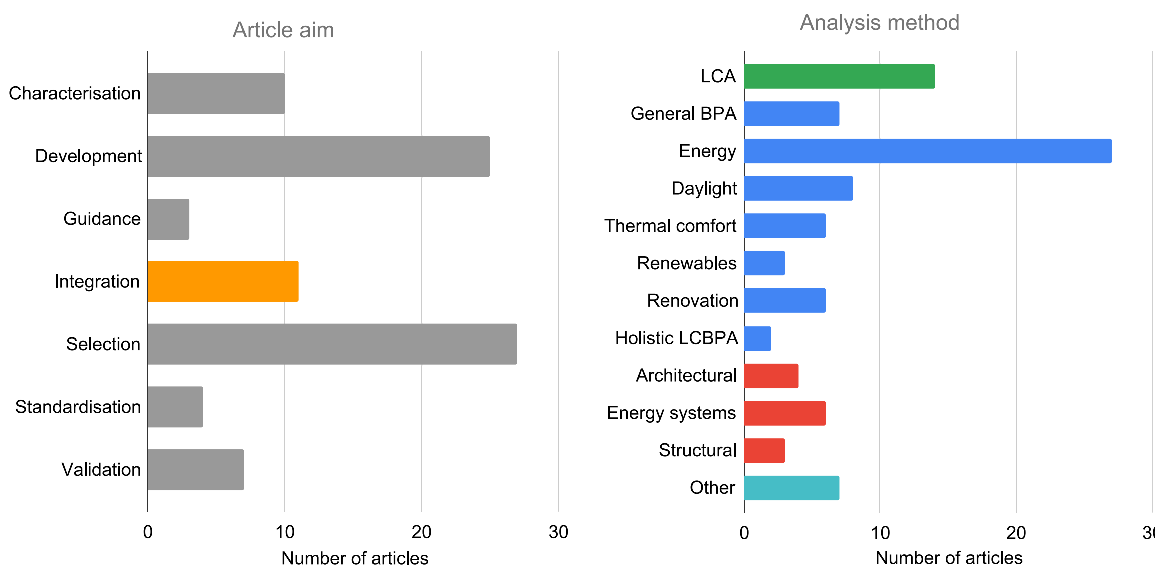
Table 1
Overview of tool reviews collected.

Reference	Aim	Intended audience	Phase
LCA			
Wallhagen et al. [26]	Characterisation	Tool developers	Not specified
Säwén et al. [37]	Characterisation	Tool developers	Early Design
Marsh et al. [38]	Development	Architects, clients	Early Design
Battisti et al. [39]	Development	Tool developers	Early Design
Wastiels and Decuypere [40]	Development	Tool developers	Design
Budig et al. [41]	Development	Architects	Early Design
Haapio and Viitaniemi [42]	Standardisation	Consultants, producers, building owners, researchers, authorities	Design & operation
Wallhagen and Glaumann [43]	Integration	Researchers	Design
Sharifi and Murayama [44]	Integration	Tool developers	Design & operation
Soust-Verdaguer et al. [45]	Integration	Engineers, architects, tool developers	Early Design
Myllyviita et al. [46]	Integration	Companies, researchers	N/A
Hildebrand and Bach [47]	Selection	Architects	Design
Hollberg et al. [29]	Standardisation	Tool developers	Design
Giordano et al. [48]	Validation	Architects, tool developers	Early Design
General BPA			
Han et al. [49]	Characterisation	Architects	Early Design
Säwén et al. [50]	Characterisation	Tool developers	Early Design
Weytjens et al. [51]	Development	Tool developers	Early Design
Solmaz [52]	Development	Tool developers	Design
Azar et al. [53]	Development	Researchers	Design
Bazafkan [54]	Integration	Architects	Design
Azhar and Brown [55]	Selection	Engineers, architects	Design
Energy			
Crawley et al. [56]	Characterisation	Researchers	Design
Attia et al. [24]	Characterisation	Engineers, architects	Design
Mahmoud et al. [57]	Characterisation	Engineers, architects	Early Design
Mills [58]	Development	Tool developers	Operation
Attia et al. [23]	Development	Tool developers	Not specified
Batish and Agrawal [59]	Development	Tool developers	Early Design
Johari [60]	Development	Tool developers	N/A
Doma and Ouf [61]	Development	Researchers, tool developers	Not specified
Abo Issa [62]	Guidance	Architects	Not specified
Bleil de Souza [63]	Integration	Engineers, architects	Design
Mahmoud et al. [15]	Integration	Architects	Early Design
Sousa [64]	Selection	Engineers	Not specified
Abdullah et al. [65]	Selection	Engineers, architects	Early Design
Farzaneh et al. [66]	Selection	Engineers, architects	Design
Baamer et al. [67]	Selection	Architects	Design
Ferrando et al. [68]	Selection	Engineers, architects, researchers	Not specified
Forouzandeh et al. [12]	Selection	Engineers, architects, tool developers	Design
Stavrakakis et al. [69]	Selection	Engineers, architects, planners	Early Design
Wen and Hiyama [70]	Standardisation	Architects	Early Design
Yezioro et al. [71]	Validation	Simulation tool users	Not specified
Esteves et al. [72]	Validation	Tool developers	Not specified
Daylight			
Ayoub [73]	Development	Architects, researchers	Not specified
Ayoub [74]	Guidance	Architects	Design
Ubbelohde and Humann [75]	Selection	Architects and lighting designers	Not specified
Roy [76]	Selection	Architects	Not specified
Ayoub [77]	Selection	Architects, researchers	Design
Reinhart and Herkel [78]	Validation	Architects and lighting engineers	Not specified
Iversen et al. [79]	Validation	Engineers, architects, researchers	Not specified
Davoodi et al. [80]	Validation	Engineers, architects, researchers	Not specified
Thermal comfort			
Adelia et al. [81]	Characterisation	Engineers	Not specified
Qavidel Fard et al. [82]	Development	Researchers	Not specified
Hu et al. [83]	Development	Architects, researchers	Early Design
Naboni et al. [84]	Selection	Researchers, designers	Not specified
Albdour and Baranyai [85]	Selection	Researchers, designers	Not specified
Hu et al. [86]	Selection	Architects	Not specified
Renewables			
Horvat and Dubois [87]	Integration	Architects	Early Design
Kanters et al. [88]	Integration	Tool developers	Early Design
Jakica [89]	Selection	Engineers, architects	Design
Renovation			
González Caceres et al. [90]	Characterisation	Homeowners, consultants, policymakers	Design & operation
Ferreira et al. [91]	Development	Researchers	Not specified
Lee et al. [92]	Development	Tool developers	Not specified
Nielsen et al. [93]	Development	Researchers, tool developers	Early Design
Thuvander et al. [94]	Integration	Researchers, tool developers	Early Design
Buda et al. [95]	Standardisation	Homeowners, consultants, policymakers	Design & operation

(continued on next page)

Table 1 (*continued*).

Holistic life cycle building performance			
Østergård et al. [27]	Development	Tool developers	Early Design
Magnusson [96]	Development	Engineers, architects, tool developers	Early Design
Architectural design			
Bueno and Turkienicz [97]	Development	Tool developers	Early Design
Nisztuk and Myszkowski [98]	Development	Architects, researchers, tool developers	Design
Donn [99]	Integration	Architects	Design
Aish and Hanna [100]	Selection	Educators, tool developers	N/A
Energy systems			
Hall and Buckley [101]	Characterisation	Energy system planners, researchers	N/A
van Beuzekom et al. [102]	Development	Tool developers	N/A
Sameti and Haghighat [103]	Development	Researchers	N/A
Allegrini et al. [104]	Selection	Energy system planners, researchers	N/A
Lyden et al. [105]	Selection	Energy system planners	N/A
Groissböck [106]	Selection	Energy system planners	N/A
Structural analysis			
Shoieb et al. [107]	Development	Tool developers	Not specified
Sadeghi and Ghaboun [108]	Selection	Engineers	Not specified
Wallin and Wasberg [109]	Validation	Engineers, architects	Early Design
Other reviews			
Moreno Nieto and Moreno Sánchez [110]	Guidance	Researchers	N/A
Finnveden and Moberg [111]	Selection	Environmental analysts	N/A
Cobo et al. [112]	Selection	Researchers	N/A
Mela et al. [113]	Selection	Decision maker	Early Design
Oosterbroek et al. [114]	Selection	Ecosystem analysts	N/A
Mustajoki and Marttunen [115]	Selection	Environmental analysts, tool developers	N/A
Ishizaka and Siraj [116]	Selection	Decision makers	N/A



a) Primary objective of collected articles. **b)** Analysis methods considered in collected articles.

Fig. 6. Overview of collected literature.

3. Approaches in existing tool reviews

An overview of the eighty-seven collected articles and their aims and audiences is shown in Table 1 and visualised in Fig. 6. It can be seen that selection and development type articles dominate the literature, whereas reviews which emphasise tool integration are few. The majority of articles were found in the field of BPA (shown in blue in Fig. 6(b)), especially studies focussing on energy analysis tools.

The most common type of reviews aims to support tool selection among architects, engineers, and other stakeholders. For instance, Forouzandeh et al. [12] develop a decision matrix intended to support potential tool users in selecting tools based on accessibility, capabilities, and intended design stage, and Hildebrand and Bach [47] aim to "build the relevant facts that apply to the choice of appropriate programs and suitable databases". While these works are useful to identify the assumptions about the design process among tool developers [99], they lack a description of the contexts where decisions are made about tools in organisations [19]. Further, it is questionable whether stakeholders look to the research community for information on the best tools. Instead of targeting stakeholders directly, research should improve the understanding of how tools are taken up by organisations.

Another type of review aims to support tool development in a market analysis, treating gaps and limitations of existing tools as opportunities for innovation [117]. As examples, Østergård et al. [27] aim to identify software candidates which fit into a simulation framework supporting proactive, intelligent, and experience-based decision making; whereas Wastiels and Decuypere [40] aim to identify different workflow strategies for integration of LCA in building information modeling (BIM), which can inspire further software development. These studies are useful in identifying technological advances which could be integrated in future tool developments. However, this technological emphasis also means the practice integration aspects highlighted in this study are overlooked.

Reviews focusing on tool integration in practice are less common, but remain the most promising in directly aiming to identify what are barriers and opportunities for widespread tool uptake. For instance, Soust-Verdaguer et al. [45] aim to find modes of integration of LCA in BIM-based design workflows. Mahmoud et al. [15] aim to identify key opportunities and limitations of building energy performance simulations in early building design through surveys and interviews. These studies, while importantly highlighting the need for considering how designers work in practice, would benefit from identifying success stories where tools have been successfully integrated, and from observing the work of the emerging professional role of computational designers, which is poorly covered by existing literature.

Methods for tool comparisons are typically the focus of the research oriented reviews, with the purpose of finding or evaluating frameworks for the objective comparisons of the tools: Attia et al. [24] aim to present a framework of tool selection criteria and rank them, and Han et al. [49] aim to categorise tools based on their application conditions and simulation principles. These studies offer a starting point for a consistent discussion in the tool development community about what aspects of tools are of the greatest importance. However, when scrutinised, these studies mostly offer little motivation for the specific criteria highlighted, and do not offer the perspective of the actual users on why those criteria are important - a gap which this study is aiming to bridge.

Further studies aim to validate novel tools compared to established ones [48], to identify opportunities for standardisation among competing tools [29], and to provide guidance for usage of tools [62]. While the validation, standardisation and learnability of tools are important factors of tool uptake as indicated in this study, these studies would benefit from a broader reflection on how these aspects become relevant when practitioners begin to adopt tools, and how they can contribute to an improved theoretical understanding of integrated design processes.

4. Critical analysis of existing tools reviews

In total, 128 different characterisation criteria were identified in the literature review. These criteria were organised into five categories as described in Section 2.

In this section, the literature is critically analysed and key research gaps related to tool uptake in practice are presented, organised according to the three critical perspectives applied: a user perspective, a design process perspective, and a design practice perspective (see Fig. 5).

4.1. User perspective

The user perspective refers to the interaction between the user and their tasks and the user interface through which they interact with the software tool. This includes aspects of usability, learnability, operability, and flexibility.

The evaluation of the usability of a tool can be based on three criteria: firstly, the success rate in meeting the specified ranges of users, tasks, and environment; secondly, the ease of use in qualitative terms (learning, using, remembering, convenience, comfort, effort, tiredness, satisfaction, etc.); and thirdly, the performance in quantitative terms (time, errors, sequence of activities, etc.) [118]. The most common usability criterion in the investigated literature is friendliness, which can be linked to, on the one hand, the ease of data entry and navigation through the workflow [51], and on the other hand, the visual appearance of the interface [54]. Donn [99] notes that assessments of user-friendliness often only reach as far as to the visual appearance of the interface, and do not discuss the interaction between the designer-user and the program. Indeed, the majority of reviews treating "friendliness" simply categorise tools as "friendly" or "complex" without defining who they consider as the user, or whether they emphasise the visual appearance or the ease of navigation. This is true also for the articles discussing "architect-friendliness" [25], which fail to define what are the tasks and competences of the architect as a tool user. Without defining a real or imagined user of the tool, and without defining the aspects covered by "friendliness", it is impossible to find out in such broad terms whether a tool is user-friendly or not [118].

Learnability is a description of the cognitive challenges inherent in any learning process [100]. As Mahmoud et al. [15] note, the learning curve is twofold — in many cases the user needs to apprehend both the analysis method and manoeuvring the analysis tool. Further, a learning curve can be understood firstly by its steepness – how long it takes for novice users to accomplish basic tasks the first time they encounter the tool [119]; and secondly by its length – the training time required before the tool can be used as intended [102]. The learning curve looks different to each potential user facing it, based on previous competences, general digital literacy [120], and motivation. Learning curves are usually tackled through the availability of supporting tool documentation or the active building of online support communities where tool users help each other [23]. Contrastingly, the output of the tool, whether visual or textual, has received limited attention as a vessel for learning. The understanding in engineering research that architects require visual material to easily absorb information overlooks the fact that architects largely work with and communicate through textual material [121]. An adjacent topic is the re-learnability of a tool which has received limited attention, i.e., how much effort it takes to resume use of a tool after a period of disuse [25]. Unfortunately, the multitude of reviews discussing learning curves do not explore these nuances, instead usually describing tools as "easy" or "complex" to learn, without mentioning how this was determined or the background knowledge of the considered learning user. A more nuanced understanding of learning curves, as proposed by Aish and Hanna [100], is needed in order to consider how the curve has different shapes for each potential tool user, and how the gradient of the learning curve can shift as the user learning progresses, see Fig. 7.

Operability refers to how efficiently an expert user can accomplish their tasks. This includes the speed of modeling and extracting useful information from the analysis. While several studies investigate the speed of running calculations, few investigate how efficient the modeling process is. This limited emphasis in the literature on the time and effort needed to transpose the architectural model into an analysis model is surprising, as it amounts to a large portion, if not a majority (see Fig. 8), of the time spent integrating life cycle building performance analysis aspects in early stage architectural design workflows [122]. The figure is schematic as the actual time allocation is missing in the reviewed articles. Further, modeling of building surroundings, both spatial and temporal, has received limited attention [70].

Aish and Hanna [100] discuss the flexibility of parametric systems and note that while they are typically extremely flexible in terms of changing the model compared to conventional CAD systems which require deletion and remodeling to handle design changes, complex parametric models are difficult to change which inhibits design exploration [123]. Early studies criticise a "wizard" modeling approach and call for further customisation [23], in tools which allow for concurrent usage by beginner and advanced users, and for use in a variety of design stages [88]. Bleil de Souza [63] proposes that "tools need configurable interfaces which can be tailored to the idiosyncrasies of each practices together with the peculiarities involved in dealing with a specific problem at hand". However, the practice implications of such customisable workflows are not further investigated, although they firstly require expert knowledge to allow for useful customisation, and secondly they often lead to tailor-made solutions which are difficult to re-use in further projects [122].

4.2. Design process perspective

The design process perspective refers to how the tool supports the communication during the design process between the tool user,

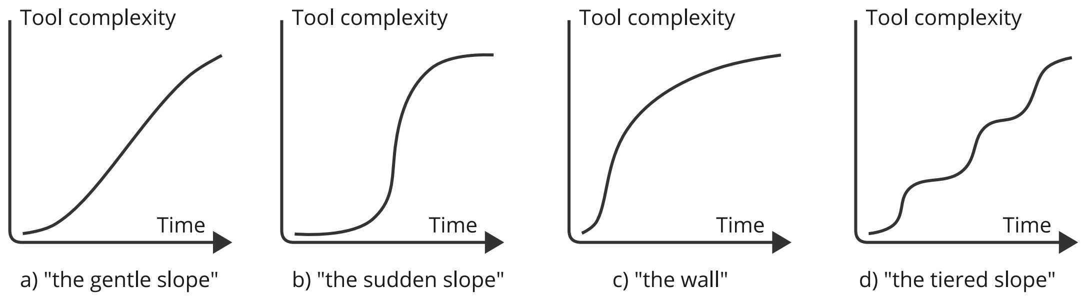


Fig. 7. Learnability: different shapes of the learning curve.
Source: Adapted from Aish and Hanna [100].

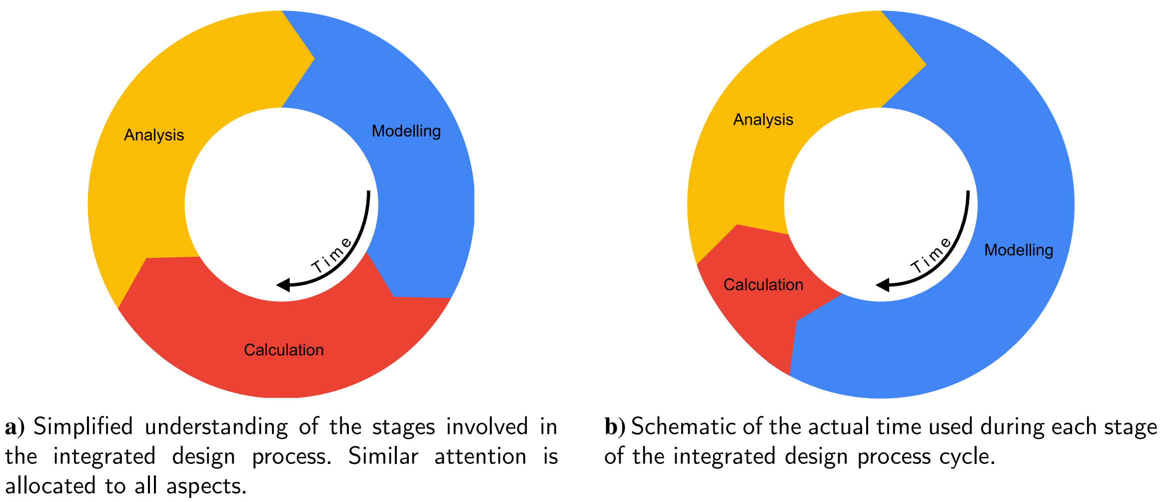


Fig. 8. Operability: stages during one cycle of the integrated design process.

the project team, and external stakeholders such as clients or decision makers. This includes design support capability, interoperability, interactivity, and accuracy.

Myllyviita et al. [46] and Nielsen et al. [93] propose that to be useful to support decision making, a tool needs to be flexible in terms of adapting the weighting and inclusion of decision criteria and modifying the decision alternatives, and further allow an iterative decision process where new ideas can be integrated in the decision making. Buda et al. [95] argue that "the choices made in a specific case, among all available options, depend heavily on the initial goal setting". The outputs provided by tools are usually described in the tool reviews, however, elaboration of how the various approaches could be in practical design processes is generally missing. Some studies propose methods such as Analytical Hierarchy Process and the Grading Method arguing that using a tool for choosing and weighting criteria early encourages stakeholders to consider sustainability aspects at an early stage [93]. Bleil de Souza [63] suggests that result display systems which allow for direct comparisons of design alternatives often fail to display the causal relationships between design parameters and analysis outcomes. She claims that these systems are less useful for design advice than for analytical purposes as they "[assume that] causal relationships are going to be evaluated by trial-and-error", which is often not the case in the design practice. In general, the tool reviews investigated do not describe the application of tools in real or hypothetical design processes which improve the understanding of how their outputs can be used to drive design forward.

Østergård et al. [27] discuss modes of interoperability, the extent to which analysis and design workflows communicate with each other, based on Citherlet [36] and Petersen [124], identifying four methods: (1) integrated, where calculations are performed within the CAD environment; (2) run-time interoperable, where simulations are performed in a desktop or web edition of the analysis tool concurrent with the CAD tool; (3) file exchange, where files are exported from the CAD environment and imported in the analysis environment; and (4) standalone, where remodeling is done from scratch in the analysis environment. Hu et al. [83] differentiate between unidirectional and bidirectional interoperability, noting that most interoperations between design platforms and computational fluid dynamics (CFD) plug-ins are unidirectional, meaning the analysis results cannot easily be transferred back into the design environment for visualisation and interpretation. The views among architects on interoperability are conflicting in the literature. Bazafkan [54] notes that the flexible ecosystem of Grasshopper enables such adaption through a "rich list of (...) simulation options available (...) making sure that architects can address most of their building performance-related questions inside a single environment". Conversely, Bleil de Souza [63] indicates that all practical attempts to build toolkits which cover the whole design process causes a situation of "extreme specialisation" where architects and engineers solve their various tasks in different software environments and communicate between model and analysis through enhanced interoperability, claiming that such "shared models that enable bi-directional feedback make design possibilities quite restricted". Abo Issa [62] notes that, on a practical level, in the transposition of BIM models to analysis environments, "healing and rebuilding" processes are often needed to ensure that the building energy model is appropriate. Bazafkan [54] also mentions that both remodeling and import/export processes between CAD and analysis tools are typically time-consuming. This debate shows that interoperability approaches need to be evaluated within a practice setting in order to understand the conflicts which arise or are resolved through different modes of interoperability, and moving on from the emphasis on what kind of interoperability is technically supported.

To be useful in design settings such as meetings within the practice or with clients, interactivity of tools is necessary. Bazafkan [54] proposes that the instant feedback needs to be comprehensible for architects without extensive building science background. Bleil de Souza [63] argues that the traditional separation of inputs and outputs could be replaced by interfaces which, through real-time feedback, support understanding the building behaviour while conceiving it. Nevertheless, few reviews specifically tackle the settings and modes of collaboration beyond the topic of interoperability. Myllyviita et al. [46] discuss the potential for consensus building using tools for sustainability analysis. They discuss the possibility to have multiple participants/tool users, the extent to which tools are aware and accept varying worldviews, the extent to which various participants are engaged from an early stage, and the extent to which conflicts are acknowledged. An evaluation of tools in real or hypothetical design situations where several stakeholders are using a tool as a basis for discussion would enable an assessment of the usefulness of the tool to support design.

While engineers typically associate accuracy with numerical precision of the analysis, architects prioritise the ability of tools to create "real sustainable design" [23]. Mahmoud et al. [15] argue that architects need tools to inform design decisions rather than to acquire accurate performance predictions. Conversely, most studies on the engineering side investigate the accuracy of results when comparing simplified tools to more advanced models. However, no reviews discuss at length how to communicate the level of accuracy to the user and making use of this information in the design process (e.g. by presenting results as ranges rather than fixed values, and presenting uncertainty values). Bleil de Souza [63] argues that tool outputs can be more useful to designers if causal relations can be established in the spatial domain, for instance through sensitivity analysis [23], in a "design-simulation-feedback-design" loop [83]. Han et al. [49] propose that sensitivity analysis can reduce the complexity of a building energy model by 90%, but does not comment on how architects can practically make use of the output of a sensitivity analysis model. Another avenue is uncertainty and risk assessment which is commonly mentioned in the reviews, but how architects can make use of such information in design processes is less clear. Han et al. [49] present five dimensions of uncertainty inherent in design processes based on Chen et al. [125]: meteorological uncertainty, urban uncertainty, building uncertainty, system uncertainty, and occupant uncertainty. Risk assessment, although crucial in all economic decision making, is also scarce in the reviewed studies and limited to studies on retrofitting options [95]. Considering the great uncertainties inherent in early stage design situations [126], it is surprising that no tool studies have explored how architects make sense of sensitivity, uncertainty, and risk assessment outputs.

4.3. Design practice perspective

The design practice perspective considers how tools mesh with the ongoing work at the design process, including digital and analogue design activities [127], and the organisational requirements for an architectural practice to invest in adopting tools. This includes knowledge building, personnel, cost, client motivation, availability, and computational requirements.

As digitalisation accelerates, tools can be used in a knowledge building process to build best practices and component databases relevant to the practice. Marsh et al. [38] propose that, instead of including material databases in LCA software which are used to define components, a number of predefined components could be pre-calculated by experts at the practice, which would improve precision and data quality [27]. Another potential knowledge database includes reference projects and case studies. Attia et al. [23] propose the inclusion of a case study database to support decision making, while Buda et al. [95] propose the inclusion of a database of best practices and links to previous projects which can serve as inspiration for selecting solutions, and find tools which offer a repository of retrofit solutions and where the analysis helps selecting relevant solutions. Of note is that none of the tool reviews suggesting such databases mention any examples of how such knowledge databases are used in practice and how they grow over time. Considering the prevalence of using references in the architectural practice [127], it is surprising that few authors have investigated the potential for tools to support feeding successful solutions forward and backward. Practical examples of how such databases are organised, maintained, and built, would be highly useful.

In order to introduce tools in the design practice, personnel with appropriate competences needs to either be trained or hired. However, few reviews cover what kind of personnel or teams are needed in order to integrate tools in design workflows. This is a critical question for practices which are considering investing in new toolkits and related to practice size: Mahmoud et al. [15] finds a correlation between energy simulation tool usage and practice size, where only 30% of practices with less than ten employees use building energy performance simulation (BEPS) tools, whereas the figure for practices with above a hundred employees is above 60%. Investigations into what competences and team structures would support tool adoption, and where these competences are available, are needed if tool reviews are to support decision making on tool investments.

Another related organisational question is the cost of implementation of tools [88]. Mahmoud et al. [15] find that, according to architects, the cost of tools is the second most prohibitive factor, following lack of BEPS knowledge, for tool integration in practice, especially in early design stages, where "expenditure is limited". However, an investigation of the link from the practice organisation, size, and projects, to acceptable tool investment and upkeep costs, is missing. Another aspect not raised in the studies investigated is how the knowledge building of using simulation tools should be financed — if tool learning and development should be funded by the project in which they are first implemented or if internal development funding within each company is to be used. Alternatively, it could be expected that newly graduated employees introduce novel technologies that they apprehended during their studies.

Mahmoud et al. [15] discuss client motivation to fund the use of simulation tools in early design stages, indicating that architects are often "faced with resistance from clients whom in many cases will not be willing to fund early stage design when there are uncertainties in relation to the viability of projects", but argue that the clients could be convinced if "costs are increased within a reasonable range". The client perspective is mostly missing in the tool reviews, e.g. what kind of analyses are relevant to them and in what kind of projects they are willing to increase the analysis expenditure. A discussion of economic benefits related to the value proposition of architectural practices is also entirely missing. An indication of what kind of clients and projects are more highly interested in tool adoptions would help architectural practices strategise in terms of in which projects to first integrate life cycle building performance assessment, and where to emphasise a formulation of life cycle building performance competences as a part of the value package offered by the practice. As Mahmoud et al. [15] argue, if architects gain more knowledge of the benefits of integrating analysis in early design they would be able to increase clients' awareness of and motivation on the issue as well.

Another factor enabling practice integration is the availability of tools, but few studies investigate how easy it is to access and integrate tools in existing workflows on a practical level, beyond the need for acquiring licenses [105], open-source access of code [102], dependencies [57], and operating systems [85]. As an example, Østergård et al. [27] notes that for analysis frameworks which require interoperation between several tools, they often need to be installed on the same computer, which proves troublesome in multi-actor, interdisciplinary collaborations. Another aspect of availability is the longevity and upkeep, discussed by Lee et al. [92]. If tools are not actively supported by tool developers over an extended time period, no stable user base can be established.

Several proposals are made to tackle the computational requirements of new tools, whether simplified or advanced, among them cloud computing [49], and machine learning [83]. However, questions of data management and ownership are mostly left unresolved. Especially when moving toward "digital twin" representations of buildings in modern applications, privacy concerns of residents may also be relevant [128]. There is also a question of the data security of cloud solutions and who has access to data which may be sensitive. Furthermore, cloud technologies are increasingly questioned due to high operational environmental impact of computational clusters [129].

5. Discussion

This study aims to identify prevailing assumptions and define widespread constructs in the available literature reviewing life cycle building performance assessment tools through the application of a meta-review methodology [30]. Thus, the findings are only valid for understanding how tools are currently conceptualised in the research community [130]. The meta-review methodology only considers the findings in other reviews, and different conceptualisations might be discovered if considering also the primary sources upon which these reviews are based. Further, other methodologies are needed to investigate the practical impact of different conceptualisations of tools when operationalised. Important theoretical contributions to how software can be developed with a practice perspective exist in software engineering research fields [131], as well as studies into how design can be improved through the integration of analysis in early design stages [122], and proposals for how tools can be successfully be adopted in practice [132]. Nevertheless, the important finding in this study that these research efforts have largely been overlooked in the existing literature reviewing tools needs to be addressed in future studies. The multitude of tool reviews within the field of life cycle building performance assessment, especially with the perspective of application by architects in early design stages, shows that this article genre is common and that the literature can only be expected to keep growing. Methodological consistency is essential for this body of literature to eventually support meaningful improvements in terms of design outcomes for practitioners.

A further limitation is that the analysis approach is qualitative and inductive, which allows the discovery of theory in a specific context, but only can be said to be valid after triangulation with other methods [130]. This gap should be bridged in future work by applying and adjusting the developed characterisation framework in practical contexts to evaluate its usefulness and to identify gaps. It should also be noted that works included in the study are limited in time of publication to the years 1998–2023, and studies published outside of this timespan may cover further topics not identified in this study. Further, as the perspective of integrating life cycle building performance assessment in early stage architectural design is applied, the relevance for other design stages and other software applications may be limited, and would need to be investigated through specific studies in those contexts.

6. Conclusion

To investigate the lack of integration of life cycle building performance assessment tools and workflows in the architectural design practice, the approaches in eighty-seven previous tool reviews were investigated in a meta-review to identify best practices and gaps. The literature was scrutinised based on three critical perspectives: those of the tool user, the design process, and the architectural practice.

From applying these critical perspectives, two main findings can be identified. The first main finding is that previous reviews have largely failed to study tools from the perspective of integration in early stage architectural design practice. Tools are instead largely evaluated based on their technological capabilities. To overcome this, it is proposed that future tool evaluation studies should be explicit about the intended tool user from whose perspective the tool is evaluated. Further, tools should be evaluated based on their application in design processes in architectural practice in a specified local context (geographical, type of practice, type of project, etc.), and not in hypothetical test cases.

The second main finding is a lack of consistent tool characterisation methodologies in previous tool reviews. Most reviews apply bespoke frameworks with limited robustness, making comparing the outcomes between each individual review difficult. By comparing and combining previous approaches, this study proposes a holistic tool characterisation framework which is supported by previous research and adapted to practice needs.

In terms of practical application of this research, the proposed framework can be used to evaluate existing tools, or to organise software requirements in tool development processes. While the direct use of the framework is mostly motivated for tool developers and researchers, the findings of this study encourage stakeholders, such as practitioners applying tools and policymakers prescribing tool usage in design processes, to challenge these developers to apply a more practice-oriented perspectives when designing tools for their use. From a research perspective, the findings indicate that the applied meta-review methodology is useful in detecting the main streams within the research on life cycle building performance assessment tools, by identifying gaps in the understanding of how tools are taken up in practice, and synthesising previous approaches into a conceptual framework with clear definitions. It could be applied in future studies which aim to identify broad research streams which could explain a gap between research efforts and practical application of the findings.

In future work, the proposed characterisation framework should be evaluated in terms of its practical usefulness and remaining gaps. This should be done through application in reviews of tools available in the market as well as those developed within architectural practice. These tool reviews should emphasise tool user, design process, and architectural practice perspectives, by explicitly defining the intended tool user from whose perspective tools are evaluated, by evaluating tools as applied in real design processes, and by emphasising key factors for design practices to adopt tools. Further, the usefulness of the characterisation framework in organising tool requirements should be evaluated through application in participatory software development processes. These practice-oriented approaches can allow the development of tools which meet the needs of stakeholders in design processes, allowing them to make well-supported decisions on life cycle building performance, improving the environmental, social, and economical impact of the built environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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