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A Simulation for Teaching Set Based Design in Architecture Engineering and Construction

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Abstract

Question: How can a simulation be designed to support teaching and learning of set-based design principles among architecture, engineering, and construction (AEC) learners? To what extent can a set-based design (SBD) simulation enhance the understanding of set-based design (SBD) principles in architecture, engineering, and construction (AEC)?

Purpose: This paper presents a simulation exercise for teaching SBD principles and processes among AEC learners.

Research Method: The simulation game is presented through a physical, in-class simulation activity. A pre-and post-test survey is also incorporated into the study to assess its effectiveness among learners.

Findings: The paper disseminates a novel physical simulation exercise that can be adopted for teaching set-based design principles among AEC learners. The findings demonstrate that the simulation can enhance learners' understanding of set-based design concepts, such as mapping the design space, imposing constraints on the design, and performing the set-based design process.

Limitations: The study involved two rounds of surveys with 26 student participants from the Architectural Engineering discipline. Including more learners from more diverse disciplines can be further explored and compared to the current findings. Further studies may also include practitioners and trainees within the construction industry.

Implications: The simulation can be adopted to train students in a set-based design process to prepare for collaborative project delivery in contexts with the involvement of construction teams early in the design process.

Value for practitioners: The paper presents a simulation that can guide practitioners in elaborating the concepts of collaborative design to project AEC teams.

Keywords: simulation, games, lean design, point-based design, set-based design

Paper type: full paper

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Introduction

The construction industry has experienced significant changes in project demands and complexities over recent decades. With these changes, the size of projects undertaken have evolved, resulting in a need for advanced, reliable, efficient, and productive techniques for designing capital construction projects. The project participants must, therefore, adopt collaborative design approaches and methods that account for the client's requirements, building systems interactions, and construction means and methods during the design phase (Knotten et al., 2017). Such an approach can steer the planning and delivery of the project toward success by initiating an early assessment of the design, enabling early and deliberate communication and knowledge exchanges among the design and construction teams (Franz & Roberts, 2022). Although the industry acknowledges the potential success of a design approach that bears these characteristics, traditional sequential design is still the norm. Lean design methods can result in efficient design processes, team integration, and project outcomes compared to traditional design methods (Herrera et al., 2021).

Like the application of lean in the construction stage, lean in design emerged due to this demand for efficiency and improved cost, schedule, safety, and quality performance certainty from the project's onset (Forbes et al., 2018). The most acknowledged methods in the design development process include Set-Based Design (SBD), Agile Planning, and Value Stream Mapping. These methods are used alongside the design process cost and scope management methods, such as Target Value Design, Design Structure Matrix, and Conditions of Satisfaction (Messner et al., 2019). Among the lean design development methods, SBD complements developing a design that meets targets set by project teams and is, therefore, an encouraged process to integrate into the Target Value Design (TVD) Process.

However, the use of SBD is challenged by the lack of sufficient knowledge and awareness of the practical implementation by project participants, a common yet unresolved problem when implementing lean methods (Bhatnagar et al., 2022). SBD as a lean design approach has also received less attention and study, compared to Agile Planning and Value Stream Mapping, among researchers and practitioners, further exacerbating the limitations in adopting a fully-fledged SBD process in TVD (Tommelein & Ballard, 2016). The implementation of SBD is challenged by the lack of a clear understanding of the application process among practitioners (Castañeda et al., 2023) and the limited experience in facilitating its adoption (Shallcross et al., 2020).This study focuses on developing and testing a simulation to support the teaching and learning of SBD principles among learners in the AEC domain.

Transition from Traditional to Set-Based Design

Point-based design (PBD) processes are inefficient, siloed, and limit knowledge exchange among the project teams (Liker et al., 1996; Ward et al., 1995). The uncertainties resulting from the growing complexities in AEC projects, which highly influence the design process, cannot be efficiently addressed using this point-based approach. SBD emerged due to inefficiencies in the traditional point-based design process in resolving these uncertainties (Singer et al., 2009). Adopting a point-based design heightens the possibility of compromising project quality, schedule, or cost (Shallcross et al., 2020) by encouraging commitment to a single solution at the earliest design stage and iterating within the selected solution space. These negative iterations are considered wasteful (Singer et al., 2009). Advancing this single solution before analyzing its impact on cost, system performance, and other aspects, such as constructability, steers the project towards poor performance. Figure 1 summarizes the point-based design process.

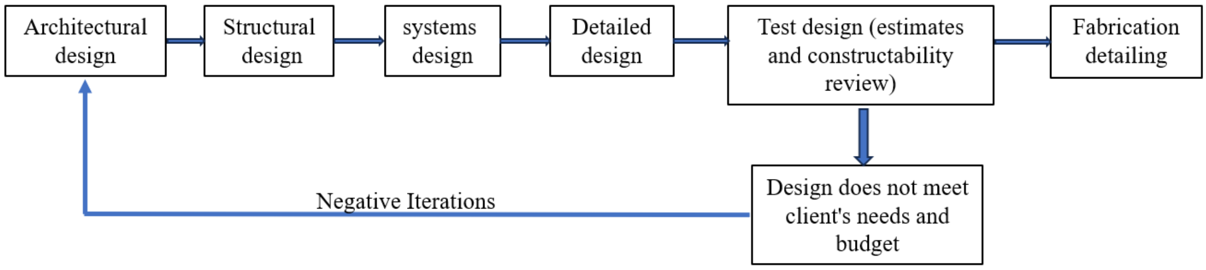


Figure 1: Non-value adding iterations in point-based design.

Embodying the Toyota paradox of 'go slow to go fast,' SBD develops and assesses multiple design options and delays commitment to a specific solution until the last responsible moment (Sobek II et al., 1999). Compared to a point-based design where redesigns significantly lengthen the design duration, the SBD approach delays the selection of final options yet hastens the overall product release to the market, (Ward et al., 1995). The concept has been widely researched and applied in other industries, including automotive (Sobek II et al., 1999), aerospace (Bernstein, 1997), naval (Singer et al., 2009), and product manufacturing (Miller et al., 2018). Recently, the construction industry has explored the potential of this technique in facilitating the design process to eliminate rework due to design errors and omissions carried over to the project's construction stage (Castañeda et al., 2023; Parrish et al., 2008).

The SBD process begins with considering a range of alternatives based on predetermined goals. These alternatives should meet the design space boundary requirements (Baierwald et al., 2022; Castañeda et al., 2023). The array of alternatives is then considered simultaneously, as sets, to allow for concurrent development of the system sets and how any decision concerning each of these systems affects the design of others (Shallcross et al., 2020). Decisions on the final designs are delayed, preventing commitments from being made too early, which may limit innovation and the exhaustive review of all possible options (Ward et al., 1995). This is commonly associated with decision-making's last responsible moment (LRM) (Lean Construction Institute, 2016). Narrowing the options is based on the project constraints, in which the team identifies the alternatives that best meet these constraints and carrying these sets of alternatives to the next stage (Parrish et al., 2008).

Once the sets have been narrowed, a detailed feasibility of the final options is conducted before committing to the solution (Shallcross et al., 2020). After establishing a commitment to a final solution, it is recommended to remain within the boundaries of the selected option unless the owner makes any changes (Do et al., 2015). The key three principles applied in the SBD process include: 1) mapping out the design space, including the boundaries, to prevent consideration of too many alternatives; 2) analyzing alternative possibilities and the intersection of these alternatives with other systems to optimize the whole project and not parts, and 3) establishing the feasibility of the solution through assessment of constructability and targets of the narrowed sets before commitment. The process culminates by maintaining the final design within the set boundaries (Shallcross et al., 2020). However, there is limited academic literature on training and teaching these SBD principles, especially in AEC projects (Castañeda et al., 2023).

Like other lean methods, a key shortcoming in the current practice of SBD is the complexity of its application and the limited knowledge and awareness of its implementation among industry practitioners (Cassino et al., 2013). To ease the understanding and improve awareness of SBD principles and practice, tangible methods of breaking down the complexities embedded in theoretical SBD into digestible practical steps and procedures are needed (Bhatnagar et al., 2022; Forbes et al., 2018; Jain & Devkar, 2023).

Simulation Games in Lean Construction Curriculum

Simulation games have been described as an efficient method of simplifying the application of lean principles, methods, or tools in design and construction contexts (Shepley, 2012). Simulations, therefore, act as a gateway for bridging the theory and practice of lean in the construction industry (Alves, 2022). Over the last three decades, more than 90 simulation games have been developed. Initially led by the Lean Construction Institute and the International Group for Lean Construction researchers, practitioners, and affiliates, these simulations aimed to enhance the teaching of lean concepts across the industry and academia (Bhatnagar et al., 2023). Most games present a proactive and hands-on approach to teaching and learning as it applies to the construction context (Bhatnagar et al., 2022). Some predominant simulation games include the Parade of Trades, LEAPCON, LEGO airplane game, Villego® Last Planner® System, and the Broken/Silent Squares games (Bhatnagar et al., 2023). The Target Value Design simulation has recently gained traction among practitioners and student trainers (Jacob et al., 2021; Kim et al., 2023; Rybkowski et al., 2016).

The parade of trades simulation demonstrates the impact of production variability on the workflow of downstream trades. It shows how the interconnectedness of closely dependent production activities requires coordinated efforts and timing in task execution. The game is played using dice and 100 units of outputs (chips or similar) passed along to the ‘assembly line’ of players, each representing a trade partner. A delay or overproduction by one trade impacts the next trade, by limiting their production or adding inventory. The game aims to help learners understand the benefits of leveled workflow based on the requirements and workload of downstream trades. Inconsistency in production, therefore, leads to variability that triggers unreliable workflow, late completion time, and increased waste on site. The parade game emphasizes the lean concepts of throughput production, flow, waste reduction, and understanding of the production value stream to determine the requirements along the construction process at the trade partner’s level of detail (Tommelein et al., 1998).

The LEAPCON simulation game complements the parade of trades game by emphasizing the benefits of throughput production using smaller production cycles, multi-skilled trades, and pull-based production. In this game, the learners simulate the construction of a typical high-rise building using the conventional construction process and compare the results with those from a construction process based on lean principles. The improvements in results demonstrate that lean promotes reduction in waste, shorter production duration, better cash flow management, and a high likelihood of work completion (Sacks et al., 2007).

Another common game that is closely related to LEAPCON is the LEGO airplane simulation. This game also demonstrates that the principles of flow, waste elimination, and pull-driven production improve production performance. Through an airplane production factory analogy, the learners are exposed to the impact of push-based production on downstream customers and how the variability from the push approach affects the outcomes. This variability impacts the customer's anticipated project duration, quality, and satisfaction (Lean Australia, n.d.; Rybkowski et al., 2008). The silent squares simulation, predominant in other sectors besides construction, has recently been extended in the construction domain. It demonstrates the benefits of smaller production cycles, teamwork, and communication during construction (Bhatnagar et al., 2023; Integral Vision learning, 2007).

More interest in simulation games grew in 2010, demonstrated by the increased number of research publications and case studies on applying these games in formal classroom teaching and industry training events (Bhatnagar et al., 2023). These simulations, albeit popular, explicitly focused on teaching the implementation of general lean principles of value, value stream mapping, pull, flow, waste elimination, customer satisfaction, and respect for people. Those that focus on implementing specific lean methods in design and construction, such as Target Value Design, Last Planner System, SBD, Takt Planning, or Big Room (Messner et al., 2019), are still limited (Bhatnagar et al., 2023).

A few methods or tool-specific simulations have recently emerged to address this. Methods such as the Last Planner System of production planning, TVD for scope and cost management, and SBD in design development have been developed and tested. For instance, the Villego® Last Planner® System (LPS) simulation allows learners, both industry professionals and students, to understand how to base the production process on pull using the principles of the Last Planner System of production planning and control. The simulation uses a set of LEGO blocks. It divides participants into different groups, allowing them to perform the project scheduling and production using both the traditional and pull-driven approaches (Warcup & Reeve, 2014).

In addition to the LPS simulation, the Target Value Design simulation is another popular simulation game that adopts a method-focused approach. The game uses a marshmallow tower analogy to teach the learners the importance of collaboratively setting and pursuing target design and construction processes. The learners are tasked to construct a tower that meets structural and aesthetic requirements while remaining within the target cost. The simulation has been demonstrated to help learners understand the concept of driving design and construction to a target based on market costs, maximum allowable costs, and estimated costs (Kim et al., 2023; Rybkowski et al., 2016). These games directly apply to ongoing and completed projects, signifying their impact on teaching and practice (Neeraj et al., 2016).

Lean simulation games in collaborative set-based design

Although the number of emerging simulation games demonstrating different lean methods continues to grow, most of these games are predominantly focused on methods applicable in production management in construction. Less emphasis has been placed on developing simulation games that teach design management using lean design methods. SBD, as a method, defies the principles of traditional design development processes by introducing concurrent assessment of constraints and value in design. This approach eliminates wasteful rework during design and introduces continuous product and process improvement (Jain & Devkar, 2023). Using simulation games to illustrate these principles is useful to enhance the learner's confidence level in understanding SBD principles. Nevertheless, the development and discussion of SBD or related training as a lean design method are significantly lacking in the literature (Bhatnagar et al., 2022).

Jain and Devkar (2023) developed one current SBD simulation. The simulation focuses on demonstrating the principles of design-space mapping, integrating feasible alternative designs, and assessing the feasibility of design for an interior design space. These processes are done through a Miro-board, where the array of pre-defined design components, instructions, and outcome tracking are presented. The teams perform all the design assessments, selections, and documentation of outcomes through the digital platform, with the discussions taking place in person.

While the principles of SBD are demonstrated in the simulation game, the implementation medium is restricted to a digital format, limiting learners' physical engagement, akin to the experience provided by model building in architecture and engineering design education or the marshmallow towers in the TVD simulation. The approach presents flexibility for digital interactions, yet confines the use of audiences with full access to these online tools. The simulation is also centered on the interior design context, which may not fully engage other design, engineering, or construction disciplines. This paper aims to bridge the gaps in current literature by generating and testing an SBD simulation game that combines physical objects and digital tools to teach the implementation of SBD principles on a building project, further enhancing understanding of SBD concepts across a wider and diverse audience.

Methodology

This study addresses a multifaceted research problem embedded in the contexts of both academia and industry practice. The challenges in implementing SBD, emerging from limited knowledge and awareness of the practical application of the principles, can be addressed through a hands-on simulation game. Such a goal requires a pragmatic methodology that infuses multiple methods to design, implement, and assess the effectiveness of the proposed solution (Kelly & Cordeiro, 2020). This study, therefore, combines qualitative and quantitative methods to generate, test, and assess an SBD simulation game curated for learners in the AEC domain. The game aims to enhance the learners' familiarity with implementing SBD and understanding of the SBD principles.

The simulation game was developed and refined over a ten-year period prior to deployment, including use with interdisciplinary and industry groups, before collecting the presented data. Further, for the data presented we tested the game in a lean production management course with learners in the AEC domain. Testing was specifically targeted to be delivered in an in-person class. We used a pre-and post-simulation questionnaire to assess the outcome of the simulation on the learners' understanding of SBD principles. A set of pictures posted on the Mural board by the groups and the author's observation of the simulation process was used to illustrate the progression in design refinement using the SBD principles. A Wilcoxon signed-rank non-parametric test was used to determine the significance level of the change in the level of understanding of the principles and confidence in performing SBD. We analyzed the open-ended responses of the questionnaire thematically to identify the key themes in the areas suggested for further emphasis and improvement. Figure 2 summarizes the methodology adopted in the study.

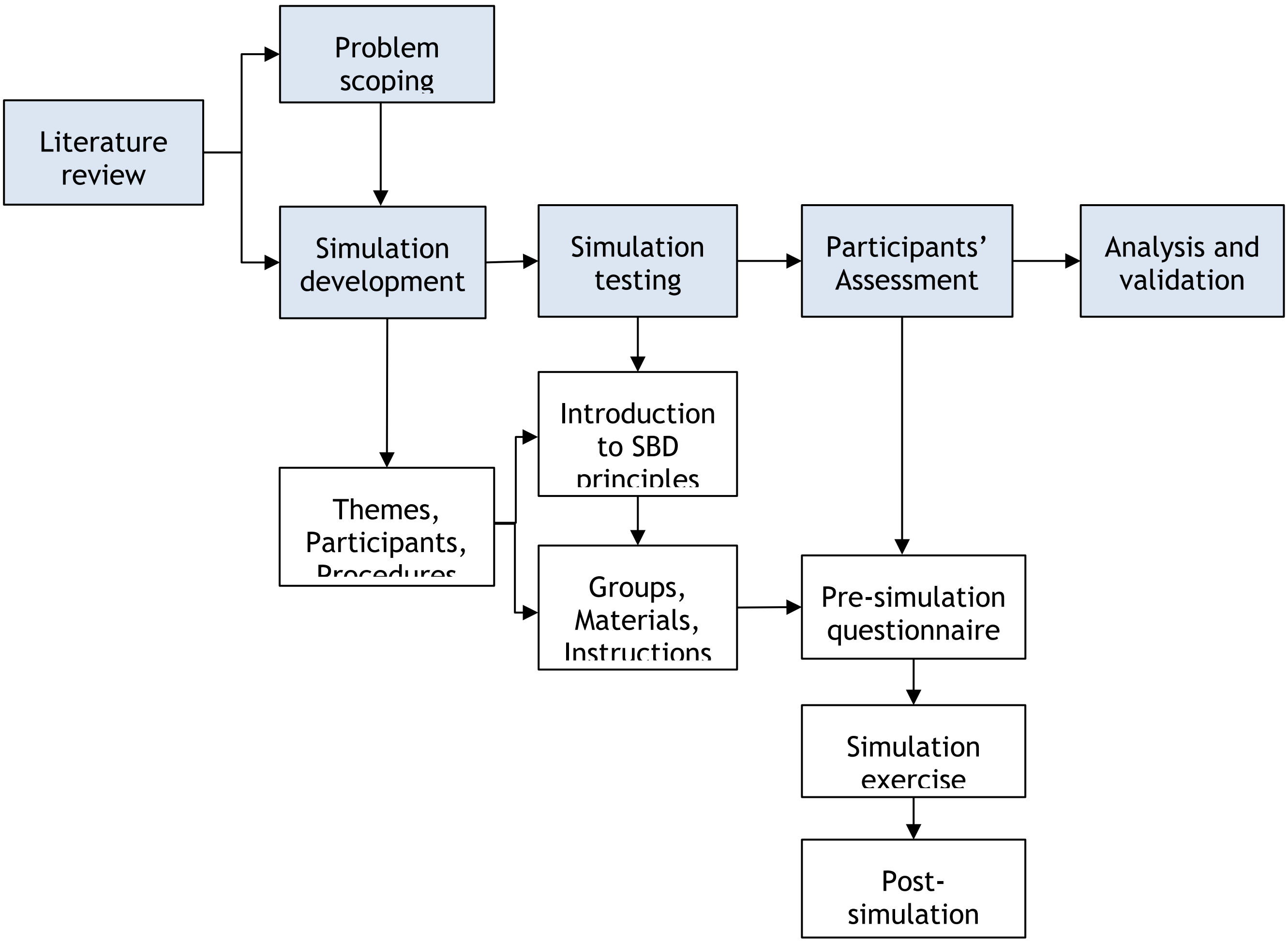


Figure 2: Steps followed in the development, validation, and testing of the simulation.

Development of the Set-Based Design Simulation Game

The game's development is based on the authors' understanding, including industry experience, using SBD. The overall inspiration for the themes is drawn from the design of theme parks by an Imagineering project team. The process began with a critical literature review to familiarize the researchers with the deployment of lean simulation games and the extension of these games in the design and construction processes. Based on this understanding, previous knowledge, and inspiration, review materials were prepared to introduce the learners to the main principles of the SBD process. The literature on simulation games was used as a basis for developing the instructions, participants and group information, rounds, instructions, and feedback. Physical blocks are used to enhance engagement and collaboration during the exercise. The next subsections present the requirements and procedures for this study's SBD simulation game.

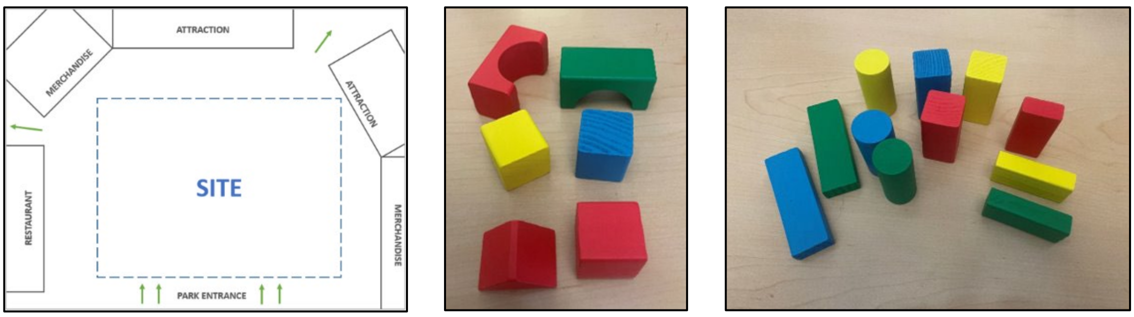
Participants and room setup

This simulation aims to teach architecture, engineering, and construction learners the basic skills and understanding of an SBD process and its implementation. The target audience is, therefore, learners and trainees in this domain with little or no exposure to the principles of SBD. The simulation must be preceded by an introductory lecture on the origin, principles, and tools used during the SBD process.

This simulation can be executed by at least two groups, with a suggested minimum of at least four participants representing an integrated project team with a client, architect, design engineer, general contractor, or specialty contractor(s) in each group. A diverse design and construction team emphasizes the need for a collaborative team to steer the design toward concurrent product and process design constraints and goals. Having more than one team is encouraged to allow the teams to share their thought processes for each design decision during the debriefing stage, as well as weighing decisions. Each group is allocated a separate table surrounded by chairs to match the number of participants. At least one facilitator is required to lead the simulation, though having a second to support the process is recommended.

Materials and equipment

This game requires a set of blocks with different shapes and colors that can represent different design systems, orientations, aesthetics, and structural functionalities. An A3 (or zzx17) sized paper with a site plan is also provided to represent the map of the site in which the design should fit, as shown in Figure 3. The teams are given the freedom to decide which shapes or colors of blocks to use as long as the requirement for each round is met. This freedom allows them to explore different design configurations.



Site Map Set A Set B

Figure 3: Simulation materials – an A3-sized site map and sets of colored blocks.

The instructor should have a shared screen where the introductory content and instruction slides are shared with the class before, during, and after the game. A link to a shared Mural board was provided to the student to host the pictures of the outcome of each round. The Mural board serves as a shared memory within and across groups of design options as the simulation progresses. One laptop and one phone are used per group to take pictures, upload them, and organize them on the shared electronic board. The instructor needs a projector or screen to share the contents of the introductory lecture, instructions, and game results. However, these may be improvised based on available teaching and learning equipment.

Themes

The design process presented in this simulation is based on an attraction park design analogy. The hypothetical client, an attraction park owner, tasks the teams to design a structure based on three themes aligning with the attraction park business model. Three main themes were selected for use in this simulation. The themes include a “skyscraper” representing a tall structure, an “other worlds” theme for a futuristic structure, and a “treehouse” representing the design of an organic structure. Each group is assigned a specific theme to ensure the design outcomes are unique. Notwithstanding, each design must conform to the requirements of each round as detailed in the instructions slides.

Introductory content slides

During the introductory lecture, the learners are introduced to the principles of SBD to give all participants a background on the process, requirements, and application. These were presented in a set of slides generated based on the level of detail desired. The recommended content covered in the slides should include the definition of SBD and the principles, tools, and case study examples. It is assumed that this lecture gives the learners an equal understanding of SBD, though this perception may introduce some bias. Since the learners are all at their final year of undergraduate study, the authors assume that their understanding of SBD is relatively similar based on previous exposure and this introductory lecture.

Rules and procedures

Instructions containing the following rules and procedures guide the simulation exercise.

- The class is divided into groups with a minimum of four participants per group
- Each team should have the required materials: 17 blocks, one site plan, a client’s brief, and a timer.
- Each group must be assigned one of the three themes: skyscraper, other worlds, or organic.
- The entire simulation consists of five rounds. Instructions for each round are given prior to the start of that specific round.
- Each team should familiarize themselves with the constraints and requirements listed in Table 1 for each round, with the instructor/facilitator reminding them.
- The duration and number of design alternatives decrease each round.
- The instructor/facilitator sets the timer each round, and during each session, the participants are encouraged to collaborate and contribute to the design.
- In the first round, the teams are given a constraint on the number of blocks from the full set that can be used in any of the designs they create.
- At the completion of the first round, a client-driven site constraint is introduced with options for allocating 25% of the site space, with different geometry. The

groups vote for the site constraint option to be adopted by all the groups, and the constraint is maintained for all future rounds.

- Following the second round, one of the system options needs to be removed (one of three options of block sets). The groups again vote for the block set to be eliminated, representing limitations to specific systems for the design in the third round. Again, all future sets must conform to this constraint.
- Following the third round, each team is asked to share the single option they feel best, and present it and their design rationale to the class. The class votes to identify the 'best' option presented.
- In the final round, the groups are asked to integrate concepts from their fourth-round option with the design selected 'best' by the group.

Table 1: variation in duration and design alternatives for each round.

Round #	Duration (Minutes)	Design alternatives	Constraints and requirements
Round 1	15	8	Number of blocks: 5 (set A) and 8 (set B)
Round 2	10	6	Usable site space restricted to 75%
Round 3	8	4	Structural system (Eliminate 3 similar blocks)
Round 4	5	1	Only one design option required
Round 5	5	1	Final design combines a group's final option with the design voted best by all groups

- Each round conveys a specific SBD concept. Details specific to each round are discussed in the simulation testing section below.
  - Round one: Mapping the design space
  - Round two: Resource constraints
  - Round three: Design system constraints
  - Round four: Robust design from Integrated intersections
  - Round five: Basing commitment on feasible design
- Throughout each round, the teams must document (take pictures) of each design alternative generated and upload them on their groups' section on the Mural board.
- At the completion of each round, a brief discussion is facilitated to gather feedback about the process and decisions made, notably as the constraints are added and the number of designs are reduced.

To support documenting the results for the purpose of this publication, each group was required to have a minimum of one phone with a high-resolution camera, a laptop with access to the Internet, and a link to the shared mural board.

Testing the Simulation Game

To determine the validity and applicability of the simulation, it was administered to a class of twenty-six (26) senior undergraduate-level Architectural Engineering students. To eliminate potential bias stemming from unequal levels of exposure to SBD, the instructor administered an introductory lecture on the fundamental concepts and principles of SBD and how this differs from the traditional sequential design process. The game aims to introduce the concept of designing concurrently in sets. It does not contrast this lean design approach with the traditional approach; therefore, no quantitative results are collected during the simulation rounds for comparison. The focus is on the feasibility of the final design solutions generated by each group based on the functionality requirements of the client.

Pre-test questionnaire

Upon completion of the introductory lecture, a questionnaire is distributed to the twenty-six participants. The questionnaire assessed learners' understanding of these concepts based on an introductory lecture. The questionnaire tests the learners' confidence level in implementing SBD and their understanding of the SBD principles. The principles assessed in the context of this exercise included mapping the design space, narrowing alternatives based on constraints, integrating design sets based on commonalities, developing a robust design solution, and making a final design commitment based on the feasibility of the solution. The confidence level is ranked on a Likert scale of one to five, with one representing strong disagreement and five representing strong level of agreement.

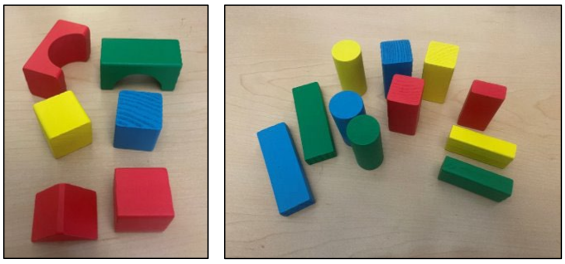
Groups and materials

All participants are divided into six groups, each with at least four participants. The materials were distributed to each group and assigned themes. The instructions were projected on the screen and read out to the groups at the beginning of each round. A total of five rounds were administered within a duration of 90 minutes. This duration can be adjusted based on the group size, number of groups, and participants' level of familiarity with SBD concepts. A design brief is issued to communicate the client's requirements with the team. The brief contains the following instructions for each round.

Round One: Mapping the design space

The first round aimed to introduce the concept of mapping the design space. Although several suitable design alternatives may fit the requirements, the project team must constrain the first set of alternatives to a reasonable number. The project team generates design concepts that align with the client's needs. In a real-world context, this involves the team assessing the owner's requirements and selecting building systems that meet those demands. For instance, in a project where the owner requires minimum environmental impact, such as in the organic theme, the team considers materials, systems, and design configurations that meet this requirement, eliminating other options that fall beyond this scope. The team, therefore, establishes the design boundaries based on defined needs, and solutions that align with the value are considered for further evaluation.

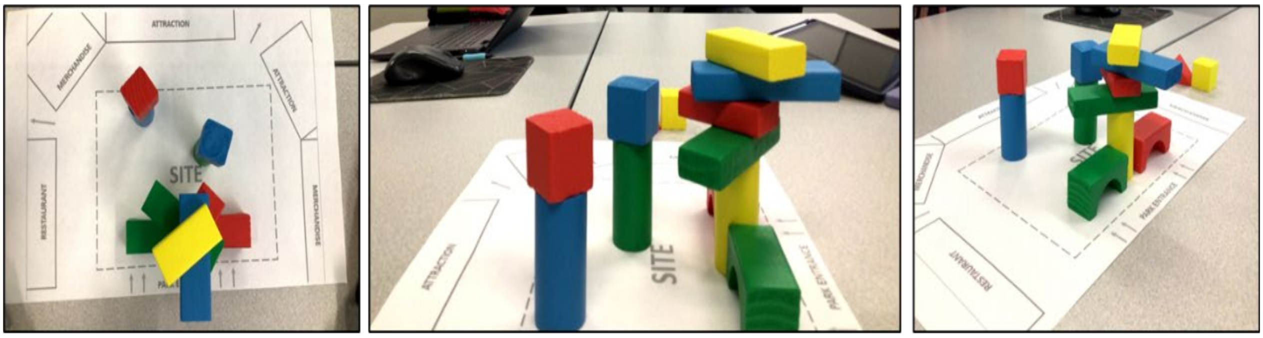
To demonstrate this concept, not all the provided blocks were used to develop the initial design alternatives. A limitation on the maximum number of blocks that can be used to generate these design options was imposed by limiting each team to only thirteen out of the seventeen provided blocks, with restrictions of five blocks from the first set (Set A) and eight from the second set (Set B) as shown in Figure 4. The groups were instructed to generate eight design options using the thirteen blocks. These alternatives had to fulfill the requirements set out in the brief. Each team was given fifteen minutes to generate the eight alternatives.



Set A Set B

Figure 4: Limitation on the number of blocks to be selected from each set.

In SBD, mapping the boundaries of the design guides the team in generating several alternative solutions while remaining within reasonable options that meet the client's needs. Figure 5 shows an example of the options developed by a group working on an organic theme based on the defined design boundary. Items of discussion by the facilitator can touch on commonalities or constraints in site use and orientation, how certain blocks are used in common or uniquely across groups, and common topics of discussion that emerge among the different teams.

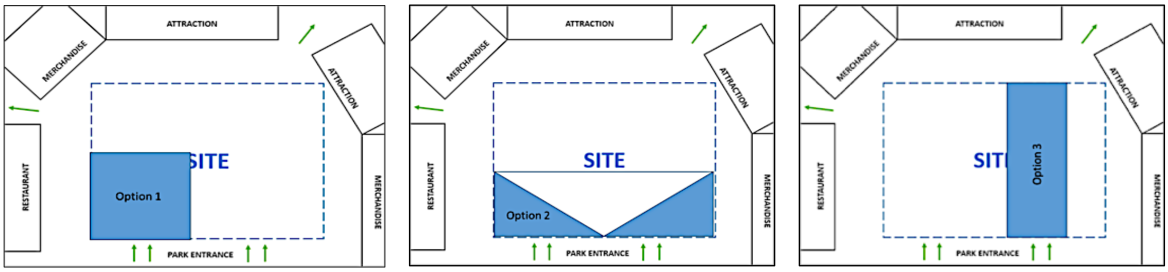


Top view Side view Iso/Angled

Figure 5: Example of an organic design from Round 1.

Round Two: Site constraints

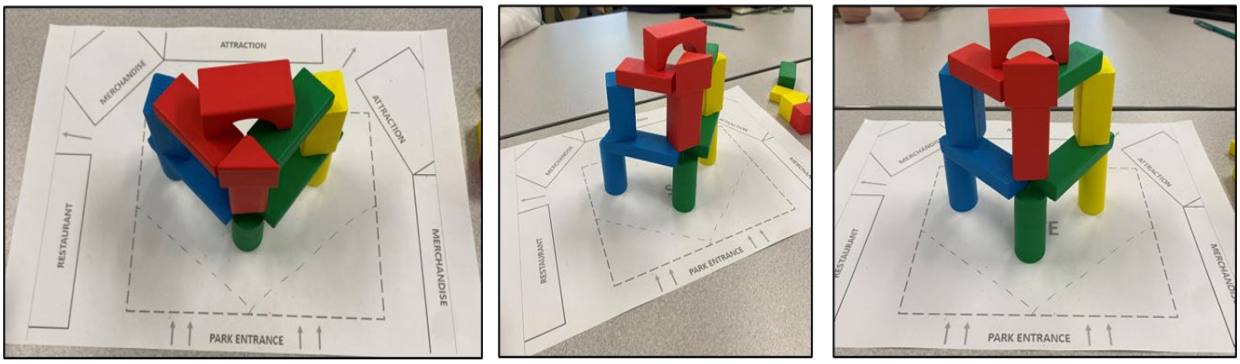
The owner of this project requires the team to provide enough circulation space to facilitate seamless access to other attraction sites within the park. Therefore, the team must consider a well-thought-out circulation space to other attraction sites. A site constraint limiting the groups to only 75% of the available site space for the building is introduced during the second round's transition to capture the circulation requirement. Three options are presented to the full group. The groups discuss internally, then jointly vote for a single site layout from the three options, shown in Figure 6, constraining the site the most preferred. All the groups generated six design options based on their assigned themes within ten minutes. The groups were expected to narrow the design alternatives to six, with permission to reuse or modify any designs from round 1 that could accommodate the new site constraints.



Option 1 Option 2 Option 3

Figure 6: Imposed site constraints.

Figure 7 shows an example of a design option generated from round two responding to the site constraint. Discussions following Round 2 can touch upon how the constraint influenced their layouts and designs, how many original designs could be re-used directly or slightly modified, and what changes had to be made to address the constraint.



Top view Side view Iso/Angled

Figure 7: Example of a futuristic design from Round 2.

Round Three: Design system constraints

The unique demands of buildings, such as energy demands or structural performance requirements, often constrain the project team to specific structural, mechanical, enclosure, or other unique systems to accommodate the demands. Therefore, the project team needs to thoroughly assess the systems that meet the specific requirements, introducing constraints on the available alternatives for building systems. In the third round, we introduced a building system-related constraint. A set of three blocks from the options in Figure 8, each representing a building system, was eliminated from the initial set of thirteen. A vote from all the groups was cast, eliminating one set; in the test data, this option was the cylindrical set of blocks. As the groups began generating the design alternatives, this constraint on the types of systems that fit the design meant each group had to rethink their designs and adapt them based on only the systems at their disposal. Four feasible design options had to be generated within eight minutes.

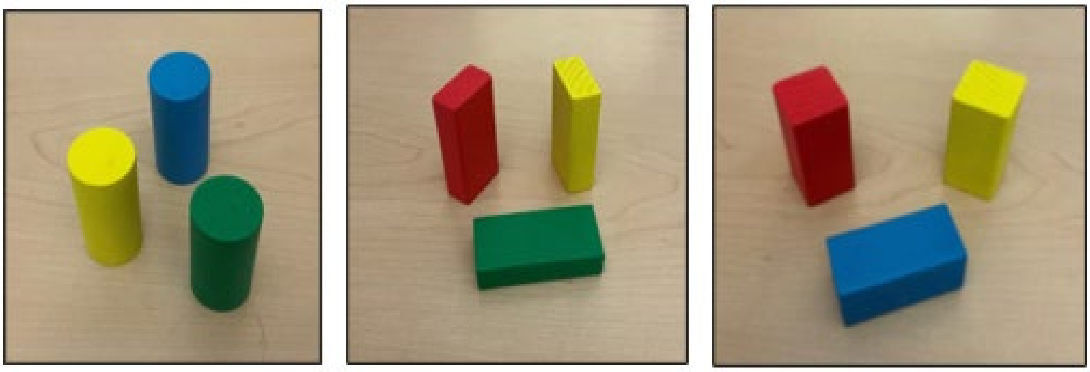
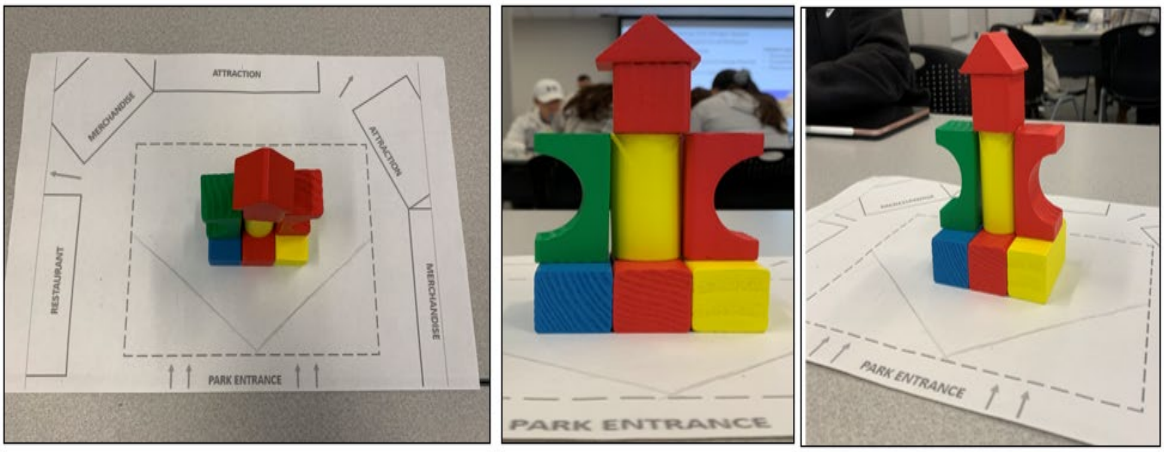
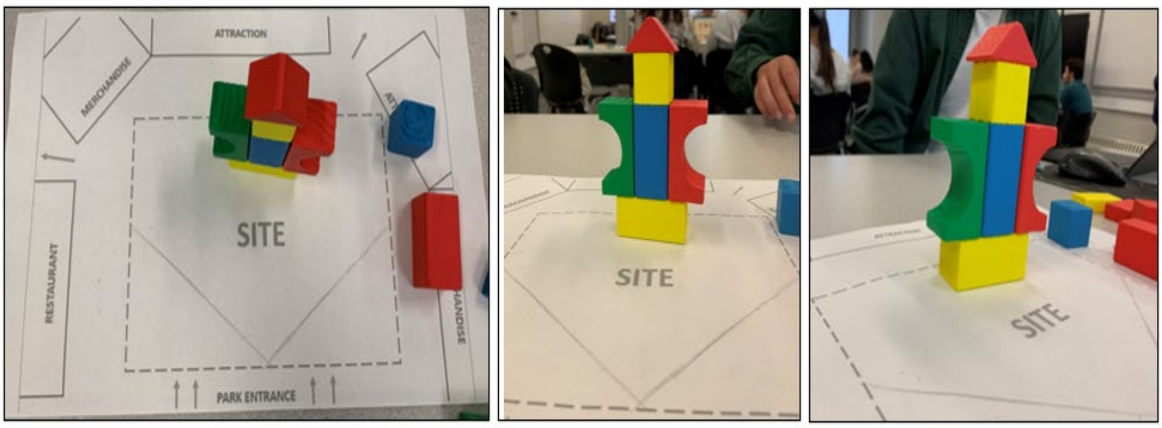


Figure 8: Three alternatives of blocks eliminated to introduce system constraints.

The design changes across the teams in this round is highly dependent on how each team had used the eliminated ‘system’. In cases where they still wanted to proceed with a similar design solution, as shown in Figure 9, the teams had to ‘replace’ the system type. Discussions again highlighted how the teams reacted to the change when narrowing the designs, how many ‘new’ designs versus modified designs emerged across the groups, and themes around how these changes or uses aligned across the groups.



Initial design from round 2



Top view Side view Iso/Angled

Revised design during round 3

Figure 9: Example of an organic design replacing the alternative system in Round 3.

Round Four: Developing a robust design concept

A design that meets all required performance requirements in line with the customer's value defined at the project's onset can be considered robust. The fourth round of the simulation focused on imparting the concept of integrating design alternatives from the fourth round to generate a final design that meets all requirements within the limits of imposed constraints. This can be termed as a representation of a robust design concept that satisfies all the client's needs and engineering requirements. Such a design is only successfully generated by integrating alternatives at the areas of intersection. Figure 10 shows an example of a final 'robust' design developed by one of the groups and voted as the best by the class.

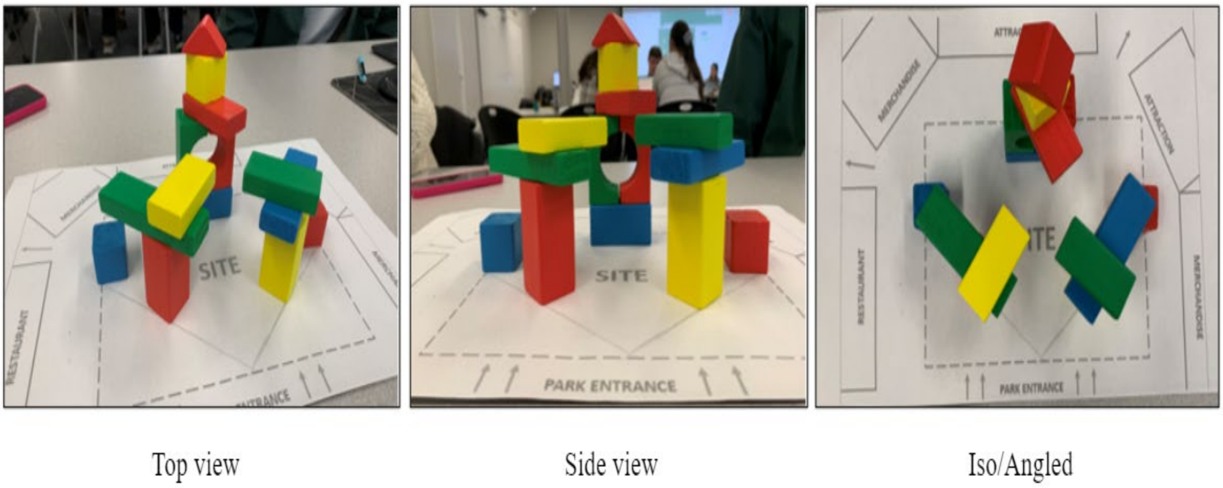


Figure 10: An organic design selected as the best final design from Round 4.

Students were asked to show and present the rationale of their integrated design. Discussion topics included whether they were able to use a design they had already created or how they integrated their options into one final design.

Final Round: Establishing design feasibility

The last round of the simulation involved each group analyzing the best design, voted for by the class at the end of round 4, and identifying its robust aspects. The final design for each group then discusses how to integrate those robust aspects with their final robust design. The decision must be based on the ability of the final output to meet the client's requirement of an iconic theme park built on 75% of the site and using only specific building systems. This step seeks to further enhance the learners' understanding of the concept of establishing feasible design by integrating robust design options, as shown in Figure 11.

Discussion at the completion reflected upon the conversations about robust elements, and the strategies the groups used, and the similarities and differences of the ultimate designs.

Post-test questionnaire

At the end of the simulation, a post-test questionnaire was distributed to all the participants to assess their understanding of the set-based concepts following the exercise.

The questionnaire assessed the learners' confidence level with the same SBD concepts assessed in the pre-test questionnaire on a Likert scale of 1 to 5. An open-ended section was introduced to collect further feedback and insights on the aspects of the simulation that the learners found useful and the concepts that needed further clarification.

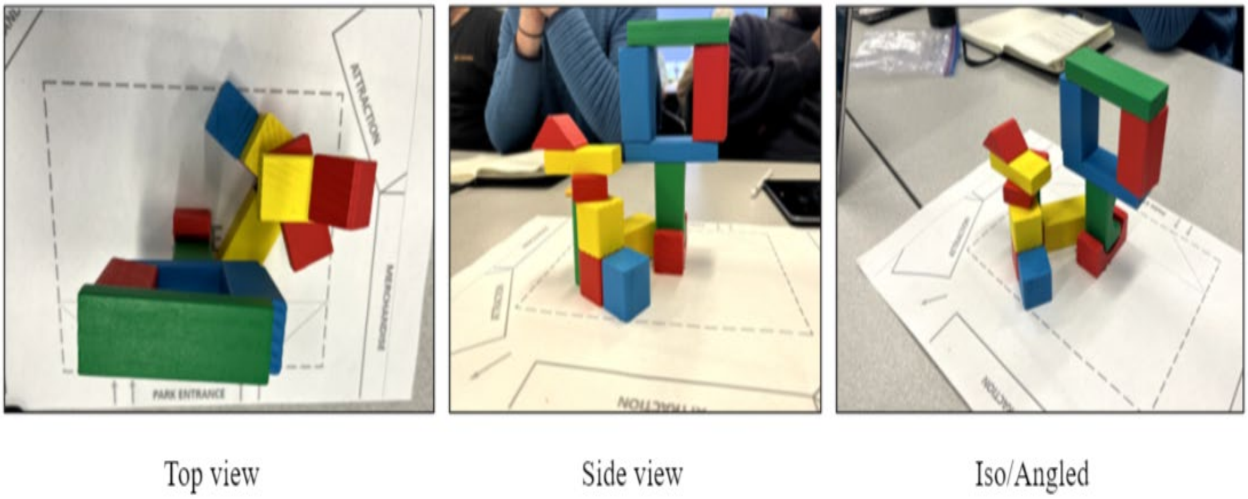


Figure 11: Example of an integrated futuristic and organic design.

Results and discussion

Simulation results

The first round focused on enhancing the learners' ability to develop multiple design options based on provided inputs. In contrast, rounds two and three introduced the concept of project constraints and their impact on design. The fourth and fifth rounds simulated how to integrate feasible design options at their intersections to generate a final design. This final design consists of the best aspects of the integrated design options, balancing meeting the design space limitations and existing constraints. The students developed eight options in the first round and narrowed the options to six in the second round. Four options were generated in the third round while the fourth and fifth rounds each required one final design.

Advancing a design from one round to the next depended on the robustness of the design options generated in the previous rounds, making it easier to adapt to new conditions. In the transition to the second round, the teams could sometimes carry over the designs, directly repeating a previous design if the site constraint did not directly affect the design. However, in the third round, where a system constraint was introduced, all teams had to rethink their design options. The extent of the redesigns depended on how the cylindrical blocks were used, either for aesthetics or as a structural component supporting the building.

The skyscraper theme relied on cylindrical blocks to achieve the heights and hence was most impacted by the introduction of the constraint in the third round. The teams could carry over most of their round three designs to the fourth round. However, a few teams integrated some of their best designs from rounds one, two, and three to generate the final design in round four. The fifth round relied on the robustness and aesthetics of other teams' designs compared to each team's current design. Figure 12 summarizes the advancement of the designs from the team towards the final design.

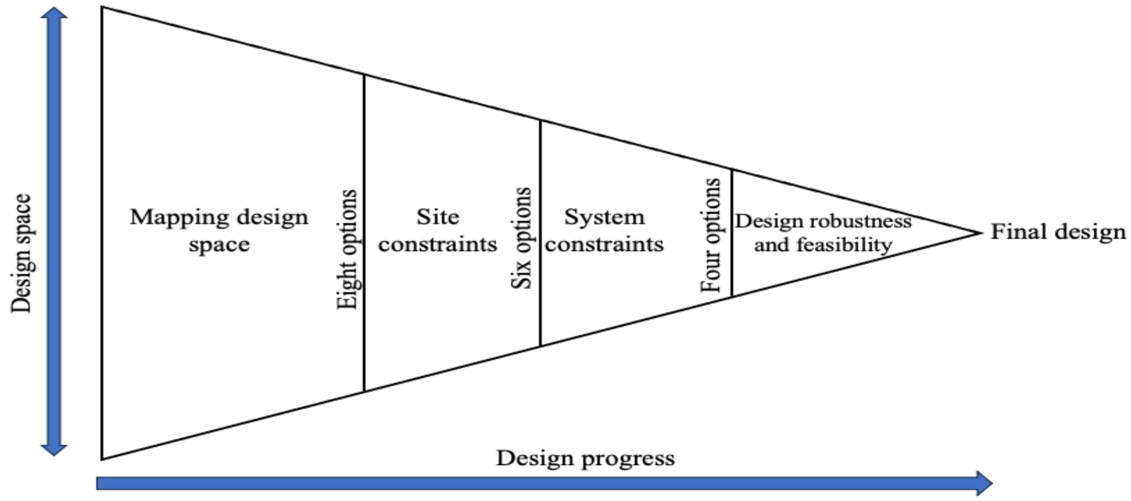


Figure 12: Advancement of the design process in the SBD simulation.

Assessment of simulation effectiveness

The pre- and post-simulation questionnaire aimed to determine any changes in the understanding of SBD principles. The confidence level of learners with SBD concepts presented during the simulation was tested both before and after the exercise. Data from a sample size of n=26 students were used for the analysis. The results indicate an increase in the level of confidence in understanding SBD concepts presented in the simulation, which included mapping the design space, imposing minimum constraints, developing robust design, and confidence in performing SBD. The improvement is higher in imposing minimum constraints, mapping the design space, and performing SBD. Developing a robust design solution received a relatively lower increase from the pre to post-test. The observed changes in responses are summarized in Figures 13 and 14.

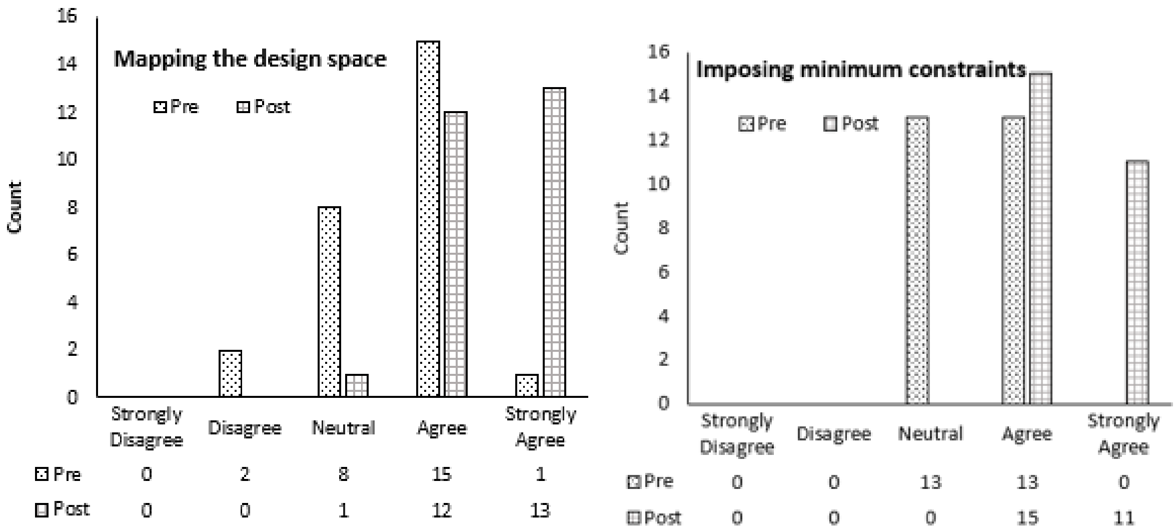


Figure 13: Change in level of confidence in mapping the design space and imposing minimum constraints.

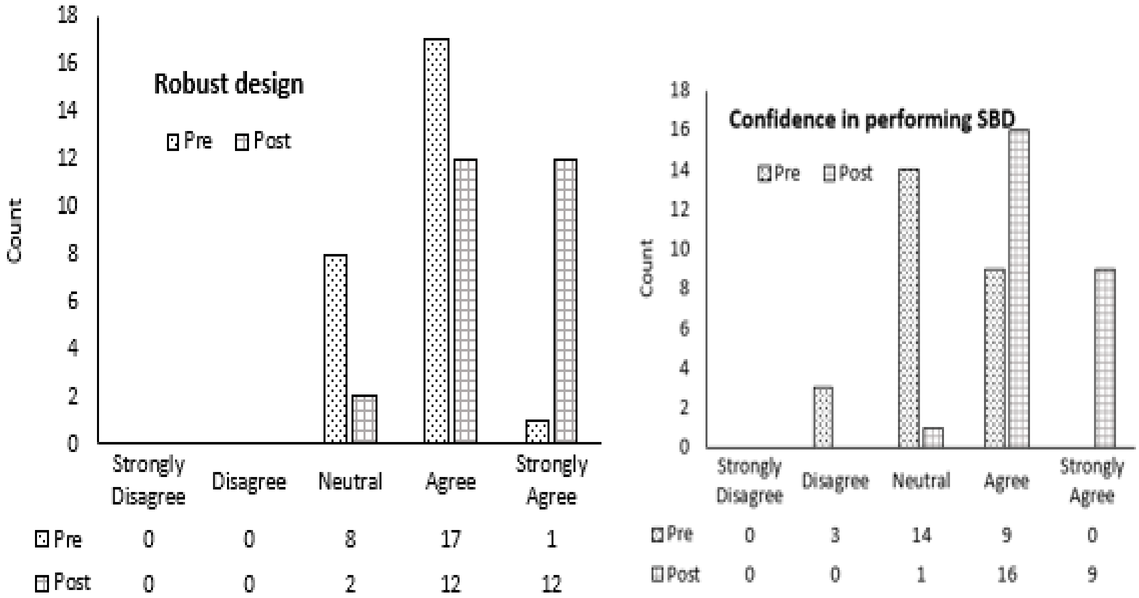


Figure 14: Change in confidence level in developing robust design and performing SBD.

There is a 25.7% increase in the learners' ability to explore design solutions by intersecting feasible sets and imposing minimum constraints. The learners also posted an 18.9% increase in their ability to generate solutions that meet a wider range of constraints. Overall, the learners demonstrated a 34.37% increase in their confidence level in understanding the process of performing SBD. A summary of these results is presented in Table 2.

Table 2: Summary of responses in the pre- and post-simulation.

	Pre-test	Post-test		Pre-test	Post-test		Pre-test	Post-test		Pre-test	Post-test	
Team	**Ability to explore design solutions by intersecting feasible sets**		**Delta**	**imposing minimum constraints**		**Delta**	**developing solutions that satisfy a broad range of conditions**		**Delta**	**confident in the process of performing SBD**		**Delta**
1. Tallest	3.9	4.8	0.9	3.3	4.8	1.5	3.8	4.5	0.8	3	4.8	1.8
2. Futuristic	2.8	4	1.3	3.3	4.5	1.3	3.5	4.8	1.3	3.3	4.3	1
3. Organic	4	4.8	0.8	3.5	4.3	0.8	3.3	4.3	1	3.8	4.8	1
4. Tallest	3.5	4.5	1	4	4.5	0.5	3.8	4.5	0.8	3	4.5	1.5
5. Futuristic	3.3	4.5	1.2	3.7	4.5	0.8	4.2	4	-0.2	3.2	4.3	1.2
6. Organic	3.8	4.3	0.5	3.3	4	0.8	3.8	4.5	0.8	3.3	3.8	0.5
Mean	3.5	4.5	0.9	3.5	4.4	0.9	3.7	4.4	0.7	3.2	4.4	1.1
Median	3.6	4.5		3.4	4.5		3.8	4.5		3.2	4.4	
Mode	4	5	1	3	4	1	4	5	1	3	4	1

We formulated a hypothesis to explain the changes in the level of understanding and confidence in SBD principles and concepts.

- Null Hypothesis: There is no significant increase in the understanding of SBD concepts after the simulation. H_0: $\eta = 0$
- Alternative Hypothesis: There is a significant increase in the understanding of the SBD concepts after the simulation. H_1: $\eta < 0$

To test the significance of the change, a comparison of the difference in mean and median scores was performed using a paired sample t-test and a paired Wilcoxon signed rank test of the differences at a 95% confidence level. The results of the hypothesis test indicate that at a 95% confidence level, there is evidence to conclude that the simulation presented in this paper enhances the understanding of SBD among AEC learners with a p-value < 0.05 in all four categories, as summarized in Table 3.

Benefits and limitations of the simulation

Based on the open-ended questions, the learners indicated that analyzing the impact of constraints on design decisions and generating feasible alternative options was the most beneficial aspect of the simulation. They appreciated the progressive design development process that accounts for many options and narrows them to a single design solution. These aspects cover two of the core principles of SBD: mapping the design space boundaries to come up with a wide range of alternatives and integrating designs through intersections before committing to one design.

The concepts that remain unclear from the simulation include strategies for best bringing previous design alternatives forward to the next design stage. Several questions regarding the concept of constraints emerged. These include the point at which constraints bear the highest influence on the design, the sources of these constraints in a typical project, and how they impact the means and methods adopted during construction. The last responsible moment (LRM) in SBD, which the simulation did not sufficiently address, was also identified as unclear to the learners.

Table 3: paired t-test and Wilcoxon signed rank test for pre- and post-test questionnaires.

Sample	N	Pre-test Mean	Post-test Mean	Paired difference (Mean)	t-test p-value	Pre-test Median	Post-test Median	Paired difference (Median)	Wilcoxon p-value
Mapping design space	26	3.58	4.46	-0.885	0.000	4.00	4.50	-1.0	0.000
Impose constraints	26	3.50	4.42	-0.923	0.000	3.50	4.00	-1.0	0.000
Robust design	26	3.73	4.39	-0.654	0.000	4.00	4.00	-0.5	0.002
Confidence to Perform SBD	26	3.23	4.31	-1.077	0.000	3.00	4.00	-1.0	0.000

Some students were interested in understanding how the process translates to a real-world design scenario, given the cultural resistance to change within the industry. Discussions regarding initiating a change in culture from the traditional point-based design to a set based within the construction industry were particularly interesting to the learners. The impact of adopting an SBD process on the schedule performance of a project was also an area in which students indicated a need for further insights. These highlighted aspects can be further clarified through further development of the simulation and case studies of projects implementing SBD within the construction industry.

The simulation did not include the contrast between traditional and SBD. Future studies can assess the impact of the transition by introducing measurable parameters during the simulation exercise, such as the overall duration of design, the cost impact, and the difference in the number of design alterations in both scenarios. The simulation can also be tested on industry practitioners and trainees.

Discussion and conclusion

Simulation in teaching and learning technical concepts has been acknowledged to enhance researchers' and practitioners' understanding of complex concepts. This paper sought to develop, validate, and assess the effectiveness of an SBD simulation in understanding SBD processes and principles among AEC leaners as part of applying lean methods in the design process.

The simulation provides a guided design development exercise using a set of blocks to design an iconic centerpiece built on a pre-planned site with adjacent attraction features. The learners are instructed to develop a range of design options in five simulation rounds based on assigned themes and constraints. The developed design options demonstrate the changes that each team adopted to align their designs with the design input limitations and imposed constraints on the site space, as well as building systems components, which influence the ability to carry forward the design to the next stage. A set of questions assesses the learners' confidence level in understanding the SBD concepts before and after the simulation.

The results from the questionnaires indicate a significant improvement in the learners' level of understanding of SBD concepts and an increase in confidence in performing SBD. Although there was an improvement in the level of understanding, the learners expressed the benefits of incorporating other associated concepts in the simulation. These main areas of improvement include an emphasis on defining boundaries and constraints, the impact of SBD on project timelines, culture change from point-based to SBD, and implementing the last responsible moment in decision-making during SBD.

However, it is worth noting that the simulation was tested on learners at the senior undergraduate level, and the outcomes may differ when applied to another audience. Future research can incorporate the suggested improvements and validate these findings through a simulation with industry practitioners. These findings demonstrate that the simulation presented in this paper can enhance the teaching of SBD in AEC. The study contributes to advancing the efforts of teaching and training on SBD to improve the project design process, therefore impacting the overall performance of construction projects compared to the inefficient point-based approach in project design.

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