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SET-BASED DESIGN IN CONSTRUCTION PROJECTS: BENEFITS, DIFFICULTIES AND TRENDS

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ABSTRACT

Design processes generate inputs to plan and control the development of project construction processes. There is a growing interest in implementing design techniques involving various options to reach a systemic overview and select the best proposal. One such technique is Set-Based Design (SBD) which identifies and explores multiple design options simultaneously. Although several studies have been carried out focused on the SBD implementation in construction projects, there need to be more studies that synthesize the main findings to facilitate a proper implementation according to the different contexts. Considering this gap, this paper focuses on presenting a synthesis of SBD's benefits, difficulties, and trends in construction projects. The research method corresponds to a systematic literature review of a sample of 281 documents initially drawn from Scopus database and finally, with 32 documents screened, this study undertook the following stages. The research method has five stages: 1) scope definition; 2) searching of relevant documents; 3) document selection; 4) evidence collection, analysis, and synthesis; and 5) results report. The findings show a trend towards adopting the SBD technique for the design of structural elements of buildings and bridges. The three most frequently reported benefits of SBD adoption are: 1) transparent decision-making processes, 2) better collaboration in decision-making, and 3) better communication among designers. The three most frequently reported difficulties 1) inadequate organizational structure for the adoption of SBD, 2) lack of staff experience, 3) resistance to change in organizations.

KEYWORDS

Set-based design, point-based design, benefits, difficulties, trends, systematic review.

INTRODUCTION

The adoption of Lean Construction tools in the architecture, engineering and construction sector has increased considerably in recent years (Wong et al., 2009). Several studies show that the inclusion of Lean Construction tools in design processes increases product quality, because it promotes compliance with project requirements and increases the value expected by the client (Rischmoller et al., 2006). Nonetheless, if the project design fails, it can compromise the success and continuity of the project. The strong influence of design on construction projects is due to waiting times, rework, accidents, and other events that can result from design defects,

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which are identified only at the construction stage (Koskela et al., 2012). If a contractor identifies a design failure, he should request an adjustment or clarification from the designer and wait for a response. The designer can take a significant period to generate a response, which can result in deviations from planned schedules, budgets, and scope; phenomena that have been observed in construction projects around the world (Herrera et al., 2020). Therefore, it is necessary to study methodological and technological approaches that can contribute to improve the design processes. The design process of a construction project involves the interaction of professionals from different disciplines and various analyses to define the characteristics of the project components that meet the requirements and needs of project stakeholders (Herrera et al., 2021). The multidisciplinary nature of design and the associated volume of information generate complex systems to organize and manage (Hannapel & Vlahopoulos, 2014). Nonetheless, in most projects, design processes are based on linear methods that focus on the development of a single design alternative, which limits the possibility of achieving efficiency and generating value for the client.

Several studies have shown benefits of implementing SBD in design processes. For example, Chuquín et al. (2021b) applied a survey at the end of a design process with SBD, the findings showed that 72% believed that the quality of their work had increased, and rework had decreased. Besides, Chuquín et al. (2021a) conducted a survey of the usefulness of SBD among the participants of a case study of a high-rise building. The results showed that 70% of the respondents highlighted the usefulness of SBD and expressed their intention to adopt SBD in future projects. Additionally, Kerga et al. (2016) performed a systems dynamics model to simulate five design alternatives. The findings showed that SBD can contribute to reduce the average project duration by 25%, the total cost by 40%, and significantly improve the return on investment. As in the construction industry, SBD has shown benefits in design processes in other industries. Also, Yamada et al. (2016) performed SBD implementation to generate sustainable design alternatives of a laser printer. The results showed that the total price can be reduced by 18.7% to 36.8% compared to a conventional product, and the total amount of CO_2 emissions of the product can be reduced by 21.9% to 18.8%.

The potential of SBD to improve various design issues has generated interest among industry practitioners and researchers, which has been observed with the publication of several papers addressing the topic (Lee et al., 2012; Shallcross et al., 2020; Singer & Doerry, 2009). However, there is a lack of studies focused on compiling and synthesizing the main findings of SBD implementation in the design activities of construction projects. Therefore, this study has two aims: 1) to identify the benefits and difficulties of SBD adoption in construction projects, and 2) to synthesize the trends of SBD in the construction industry.

TRADITIONAL DESIGN BACKGROUND

Point-Based Design (PBD) has been characterized in the AEC industry as the traditional way of design. PBD is based on an initial design proposal that is progressively detailed. The degree of detail increases as design disciplines become more involved, a characteristic that can be considered ideal (Lee et al., 2012). However, on the one hand, the linearity of PBD compromises the efficiency of the process when a new design requirement arises. A scenario in which designers must perform extensive rework processes to adjust designs to the new requirement. On the other hand, the linear character leads to assume aspects of the design that can lead to issues of incompatibility, inconsistency, and inefficiency in the integration of project elements.

The limitations of the PBD approach have led industry practitioners and researchers to make efforts to adapt and improve techniques that involve the analysis of various design alternatives. In the design of construction projects, one of the techniques that has shown remarkable benefits is Set-Based Design (SBD), which can be assumed as a design management methodology of Lean thinking (Singer & Doerry, 2009). SBD is based on a set of alternatives that when properly combined lead to an efficient design solution, which is aligned with the client's requirements and project constraints (Toche et al., 2020). In the design of a building project based on SBD, the team of architects proposes a set of alternatives for the distribution of spaces and finishes that meet the client's requirements. The structural engineering team generates a set of structural system alternatives in accordance with the general characteristics of the project. Similarly, other design teams propose a set of alternatives, such as sanitary engineering, electrical engineering, sustainability, and others as required. The initial design alternatives are formulated at a low level of detail in order to promote efficiency in the process.

For the selection of the appropriate combination of alternatives, the SBD technique involves a set of objective-based tests that are related to the project requirements (Singer & Doerry, 2009; Toche et al., 2020). Therefore, some of the tests can be focused on objectives related to budgets, schedules, emissions, functionality, construction processes, and materials, among others. Thus, SBD may be adopted for the formulation and evaluation of design alternatives generated by one or more design disciplines of a project. The analysis of various alternatives leads to the adoption of methods to support decision-making processes. SBD integrates criteria evaluation factors for the selection of alternatives based on project requirements (Shallcross et al., 2020). These characteristics generate the need to integrate SBD with computational and methodological tools that support the generation and evaluation of design alternatives. Therefore, several studies have been carried out focused on the joint implementation of SBD and technological and methodological approaches, such as: building information modeling, value stream mapping, choosing by advantages, multi-criteria decision analysis, among others (Lee et al., 2012).

RESEARCH METHOD

For literature review, there are several methodologies, among which bibliometric analysis, meta-analysis and systematic review stand out. According to Donthu et al. (2021), the systematic review is recommended for samples up to 300 documents. Thus, the research method adopted corresponds to a systematic literature review, which focuses on identifying existing knowledge based on systematic procedures to answer a research question. Compared to other review methods, systematic review reduces subjectivity in the extraction of information and analysis of results, which is achieved through the evaluation of a set of inclusion/exclusion criteria for the selection of the sample documents. This study uses systematic review to identify benefits, difficulties, and trends of SBD in construction projects. Therefore, the research method was divided into five main stages: 1) scope definition; 2) searching of relevant documents; 3) document selection; 4) evidence collection, analysis, and synthesis; and 5) results' report. The scope definition was based on the research aims mentioned in the introduction section.

The search and selection of the sample focused on documents that offered the reliability of having undergone peer review processes, this reliability being a relevant factor for the selection of the search engine. Scopus provides this reliability and is considered a search engine that addresses a large number of areas of study in the field of research, so the use of other search engines in addition to Scopus can be considered as a complementary and equally important search. Thus, the search and collection of relevant documents was performed in the Scopus search engine using the following search equation: ("set-based design" OR "set based design" OR "set-based-design" OR "set based-design"). An initial sample of 273 documents was collected, including conference papers, articles, conference reviews, and reviews published between 1994 and 2022. In addition, considering the focus of the research, documents related to the research topic that are available in the IGLC database were included, with the same search equation. A second sample of 16 documents was collected, from which 8 documents repeated from Scopus were discarded, leaving a total of 281 documents.

The final document selection was carried out by applying two inclusion/exclusion criteria: 1) the paper addresses topics related to SBD methodology, and 2) the paper addresses topics related to SBD adoption in the construction industry. The criteria were evaluated by three researchers with knowledge of the topic studied and experience in the systematic review methodology. Each researcher evaluated the criteria individually, thus, for each document and criterion, "yes" was assigned if the document meets the criterion, and "no" if it does not. At the end of the evaluation, it was observed that in 10 of the 281 documents analyzed there was a difference in the evaluation results. Therefore, a meeting was held between the three researchers, and a consensus was reached. By applying the first criterion, 60 documents were discarded. Thus, a total of 221 documents were analyzed with the second criterion, of which 32 documents were selected, and 191 documents were discarded. Therefore, the evidence collection, analysis, and synthesis were performed by reading the resulting 32 documents selected on the basis of the two criteria. The information was collected and organized in an Excel table.

To collect and analyze the information from the selected sample, a detailed reading of each of the documents was carried out. Thus, benefits, difficulties and trends of SBD implementation in construction projects were identified. The information gathered was analyzed by three experts in the research topic. In addition, as part of the discussion of results, four categories were identified for the classification of complementary SBD tools. These categories are part of the added value provided by the group of experts (professionals in the construction industry with a doctorate degree and more than 10 years of experience) who, based on the approach of SBD complementary tools in the documents and the analysis of Lean tools vs. Lean objectives performed by Aslam et al. (2022), made the proposal of categories. Each expert related the SBD complementary tools to the categories, based on affinity and grouping exercises. As part of the classification exercise, the expert group held consensus meetings to discuss and eliminate variations between the complementary SBD tools and the categories. Finally, a frequency analysis has been carried out as part of the exploratory study and identification of the most adopted SBD complementary tools in the AEC industry.

RESULTS

This section presents the benefits, difficulties and trends of SBD adoption in construction projects, according to the analyzed sample. As a result of the research, 23 benefits, 22 difficulties and trends of SBD adoption were identified. The benefits and difficulties of adoption are presented through an absolute and relative frequency analysis. This frequency analysis provides a summary statistic, with which it is possible to compare the benefits and difficulties most frequently evidenced in the literature, as well as the weight of each benefit and difficulty within the set. This analysis could provide an impetus for SBD research in the AEC sector by presenting the results of research within the industry. Finally, a subsection of research trends and complementary approaches to SBD implementation in construction projects is presented. The approaches have been categorized according to their affinity by a group of experts in the research field.

BENEFITS OF SET-BASED DESIGN ADOPTION

Table 1 shows the top-10 most frequently reported SBD benefits in construction projects. The adoption of SBD promotes transparent decision-making processes, based on the selection of design alternatives that focus on satisfying project requirements. This feature helps to prevent decisions from being affected by the particular interests of the designers (Mathern et al., 2019; Parrish & Tommelein, 2009; Sahadevan & Varghese, 2019). Therefore, one of the most frequently reported benefit is 'transparent decision-making processes' (B_1). With the same frequency, the benefit 'better collaboration in decision-making' (B_2) was identified, which is obtained from the collaborative process of analysis and proposal of design alternatives involved in the SBD adoption (Lee & Cho, 2012; Lee et al., 2010). A process that requires the joint participation of the professionals involved, on the one hand, to verify the compatibility and coherence between the options analyzed. On the other hand, to select the combination of alternatives that best meets the requirements of the project.

Table 1: Benefits of SBD adoption in the construction industry.

Id	Benefits	Absolute frequency	Relative frequency (n=32)	References*
B_1	Transparent decision-making processes	10	31.3%	10, 11, 12, 13, 15, 16, 18, 22, 26, 30
B_2	Better collaboration in decision-making	9	28.1%	7, 8, 10, 14, 18, 19, 20, 25, 26
B_3	Better communication among designers	7	21.9%	7, 13, 19, 21, 22, 23, 26
B_4	Improvement of the design solution	7	21.9%	1, 5, 11, 14, 23, 25, 26
B_5	Analysis of various design alternatives	6	18.8%	7, 8, 10, 13, 21, 22
B_6	Increased design solution functionality	6	18.8%	4, 9, 10, 21, 26, 28
B_7	Reuse of design knowledge	6	18.8%	10, 12, 14, 15, 26, 28
B_8	Reduction of rework	6	18.8%	5, 15, 20, 24, 26, 27
B_9	Increased design solution efficiency	5	15.6%	7, 8, 20, 23, 28
B_{10}	Promotes sustainability in the projects	4	12.5%	3, 10, 16, 17

*1. (Chuquín et al., 2021b), 2. (Chuquín et al., 2021a), 3. (Gomez & Rameson, 2019), 4. (Inoue, Takahashi, et al., 2013), 5. (Zoya Kpamma & Adjei-Kumi, 2011), 6. (Kim & Lee, 2010), 7. (Lee & Cho, 2012), 8. (Lee et al., 2012), 9. (Inoue, Nahm, et al., 2013), 10. (Mathern et al., 2019), 11. (Padala & Maheswari, 2017), 12. (Parrish & Tommelein, 2009), 13. (Parrish et al., 2008b), 14. (Parrish et al., 2007), 15. (Parrish et al., 2008a), 16. (Mathern et al., 2018), 17. (Rempling et al., 2019), 18. (Sahadevan & Varghese, 2019), 19. (Tauriainen et al., 2016), 20. (Tuholski & Tommelein, 2010), 21. (Unal, Eeri, et al., 2017), 22. (Wong et al., 2009), 23. (Wong et al., 2007), 24. (Lee et al., 2012), 25. (Lee et al., 2010), 26. (Arroyo & Long, 2018), 27. (Ballard, 2000), 28. (Haymaker et al., 2013), 29. (Knotten et al., 2014), and 30. (Nguyen et al., 2008).

The third most frequent benefit is 'analysis of various design alternatives' (B_3). Some characteristics of construction projects, such as unique and multidisciplinary character, complexity and uncertainty, and required financial capital make the analysis of various design options indispensable during the early stages of the projects (Chuquín et al., 2021a; Rempling et al., 2019). Therefore, benefit B_3 has a positive effect on ensuring that the design solution generates the value desired by the client and satisfies the requirements that gave rise to the project. The fourth benefit is 'better communication among designers' (B_3), which is integrated with benefits B_1, B_2, and B_5 considering that communication is transversal to the decision making and collaboration processes among design teams (Tauriainen et al., 2016; Unal, Eeri, et al., 2017; Wong et al., 2009). Thus, communication favors the proposal and analysis of various design options. The fifth benefit is 'improvement of the design solution' which is obtained by exploring a space of possible design solutions, from which the team has the possibility to choose the alternative that best aligns with the project requirements.

DIFFICULTIES OF SET-BASED DESIGN ADOPTION

Table 2 shows the top-10 most frequently reported SBD adoption difficulties. The 'inadequate organizational structure for the adoption of SBD' (C_1) is the most reported difficulty, which is related to the staffing requirements and organizational structure in the design disciplines of a construction project (Chuquín et al., 2021b; Gomez & Rameson, 2019). C_1 has a major impact on some organizations because it is common to subcontract some of the design disciplines with specialized firms (Hassan & Le, 2021). Subcontracting means that two or more firms must adapt their workflows to integrate design teams according to SBD principles. The second difficulties is 'lack of staff experience' (C_2) which is based on the knowledge and experience needed to adopt SBD by the professionals involved in the design of a construction project (Lee et al., 2010; Zoya Kpamma & Adjei-Kumi, 2011). The emerging nature of SBD in the construction industry leads to a lack of human talent with experience and knowledge in the adoption of SBD. In addition, there is a lack of efforts focused on including SBD in education programs related to the training of professionals in charge of the design of construction projects.

Table 2: Difficulties of SBD adoption in the construction industry.

Id	Difficulties	Absolute frequency	Relative frequency (n=32)	References*
C_1	Inadequate organizational structure for the adoption of SBD	7	21.9%	1, 3, 4, 11, 15, 18, 19
C_2	Lack of staff experience	6	18.8%	1, 4, 9, 11, 21, 26
C_3	Resistance to change in organizations	6	18.8%	1, 3, 4, 26, 27, 29
C_4	Lack of information compatibility between design disciplines	5	15.6%	3, 12, 15, 19, 28
C_5	Limited information to propose design alternatives	4	12.5%	2, 6, 12, 17
C_6	Greater design effort	4	12.5%	7, 12, 13, 16
C_7	Difficulty in managing design processes	4	12.5%	4, 7, 19, 31
C_8	Barriers related to the legal framework	3	9.4%	4, 7, 11
C_9	High dependence on designer's judgment in decision making	3	9.4%	7, 8, 9
C_{10}	Increased design time due to more alternatives	3	9.4%	7, 9, 26

*1. Notation according to Table 1.

'Limited information to propose design alternatives' (C_3) is the third most frequently reported difficulty. The adoption of SBD requires the availability of the information required for the proposal and analysis of design alternatives (Parrish et al., 2008a; Unal, Eeri, et al., 2017). The complexity of the interactions between design disciplines and the multidisciplinary nature of the teams make it difficult to provide, at the right time, the necessary information to propose design alternatives. 'Greater design effort' (C_6) has the same frequency as C_5. Proposing and analyzing several alternatives instead of a single design alternative requires more effort from the design team (Mathern et al., 2018, 2019). However, the consideration of a greater number of design options contributes to the 'reduction of rework' (B_8) and the 'reduction in design times' (B_{12}). Therefore, investment in increased effort by designers could generate positive return on investment (ROI) rates.

Despite the fact that 'Lack of information compatibility between design disciplines' (C_4) does not have the same frequency as C_5 and C_6. The various engineering processes carried out in the design stage of a construction project lead designers to use different tools for the information capture, processing and analysis (Gomez & Rameson, 2019; W. Lee et al., 2010). The diversity of tools and methods has generated difficulties in the integration of information due to the difficulty in making information compatible between design disciplines. Despite the efforts for the adoption of methodologies such as Builiding Information Modeling (BIM) with information exchanges based on Industry Foundation Classes (IFC), difficulties are observed in the exchange of information between design disciplines, which affects the efficient adoption of SBD (Lee et al., 2012)

DISCUSSION

COMPLEMENTARY APPROACHES TO SET-BASED DESIGN

This study found that the SBD is boosted when complementary design management techniques are used. This section summarizes these techniques in four categories: 1) information and process management, 2) decision making, 3) analysis tools, and 4) design (see Table 3).

Table 3: Complementary approaches of SBD adoption in the construction industry.

ID	Category	Complementary SBD		Fr.	Relative frequency (n=32)
1	Information and process management	Building Information Modeling	BIM	6	18.8%
2		Value Stream Mapping	VSM	2	6.3%
3		Design Structure Matrix	DSM	3	9.4%
4		Big Room	Big room	1	3.1%
5		Activity Cycle Diagrams	ACD	1	3.1%
6		Lean Project Delivery	LPD	1	3.1%
7		Lean Project Delivery System	LPDS	1	3.2%
8		Last Planner System	LPS	1	3.2%
9	Decision making	Multi-Criteria Decision Analysis	MCDA	6	21.9%
10		Choosing by Advantages	CBA	6	18.8%
11		Analytic Hierarchy Process	AHP	3	9.4%
12		Group Decision Making	GDM	1	3.1%
13		Sequential Decision Process	SDP	1	3.1%
14		Design by Shopping	DBS	1	3.1%
15		Knotworking	knotworking	1	3.1%
16		A3 reports	A3 reports	1	3.1%
17		Belief Propagation	BP	1	3.1%
18	Analysis tools	Finite Element Method	FEM	3	9.4%
19		Artificial Intelligence	IA	1	3.1%
20		Monte Carlo Analysis	MC	1	3.1%
21		Genetic Algorithm	NSGA	1	3.1%
22		Space Syntax Analysis	SSA	1	3.1%
23		Simulation	Simulation	1	3.1%
24	Design	Target Value Design	TVD	5	15.6%
25		Parametric Design	PD	2	6.3%
26		Depthmap	Depthmap	1	3.1%
27		Set-Based Parametric Design	SBPD	1	3.1%
28		SetPlan	SetPlan	1	3.1%
29		Tekla Structures 14.0	TS 14.0	1	3.1%
30		Lean design	LD	1	3.1%

The SBD technique can be integrated with various complementary approaches to improve the information management processes of the design of construction projects. Therefore, there is a growing interest in integrating SBD with approaches to improve information management processes, such as: Building Information Modeling, Value Stream Mapping, Design Structure Matrix, and others (see Table 3). It is observed that BIM is one of the complementary approaches to SBD that has a higher frequency within the Information and process management category. Studies that have addressed the integration of BIM and SBD have focused on the development of improvement tools for the creation of alternatives in various fields, such as constructability, structural safety, economic feasibility, design management, and shared understanding, among others (Lee & Cho, 2012; Tauriainen et al., 2016; Tuholski & Tommelein, 2010; Wong et al., 2009). Integrating BIM and SBD makes it possible to improve information flows and communication during design activities that are developed by professionals from different disciplines during the early stages of projects. Improving information management processes has a positive impact on the development of construction projects considering that projects involve considerable volumes of information during the design stage.

MCDA is the most commonly adopted complementary tool to SBD in decision-making processes. Evidence of MCDA adoption was identified mainly in the development of road infrastructure projects. Some of the approaches, on the one hand, are oriented to support the selection of strategies for the development of facilities in road projects, evaluate design processes, support decision making, analyze constructability concepts and sustainability criteria, in the structural design of bridges. On the other hand, MCDA has adopted to optimize the structural design of buildings based on sustainability criteria and design alternatives among others (Mathern et al., 2018, 2019; Padala & Maheswari, 2017). Thus, the evaluation of various design alternatives using the SBD tool leads to the need to integrate tools to support the decision-making processes that focus on the evaluation and selection of design alternatives. Hence, there is a trend towards the joint adoption of SBD with techniques that support the decision-making processes during the analysis of alternatives, such as: Multi-Criteria Decision Analysis, Choosing by Advantages, Analytic Hierarchy Process, and others.

The multidisciplinary nature of a construction project means that the design process integrates various engineering analyses that require specialized techniques to carry out the design of the components of a construction project. Hence, there is a trend towards the integration of SBD with tools that can improve and automate the design processes, such as: Finite Element Method, Artificial Intelligence, Monte Carlo Analysis, and others (see Table 3). In turn, these tools can be complemented with design techniques, such as: Target Value Design, Parametric Design, and others. It is noteworthy that in the design category, the TVD approach is the one with the highest frequency, which is related to the complementary nature of the two tools. On the one hand, SBD focuses on the proposal and selection of alternatives, and on the other hand, TVD focuses on the development of the design from a set of budgetary requirements. Therefore, integrating TVD and SBD has a high potential to promote the generation of value for the client from the analysis of several design alternatives that are framed in a budgetary requirement. The findings show that the joint adoption of SBS and TVD has been focused on building, road infrastructure, and bridge projects (Arroyo & Long, 2018; Gomez & Rameson, 2019; Kim & Lee, 2010). Despite the existing studies, it is evident that there are several knowledge gaps, which can be analyzed from the moderate number of documents and the few fields of knowledge that have been focused on: sustainable development, design and evaluation of spaces, and others. Furthermore, there is a lack of studies focused on design and information workflows that facilitate the joint adoption of SBD with complementary tools by the design disciplines that interact in a construction project. Thus, it is expected that in the coming years there will be a growing interest in the development of computational tools based on the integration of SBD principles and complementary approaches specialized in the design of building components.

The adoption of SBD can significantly contribute to improve various aspects of the design of construction projects. Therefore, in the construction industry, it is crucial that researchers and practitioners undertake actions focused on the development of works that make possible the implementation of SBD in the different design disciplines that interact in a construction project. The integration of SBD with emerging tools and methodologies such as: BIM, Multi-Criteria Decision Analysis, Target Value Design, and others (see Table 3) can contribute to improve the decision-making processes that are carried out during the design activities of a construction project. Despite its potential, the findings of this study show that there are several knowledge gaps in the characterization of SBD integration with various complementary approaches. Therefore, it is expected that the coming years will see an increasing number of studies focused on characterizing SBD integration with methodological and technological approaches that can be conducive to leveraging SBD principles, which is focused on the requirements of construction projects.

KNOWLEDGE GAPS AND TRENDS OF SET-BASED DESIGN

There are knowledge gaps of SBD adoption in different types of construction projects. From the set of documents analyzed (n=32; 100%), the types of construction projects identified with SBD adoption were: buildings (n=18; 56.3%), bridges (n=5; 15.6%), road infrastructure (n=3; 9.4%), and other projects (n=6; 18.8%). Hence, there is evidence of a gap in the adoption of SDB in horizontal projects, in which the characteristics of SBD can contribute to obtaining more efficient and sustainable projects. In road projects, SBD can contribute to the analysis and selection of road alignment alternatives based on a set of requirements and limitations defined for the project. Once the alignment is selected, SDB can be adopted to analyze and define a space of possible design configurations, from which designers can select the one that best aligns with the needs of the project. Although there has been a greater adoption of SBD in vertical projects, it has focused mainly on the design of structural elements. Therefore, there are gaps in the adoption of SBD in other design disciplines that are crucial, such as: utility service networks, geotechnics, architecture, HVAC, and sustainability, among others. In addition, there is a lack of studies focused on the analysis and selection of vertical project design alternatives with a multidisciplinary and multi-criteria approach.

Efforts are being made to integrate SBD with various methodological and technological approaches to support the design processes of construction projects (see Table 3). However, the results show gaps in the joint adoption of SBD with systems based on artificial intelligence and cloud computing. A situation that is similar to the joint adoption of SBD with workflows based on virtual reality, internet of things, big-data, machine learning, and others. Therefore, it is expected that in the coming years industry practitioners and researchers will make efforts to integrate SBD principles with construction 4.0 approaches. An integration that has a high potential to automate and improve the efficiency of design processes for construction projects.

CONCLUSIONS

The theoretical contribution of this study is the identification of benefits, difficulties, and trends of the adoption of SDB in construction projects. The research method was based on a systematic literature review of an initial sample of 281 documents. The five most frequently reported benefits of SBD adoption are: 1) transparent decision-making processes (B_1), 2) better collaboration in decision-making (B_2), 3) better communication among designers (B_3), 4) improvement of the design solution (B_4), and 5) analysis of various design alternatives (B_5) (see Table 1). The results show a wide potential of SBD to improve various construction project design issues, however, there are some difficulties that have limited the adoption of SBD in the construction industry. The five most frequently reported SBD adoption difficulties are: 1) inadequate organizational structure for the adoption of SBD (C_1), 2) lack of staff experience (C_2), 3) resistance to change in organizations (C_3), 4) lack of information compatibility between design disciplines (C_4), and 5) limited information to propose design alternatives (C_5) (see Table 3). It should be noted that the contributions of this study are based on a structured review of the literature rather than data obtained through the adoption of SBD in any activity of the life cycle of construction projects. Thus, it is expected that with the emergence of new studies, modifications in benefits, difficulties and trends will occur.

Several of the identified difficulties can be addressed by integrating SBD with approaches that encourage the automation of design processes based on various alternatives. Therefore, there is a trend towards the integration of SBD with complementary technological and methodological approaches to support the processes of proposal and analysis of design alternatives. Among the complementary approaches identified, the following stand out: building information modeling, multi-criteria decision analysis, choosing by advantages, target value design, and finite element method, among others. Therefore, it is expected that in the coming years SBD adoption research will focus on proposing, adopting, and improving design process workflows from the integration of both the complementary tools identified (see Table 3) as well as emerging approaches related to construction 4.0.

The main limitations of this study are: 1) the review's focus on the adoption of SBD in the construction industry without including other industries; 2) the lack of documents from databases other than Scopus; 3) the scope of the review focused on the benefits, difficulties, and trends of SBD, leaving aside other topics of interest; 4) the method of analysis is based on a frequency analysis due to the moderate number of documents that address the adoption of SBD in construction projects, therefore, this study can be classified as exploratory; and 5) all the analyzed documents are assumed to be on equal conditions, which is motivated by the exploratory nature of most of the existing studies that address the adoption of SBD in construction projects. Therefore, future work could focus on 1) review and analyze SDB developments in other industries, 2) update the review presented with documents published in other databases, 3) review SBD developments in the construction industry with complementary approaches to the one presented in this study (see Table 3); 4) adopt more sophisticated analysis methods to study the adoption of SBD in construction projects; and 5) propose approaches that integrate SBD theoretical principles and tools based on artificial intelligence to facilitate the proposal and analysis of design alternatives.

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