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A Hybrid Framework for Multi-Objective Construction Site Layout Optimization

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Abstract: Effective Construction Site Layout Planning (CSLP) ensures the organized placement and sizing of temporary facilities, enhancing workflow and logistical efficiency. Poorly planned layouts, however, can increase material handling times, create bottlenecks, and reduce productivity, ultimately leading to higher costs. The main objective of this study is to introduce a BIM-based hybrid framework for CSLP that integrates Systematic Layout Planning (SLP) with a Genetic Algorithm (GA), developed through a Design Science Research approach. This Construction Site Optimization Framework (CSOF) addresses CSLP as a multi-objective optimization problem, prioritizing efficient positioning of facilities while accounting for workflow intensity, safety, and manager preferences. The framework's continuous-space modeling supports a realistic approach, moving beyond fixed-location models. Exploratory case studies demonstrated CSOF's effectiveness, achieving 30.79% to 40.98% reductions in non-value-adding travel distances and adaptability across varied site conditions. In this way, this research provides a decision-support tool that balances automation with decision-maker input, enhancing layout efficiency and operational flexibility in construction site management.

Keywords: decision-making; systematic layout planning (SLP); building information modeling (BIM); construction site layout planning; optimization; genetic algorithm (GA)

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1. Introduction

Construction management encompasses various decision-making stages, where on-site management is crucial. Effective Construction Site Layout Planning (CSLP) coordinates all facilities' functions, positions, and sizes throughout the site. These decisions influence the workspace's efficient organization and functionality, supporting operational logistics and project flow [1]. CSLP strategically arranges temporary and permanent facilities to enhance workflow, resource efficiency, and site safety. Temporary facilities (TFs) support construction projects with functions like offices and storage, with research targeting efficient design and reduced environmental impact. Fixed facilities (FFs) are permanent structures, with studies focusing on sustainable design. Access roads (ARs) ensure site access, with research prioritizing safety and material optimization [2].

While CSLP may not be directly linked to the technical aspects of a project, a poorly designed site layout can have significant budgetary impacts. Inefficient layouts increase material handling time, create bottlenecks, and reduce worker productivity, leading to unnecessary costs [3]. On the other hand, a well-structured layout plan enhances on-site maneuverability, improves safety, and increases productivity, supporting smooth operations and contributing to overall project effectiveness [4].

CSLP is classified as an NP-hard problem, making it computationally complex. In computational complexity theory, an NP-hard problem becomes increasingly difficult to solve as the number of variables and constraints grows. The exponential increase in potential solutions makes it challenging to optimize layouts efficiently, especially in cases like CSLP, where there are numerous facilities, spatial restrictions, and proximity requirements to consider. Researchers have used exact and heuristic methods to tackle this challenge. These methods include mathematical models, various computer algorithms, and knowledge-based rule approaches, each bringing distinct advantages for tackling layout challenges [5].

While exact methods can yield optimal solutions, they become computationally intensive as the problem size increases, demanding excessive processing time. Heuristic methods offer key benefits, including faster computational times and the flexibility to handle additional constraints and objectives [6]. However, their main disadvantage lies in their limited ability to ensure optimal solutions, which can be a significant compromise. This trade-off between computational efficiency and solution quality is generally accepted, especially for large-scale, complex problems where speed is a priority [3].

The Genetic Algorithm (GA), a heuristic method, is the most widely used optimization technique for CSLP [7]. The Genetic Algorithm (GA) is a computational approach inspired by Darwin's theory of biological evolution. It utilizes principles of natural selection and genetic processes to search for optimal solutions (OSOs) by mimicking the process of natural evolution [8].

GAs are particularly valuable due to their global search capabilities and effectiveness in addressing complex, non-linear problems. However, their implementation can be intricate, and they often have slower search speeds, which can increase the risk of premature convergence, where solutions become suboptimal before reaching the true optimal outcome [9].

Although CSLP is essential, it often receives limited focus from professionals. Site elements are typically placed based on arrival, with layout planning deferred to supervisors' daily routines. Layouts tend to draw on practical knowledge and prior experience rather than systematic methods when planned [5]. Various factors often hinder the adoption of advanced layout planning techniques in construction [10]. Existing mathematical models provide segmented solutions that fall short of capturing construction projects' uncertain, dynamic environments [11]. Another significant challenge is the lengthy computational time these algorithms require to find optimal solutions, especially as the complexity and scale of the project increase [12]. An advanced tool to support CSLP should offer user-friendly functionality, rely on limited input data, and be adaptable to diverse construction projects. Ideally, it should deliver quick solutions and address critical factors such as travel distance, safety, and costs without demanding extensive effort to reach an optimal outcome [10].

To manage this trade-off between computational efficiency and solution quality, simplifying the problem is often necessary [13]. An alternative approach is using hybrid algorithms that combine exact and heuristic methods. This hybrid approach can deliver near-optimal solutions while keeping computation time within a reasonable range for more extensive, complex projects [6].

In light of these challenges, this research emphasizes the importance of involving decision-makers directly in the planning process. This approach combines a knowledge-based rule system with an optimization technique, creating a hybrid model. It aims to increase flexibility and solution accuracy, reduce computational complexity, and limit the required input data. Following this reasoning, Systematic Layout Planning (SLP) is a well-regarded method widely applied to develop efficient layouts for organizing facilities in manufacturing and service industries [14]. SLP enables using knowledge-based rules to qualitatively assess the relationships between layout elements and place them according to proximity needs [15]. Building Information Modeling (BIM) also provides a robust source of construction data, which can be leveraged to address CSLP challenges effectively [16].

Prior studies employing knowledge-based rules have explored the integration of Systematic Layout Planning (SLP) with BIM [5] or with GA [17]. Although these studies affirm that hybrid methods yield favorable results, they share certain limitations. Each study utilized a predetermined spatial model, where site locations are set before automation, and the number of available spots corresponds precisely to the number of required installations, which are modeled uniformly in shape and size. These studies contribute by offering valuable insights into combining different methods for CSLP but highlight the need for further flexibility.

This paper presents an innovative BIM-based framework for CSLP that integrates SLP with a GA. The resulting Construction Site Optimization Framework (CSOF) addresses multi-objective site layout design by enhancing operational efficiency through flexible, decision-driven planning. Leveraging BIM visualization features alongside SLP structured methodology, this framework offers a more adaptive and efficient approach to CSLP. Building upon prior research, this study represents an evolution of earlier efforts to optimize construction site layouts by addressing limitations and expanding the applicability of the methodology [18]. CSOF considers workflow intensity, safety priorities, and manager preferences as criteria to establish proximity needs between facilities. Additionally, CSOF introduces continuous-space modeling for facility placement. It calculates facility dimensions based on minimum required areas and positions them flexibly rather than constraining layouts to grid systems or predefined locations. This approach minimizes non-value-adding travel distances, aligning with critical research findings that emphasize the impact of tailored layout planning on improving operational efficiency and site adaptability [10,16].

Based on what has been presented, this study aims to answer the following question:

RQ1. *What potential does a construction site planning tool based on SLP have for reducing non-value-added distances on a construction site?*

The rest of this article is structured as follows: Section 2 presents the framework of the CSLP problem, including ways of representing space and time in the models. It also differentiates existing optimization approaches and techniques, the objective functions adopted in previous studies, and the specific functions used in 69 relevant articles published over the last decade, resulting from a Systematic Literature Review. Section 3 consists of a detailed description of the methodology used to develop and test the proposed work structure. Section 4 presents the results of the tests carried out in exploratory studies. Section 5 presents the main contributions of the research, limitations, and suggestions for future research.

The methodology section outlines the research approach by explaining how the steps of Design Science Research were carried out to construct the artifact, which is the framework for CSLP. The results section presents the SLP-based decision-making model, details the Genetic Algorithm and the efficiency indicator created, the framework's application, the data obtained from the exploratory studies and the final CSOF.

2. Research Background

2.1. Construction Site Layout Planning Representation

CSLP should be thought of as a method to maximize the construction space by placing jobsite facilities in vacant spaces while satisfying a series of conflicting and congruent objective functions within a set of layout constraints [19]. An efficient job site layout plan ensures optimal use of available space, lower design costs, less need to relocate materials during construction, and better accessibility and safety of the work environment [20]. Understanding CSLP requires several vital definitions, including how space, time, and construction elements are represented.

Regarding space modeling, three main approaches are used to represent job site space. The first one, predetermined locations, simplifies CSLP by reducing it to an allocation problem, aiming to assign objects to predefined locations [21]. The grid system divides the job site into cells, each with a reference point, allowing the entire space to be utilized for object placement [22]. The continuous-space approach models the site as a continuous area, enabling elements to be placed anywhere on the terrain. However, this adds complexity, requiring advanced algorithms to avoid spatial conflicts and increasing computational time [23].

Several methods exist for representing construction site boundaries, including size and shape. Current approaches differ significantly in dimensionless representation, approximate geometry, and actual shape. The dimensionless method represents elements as single points without size or shape [24]. Approximate geometry uses basic 2D or 3D shapes, such as rectangles and cylinders, to outline elements [21]. Finally, actual shape representation offers the most accurate depiction of the job site, including available space and site objects.

The duration of elements on a construction site is directly linked to associated activities [25]. As the project progresses, the required elements and their spatial needs change [1]. There are three approaches to representing time variations in CSLP. The static approach assumes all elements are needed throughout the project, overlooking time-based changes [26]. The phased approach addresses this limitation by dividing the project into time intervals and creating partial layouts for each phase [27]. In contrast, the fully dynamic approach considers the actual duration of each element, adjusting layouts based on real-time site changes, unlike the phased method where elements remain for multiple phases [28].

2.2. Optimization Approaches and Techniques

Optimization methods for CSLP are categorized into exact, heuristic, and hybrid approaches [6]. Exact methods aim to find optimal solutions based on objective functions [29], but they require significant computational effort, making them impractical for large projects [30]. Heuristic methods provide near-optimal solutions when finding the absolute optimal is too costly [31]. Hybrid methods combine exact and heuristic elements, using mathematical models and algorithms to enhance solution quality [29].

The literature identifies three primary techniques for layout optimization in Construction Site Layout Planning (CSLP). **Mathematical models** represent optimization problems using quantitative methods from operations research, such as linear, integer, and mixed-integer programming [32]. However, as the problem becomes more complex with additional objectives and constraints, these formulations become exponentially more complex to solve [33]. **Knowledge-based rules** leverage personal experience to create guidelines that support planners instead of focusing on specific optimization goals [12]. **Algorithms** are designed to find optimal or near-optimal solutions to complex optimization problems, particularly those classified as difficult in computational complexity theory [9]. Advances in computational methods have led to the widespread use of optimization algorithms for addressing CSLP challenges [5].

Some studies use advanced technologies to create platforms for data collection, processing, and analysis in CSLP. Notable tools include CAD, BIM models, location tracking systems, and simulations [33]. Introduced in 1992, Building Information Modeling (BIM) has evolved from a simple computational tool into a digital management method integrating policies, processes, and technologies [34–36]. The strength of BIM in construction planning lies in its ability to analyze activity flows, such as material unloading, pathways, and work areas [37,38]. Therefore, it offers detailed 3D models to support decision-making [39].

2.3. Optimizing Objective Functions

A Systematic Literature Review (SLR) was conducted to identify the objective functions and optimization techniques used in CSLP works. The review's operationalization details can be found in Appendix A to maintain a smooth reading flow. Figure 1 summarizes the extraction and categorization of data from the 69 reviewed articles. Additionally, a full list of optimization techniques with their complete names can be found in Appendix A, shown in Table A2.

Year	Works	Objective function A	B	C	D	E	F	Support Technology	Optimization
2013	Ning and Lam (2013)	■	■						ACO
	Said and El-Rayes (2013)		■		■				GA
	Andayesh and Sadeghpour (2013)	■	■						MTPE
	Said and El-Rayes (2013)		■			■			GA and ADP
2014	Yahya and Saka (2014)	■	■			■			RBC and ABC
	Lien and Cheng (2014)		■			■			ABC and PSO
2015	Wang et al. (2015)		■					BIM	FA
	Abdelmegid, Shawki and Abdel-Khalek (2015)			■					GA
	Kumar and Cheng (2015)			■				BIM	GA and A*
	Li et al. (2015)	■							PSO
	Huang and Wong (2015)		■						BBA
	Adrian et al. (2015)					■			GA, PSO and ACO
	Abdelrazig (2015)		■						ACO
2016	Kaveh et al. (2016)		■	■					CBO
	Xu, Lie and Lei (2016)		■						GA
	Xu et al. (2016)		■						GA
	Abune'meh et al. (2016)	■	■					SIG	GA
	Abotaleb, Nassar and Hosny (2016)	■	■			■			GA
	Akanmu et al. (2016)		■					BIM, RFID	GA
	Hammad et al. (2016)	■	■					BIM	EO - CPLEX
	Hammad, Akbarnezhad and Rey (2016)		■						EO - SCIP
	Papadaki and Chassiakos (2016)	■	■						GA
	Ning et al. (2016)						■		RBC
	Yu, Li and Luo (2016)			■				BIM	GA
2017	RazaviAlavi and AbouRizk (2017)						■		RBC and GA
	Song et al. (2017)	■						SIG	GA
	Huang and Wong (2017)		■						BBA
	Hammad, Rey and Akbarnezhad (2017)			■					CPA1
2018	Ning et al. (2018)	■							ACO
	Kaveh and Vazirinia (2018)		■			■			CBO and VPS
	Kaveh, Moghaddam and Khanzadi (2018)	■	■						CBO and ECBO
	Kaveh et al. (2018)		■			■			CSS, MCSS and PSO
	El Meouche et al. (2018)	■						SIG	GA and Dijkstra
	Farmakis and Chassiakos (2018)	■	■						GA
	Yi , Chi and Yang (2018)	■	■						GA
	Ning, Qi and Wu (2018)	■							RBC
	Jin, Zhang and Yuan (2018)						■		RBC
2019	Ning et al. (2019)	■	■						GA and ACO
	Li, Luo and Skibniewski (2019)		■					BIM	GA
	Cheng and Chang (2019)		■					BIM	SOS
	Kaveh and Vazirinia (2019)		■			■			EVPS
	Huang and Wong (2019)		■						BBA
	Le, Dao and Chaabane (2019)		■					BIM	RBC and e-con.
	Schwabe, Teizer and König (2019)	■						BIM	RBC

Figure 1. *Cont.*

	Works	Objective function						Support Technology	Optimization
		A	B	C	D	E	F		
2020	Benjaoran and Peansupap (2020)		■						PSO
	El Meouche et al. (2020)	■						SIG	DEA
	Xiang et al. (2020)	■							PSO
	Kaveh and Vazirinia (2020)		■			■			SCA
	Singh, Karmakar and Delhi (2020)		■					BIM	GA
	Riga et al. (2020)		■					BIM	EO
	Singh and Kumar (2020)		■					BIM	GA
	Lai et al. (2020)		■						RBC and GA
	Hammad (2020)	■	■						EO - e-con.
	Prayogo et al. (2020)		■			■			SOS
2021	Petroutsatou et al. (2021)		■						GA
	Jaafar, Elbarkouky and Kennedy (2021)	■	■						BBA
	Nguyen (2021)	■	■			■			ABC
	Rezaee et al. (2021)			■					GA
	Zhang and Yu (2021)				■			BIM	PSO
	Jiang and Miao (2021)			■					AS
	Yang et al. (2021)		■					BIM	GA and PSO
2022	Zavari et al. (2022)	■						BIM, GIS	GPAWOA
	Gad et al. (2022)	■							GA
	Tao et al.(2022)	■	■					BIM	PSO
	Karkamar, Singh and Delhi (2022)			■					CSA
2023	Lu and Zhu (2023)	■	■						GA
	Yao, Li and Yang (2023)			■					GA
	Kim et al. (2023)			■					A*
	Dienstknecht (2023)		■						BBA

Figure 1. Categorization of 69 articles collected through the Systematic Literature Review. This figure classifies the reviewed articles based on the addressed objective functions (A—increase safety; B—reduce costs; C—minimize distances; D—reduce time or schedule criticality; E—comparison; F—assessment), the use of supporting technologies, and optimization techniques, and provides the corresponding reference number in the final column [5,7,9,12,17,24,30–32,34,40–97].

Articles in CSLP generally fall into six main categories regarding objective functions pursued in optimization. However, as many articles adopt a multi-objective approach, they commonly fit into more than one group. The primary objective of CSLP is to minimize the costs associated with moving resources and mobile facilities, taking into account factors such as type, size, travel distance, handling time, worker hourly wages, and the cost of equipment used for transport [85].

The second most common goal is to enhance construction site safety by reducing risks from waste, hazardous materials, heavy machinery, and accidents. Decision-support systems are developed to help planners input data, which are then assessed and used for optimal planning [98].

The third article category focuses on comparing layout optimization models' outcomes. This analysis typically evaluates solutions based on factors such as distance reduction [87], cost savings [48], space utilization with varying geometric shapes [54], model complexity, and efficiency in reducing computational processing time [41].

Most researchers have focused on developing optimization models that generate optimal construction site layouts through various algorithms. However, less attention has been given to the methods for evaluating and selecting the best site layout produced by these models. Project cost is often included in optimization models as part of the objective function.

Finally, some studies aim to shorten the project timeline or reduce its criticality by optimizing the construction site layout. Efficient planning of temporary facility layouts enables construction planners to position facilities strategically, reducing the travel distance for materials and equipment, which helps minimize the overall construction duration. This approach reduces the distance traveled between temporary facilities based on their respective flow requirements. Unlike the cost reduction category, this method does not assign transportation costs [99].

2.4. Systematic Layout Planning

The traditional concept of SLP is a structured process consisting of phased steps and guidelines for identifying, assessing, and visualizing the elements and spaces involved in layout planning [100]. SLP can also be described as a procedural method that aids in generating and analyzing data using knowledge-based rules [5]. Its main objective is to reorganize the workspace to ensure the most efficient layout, ultimately maximizing the operation's productivity [101].

Figure 2 outlines the sequence of SLP procedures, showing the outputs at each stage.

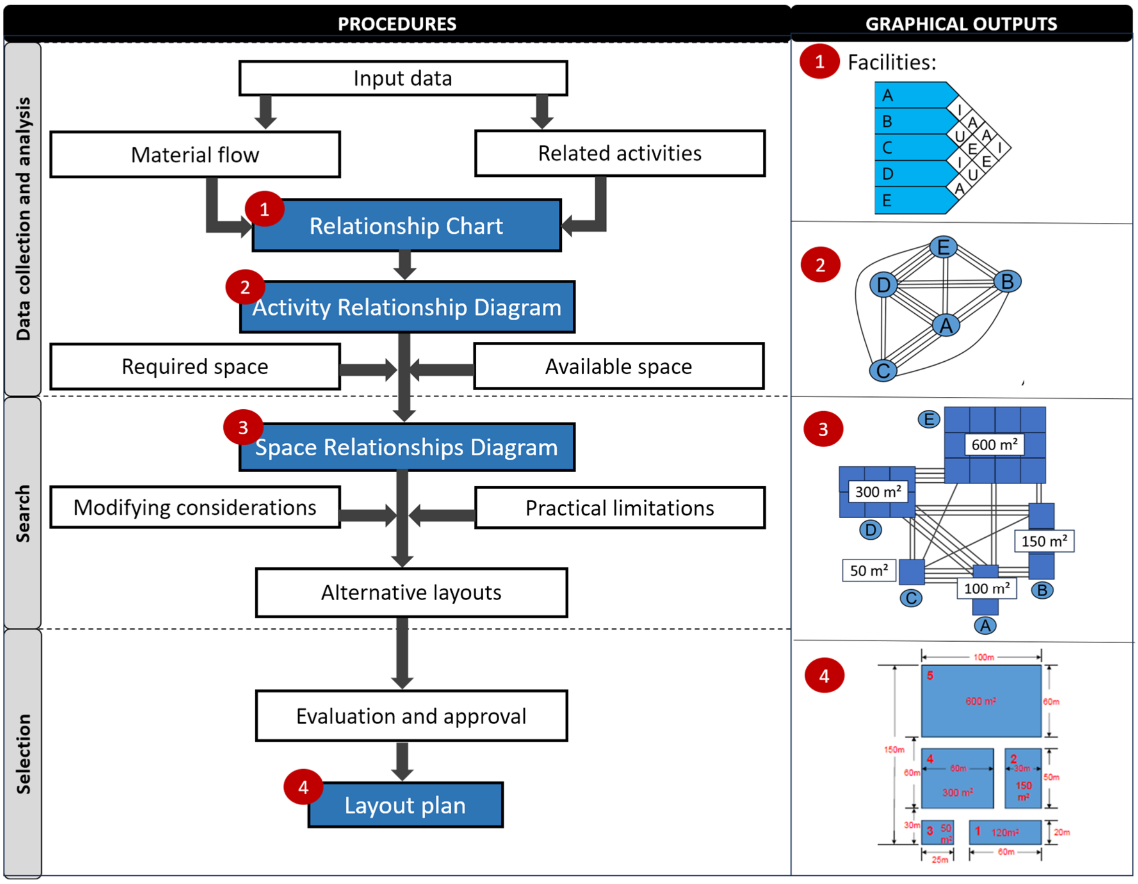

Figure 2. Overview of the Systematic Layout Planning (SLP) procedures. This figure illustrates the structure of the SLP method, organized into three main phases: data collection and analysis, search for layout alternatives, and selection of the best solution. Blue rectangles highlight the critical steps that generate graphical outputs, which are depicted in the right of the figure.

SLP is built on three key principles: the relationships between activities in the layout; the amount, type, and shape of space needed for each activity area; and the alignment of relationships and space into an effective plan. By following these principles, planners can make better decisions and develop more efficient layouts. These foundations guide the sequential steps of SLP construction, which include data collection and analysis, exploring potential layout solutions, evaluating alternatives, and selecting the most suitable layout [102].

The initial step evaluates material flows between two areas and their related activities using the preferred interconnection chart. This tool enables the analysis of area pairs to determine their proximity, resulting in the activity relationship diagram. Each rhombus in the chart is assigned a value reflecting the proximity level [103].

Specific conventions for SLP were established: "A" for absolutely important, "E" for especially important, "I" for important, "O" for ordinarily important, "U" for unnecessary, and "X" for undesirable. The activity relationship diagram visually represents the activities identified in the interconnections chart, in which departments are depicted as similar geometric shapes connected by lines, where the number of lines between two areas corresponds to the value assigned [101].

In the second phase, the planner considers space requirements for departmental operations, machinery, equipment, and available site space to create an optimal layout [104]. The space interrelationship diagram is developed after gathering and analyzing the relevant data.

Next, a further analysis evaluates potential design modifications and assesses the feasibility of the proposed layouts. Each adjustment should be reviewed against practical constraints, such as costs, technical limitations, and safety concerns. The final step in the SLP process involves evaluating the alternative layouts and selecting the best proposal by comparing their advantages and limitations.

3. Materials and Methods

The Design Science Research (DSR) method was chosen as the research approach. DSR provides a structure and process for the investigation. DSR products are called artifacts [105]. They are human-made objects and can be understood by their purpose, function, and adaptability or as interfaces between a system's internal and external environments [106].

Artifacts are assessed based on their value or utility. They are classified into four types: constructs, models, methods, and instantiation. Moreover, they have the potential to enhance theories [107]. In this study, the artifact is a BIM-based framework for planning the construction site layout, inspired by SLP decision-making procedures.

Figure 3 shows the research design. It is divided into five stages: problem identification, suggestion, development, evaluation, and conclusion. For each phase, specific activities were outlined, leading to derived outputs that contribute to the progression of the study and the final framework implementation. More detailed explanations of each stage are provided in the following sections.

3.1. Problem Awareness

At this stage, a Systematic Literature Review regarding CSLP was conducted to understand the different approaches to construction site layout optimization, their limitations, and their advantages to identify the most appropriate one to solve the problem.

In the proposed framework, the integration between Dynamo, Python, and Revit 2023 plays a crucial role in automating the CSLP. Dynamo is used as a visual programming platform to prototype the computational tool, allowing for flexible, node-based programming. Python scripts are embedded within Dynamo workflows to introduce more complex functionalities, such as implementing a Genetic Algorithm for optimizing layouts. This algorithm generates multiple layout configurations by adjusting parameters and selecting the best solution. Dynamo's connection with Revit ensures that optimized layouts are directly visualized in the BIM environment, enabling detailed analysis and refinement of site layouts in real time. The results section presents additional details about the automation in Dynamo, the parameters of the Genetic Algorithm developed, and the final visualization in Revit, as these are outcomes of the artifact's construction.

The SLP methodology was chosen as the basis for inputting data into the computational tool to ensure flexibility in supporting decision-making. This approach allows users to engage actively in the planning process, enhancing the precision of the proposed layouts. Moreover, the SLP-based structure offers the tool adaptability, making it suitable for various construction contexts. This flexibility ensures that the tool can be applied effectively across different projects while maintaining the reliability and accuracy of decisions in site layout planning.

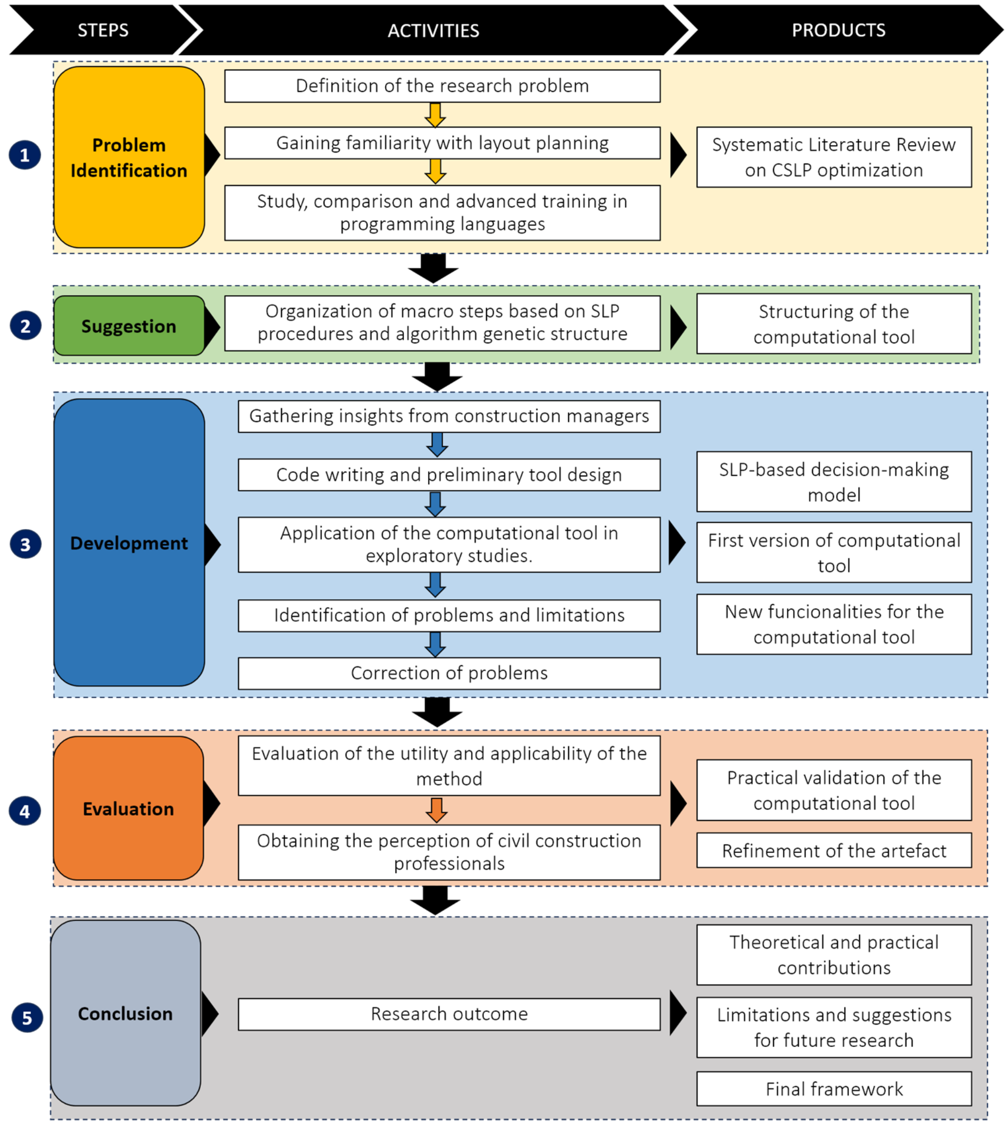

Figure 3. Research design. This figure presents the research design, illustrating the standard stages of Design Science Research (DSR), numbered from 1 to 5 and distinguished by colors. The activities performed are listed in the middle column, while the corresponding outcomes are detailed in the final column.

3.2. Suggestion

The suggestion stage relies on the abductive scientific method, where the researcher uses creativity and prior knowledge to convert descriptive information into principles for developing the artifact [106]. With the support of theoretical and empirical knowledge, macro steps were outlined to guide the framework's creation based on SLP procedures and the structure of a GA.

3.3. Development

The artifact development phase turned the proposed concept into a fully functional tool. This included coding and developing the preliminary version of the artifact. Throughout this process, feedback from five construction managers was integral to refining the system. As potential users, two of them offered insights during the development to ensure the tool aligned with real-world demands. They proposed changes to the SLP procedures and conventions, such as the scales and values for proximity relations. This collaborative effort resulted in the creation of the SLP-based decision-making model.

Following this, the tool was tested across three case studies, each guided by a different manager, to identify and address any issues before releasing the final version of the artifact. Considering each case study, the tool became increasingly refined, demonstrating improved robustness and efficiency. As feedback was incorporated, its ability to generate optimized layouts and address the complexities of different construction site conditions was enhanced, making the tool more reliable and adaptable for future use.

In the case studies, construction managers were first asked whether they followed any specific method for site layout planning. Afterward, they filled out the relationship matrix, indicating the need for proximity between elements. The tool then replicated the site's original layout.

An evaluation function implemented within the Dynamo routine calculated the sum of the weighted distances between elements, based on proximity requirements defined by the site manager. The computational tool then generated an optimized layout, and the Genetic Algorithm chose the best layout solution with a higher score. This allowed for a comparison between the initial and optimized layouts, with an indicator showing the improvement achieved.

3.4. Evaluation

The performance of the artifact is measured in DRS by the opinions of process professionals and knowledge experts. Throughout the development of this study, two potential users with expertise in construction planning collaborated in the study, evaluating and suggesting improvements to the artifact. At the end of the research, asynchronous focus groups were held with the employees who contributed to the case studies. A single, simultaneous focus group was not held due to scheduling conflicts among the professionals involved.

They evaluated the ease of using the method developed to plan the construction site, as well as its practical usefulness and the effectiveness of the results obtained.

3.5. Conclusions

In DSR, artifact performance is assessed through feedback from both process professionals and subject matter experts. During this study, two experienced managers in construction planning collaborated actively, offering valuable evaluations and suggestions to improve the artifact. After completing each case study, the three other construction managers tested and validated the tool, providing practical feedback on its effectiveness and further contributing to the refinement of the artifact.

4. Results

4.1. SLP-Based Decision-Making Process

This section outlines the decision-making process for Construction Site Layout Planning using the developed computational tool. First, the construction manager must fill out a spreadsheet with the facilities to be placed on-site and provide a basic BIM model of the building as input data. The customizable spreadsheet allows users to rename, add, or remove installations. A second column specifies the minimum area required for each facility.

Regarding SLP proximity rules, two levels were removed based on feedback from construction managers, simplifying and speeding up the categorization process. An even number of proximity levels was strategically chosen to avoid intermediate selections.

Additionally, relations were renamed for clarity and numerical codes were assigned. The final system uses four levels, ordered numerically by importance. Thus, the conventions of the computer tool to indicate the need for proximity between two installations are "3" for high importance, "2" for average importance, "1" for low importance, and "0" for irrelevant.

The evaluation model for the relationship between two facilities considers three factors: workflow, safety concerns, and manager preferences, such as wanting an office near the site entrance for convenience, regardless of workflow or safety concerns. This model was inspired by and adapted from previous work [5], which provided a foundational approach to evaluating relationships between facilities. The adaptations were made to better align with the specific needs and practical insights provided by the managers involved in this study.

In collaboration with experienced managers specializing in vertical construction projects, the ideal proximity relationship for each possible combination of decision-making factors was analyzed. This process involved assigning "low", "medium", or "high" values for each factor. These ratings were then combined to produce a proximity relationship value ranging from 0 to 3, where 0 signifies no proximity requirement and 3 represents a high-priority proximity need. The resulting proximity relationship framework, which was developed based on the insights provided during this collaborative effort, is detailed in Figure 4.

Condition	Workflow Intensity	Safety Concerns	Manager's preferences	Proximity Relationship	Value
C1	Low	Low	Low	Irrelevant	0
C2	Low	Low	Medium	Low importance	1
C3	Low	Low	High	Average importance	2
C4	Low	Medium	Low	Irrelevant	0
C5	Low	Medium	Medium	Low importance	1
C6	Low	Medium	High	Average importance	2
C7	Low	High	Low	Irrelevant	0
C8	Low	High	Medium	Irrelevant	0
C9	Low	High	High	Low importance	1
C10	Medium	Low	Low	Low importance	1
C11	Medium	Low	Medium	Average importance	2
C12	Medium	Low	High	High importance	3
C13	Medium	Medium	Low	Low importance	1
C14	Medium	Medium	Medium	Low importance	1
C15	Medium	Medium	High	Average importance	2
C16	Medium	High	Low	Irrelevant	0
C17	Medium	High	Medium	Irrelevant	0
C18	Medium	High	High	Low importance	1
C19	High	Low	Low	High importance	3
C20	High	Low	Medium	High importance	3
C21	High	Low	High	High importance	3
C22	High	Medium	Low	Average importance	2
C23	High	Medium	Medium	Average importance	2
C24	High	Medium	High	Average importance	2
C25	High	High	Low	Low importance	1
C26	High	High	Medium	Low importance	1
C27	High	High	High	Low importance	1

Figure 4. Proximity relationship selection. This figure illustrates the possible combinations of decisions made by managers regarding the three analysis factors for each pair of facilities, resulting in a total of 27 combinations. The penultimate column presents the name of the proximity relationship, while the last column displays the relationship value, which is used to calculate the weighted distances of layout solutions. This figure only demonstrates the underlying decision-making process, which is not directly visible to the manager.

In this way, for each facility pair, managers must assign values of "High", "Medium", or "Low" for each factor. These ratings are then combined to determine a proximity relationship value from 0 to 3, based on Figure 4. CSOF captures decisions regarding these three factors in the relationship matrix, which functions similarly to the preferential interconnections chart used in SLP, as illustrated in Figure 5.

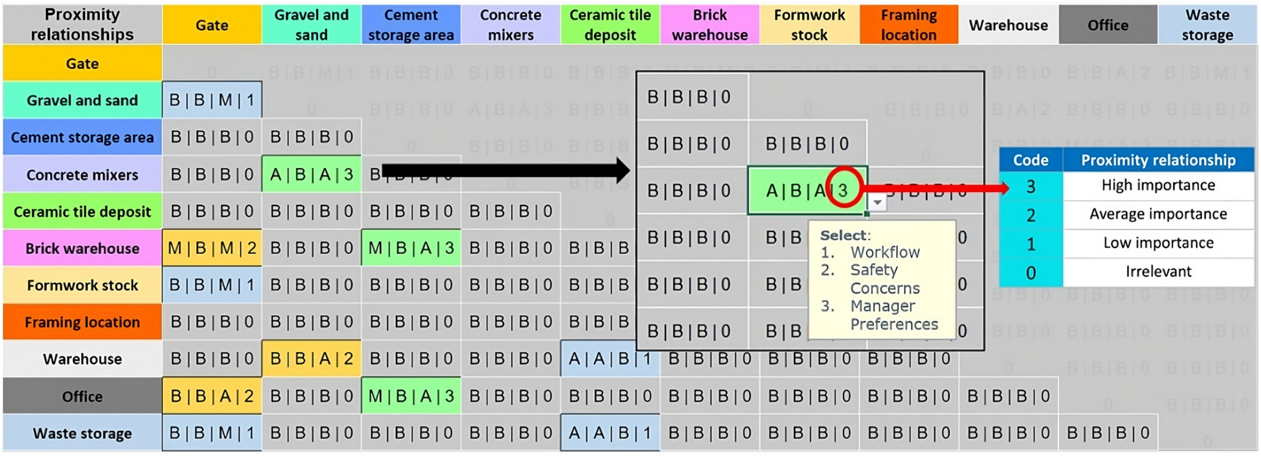

Figure 5. Filling in the relationship matrix.

When hovering the mouse over each cell, a legend appears to remind the user of the proximity rules, as illustrated in Figure 5 The letters "A", "M", or "B" are displayed, representing high, medium, and low (from the Portuguese "Alto", "Médio", and "Baixo") for the workflow, safety, and manager preference factors, respectively. The cell then displays the condition and assigns the proximity value according to the chosen inputs. The colors assigned to the cells aid in visualization, and the texts with the names of the facilities are automatically filled in based on the facilities selected by the user at the outset. Once the decision-making is complete, the computational tool generates the optimized layout.

4.2. Exploratory Studies

Throughout the research, CSOF was tested in three exploratory studies with construction sites of varying formats, constraints, elements, and user preferences. These tests aimed to identify and address tool limitations to reach the final version of CSOF. The process began with semi-structured interviews to assess the existence of structured planning procedures. In all three studies, construction managers reported that their companies lacked a formal and systematized method for construction site planning. Instead, CSLP was performed intuitively, relying primarily on the managers' personal experience and expertise.

Managers were then introduced to CSOF and completed the relationship matrix with site-specific facilities. Simulations were run to compare the original and optimized layouts, and the optimization indicator was calculated. The results of these studies are presented in the following sections.

- First case

The proposed optimization framework was used in a small housing project already carried out by this manager, whose planned land area was 300 m^2 and the construction area was 157.92 m^2.

First, the manager listed the temporary facilities at the construction stage. In the computer tool's configurations, the access gates for people and materials were considered fixed because their locations were predetermined and dependent on factors such as the street. The lifting winch was also a fixed element because its location analysis has a greater capacity than the algorithm can handle.

In addition to these elements, 14 facilities were added to the matrix to be positioned on the construction site as a continuous space. Their dimensions vary according to the minimum area indicated by the manager. After deciding the need for proximity between the elements, he filled in the relationship matrix (Figure 6).

<table>
<tr><th>N</th><th>Proximity Relationships</th><th>People Access</th><th>Material Access</th><th>Concrete mixers</th><th>Cement storage area</th><th>Gravel and sand</th><th>Formwork stock</th><th>Framing location</th><th>Brick warehouse</th><th>Electric winch</th><th>Waste storage</th><th>Warehouse</th><th>Worker dormitory</th><th>Canteen</th><th>Kitchen</th><th>Office</th><th>Sanitary</th></tr>
<tr><td>1</td><td>People Access</td><td>0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|A|2</td><td>B|B|B|0</td></tr>
<tr><td>2</td><td>Material Access</td><td>B|B|B|0</td><td>0</td><td>B|B|B|0</td><td>M|B|M|2</td><td>M|B|B|1</td><td>M|B|B|1</td><td>B|B|B|0</td><td>M|M|A|2</td><td>B|B|B|0</td><td>M|B|A|3</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>3</td><td>Concrete mixers</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td><td>A|B|A|3</td><td>A|B|A|3</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>A|B|A|3</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>4</td><td>Cement storage area</td><td>B|B|B|0</td><td>M|B|M|2</td><td>A|B|A|3</td><td>0</td><td>M|B|M|2</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>5</td><td>Gravel and sand</td><td>B|B|B|0</td><td>M|B|B|1</td><td>A|B|A|3</td><td>M|B|M|2</td><td>0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>6</td><td>Formwork stock</td><td>B|B|B|0</td><td>M|B|B|1</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td><td>B|B|M|1</td><td>B|B|M|1</td><td>M|B|M|2</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>7</td><td>Framing location</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|M|1</td><td>0</td><td>B|M|M|1</td><td>M|B|M|2</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>8</td><td>Brick warehouse</td><td>B|B|B|0</td><td>M|M|A|2</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|M|1</td><td>B|M|M|1</td><td>0</td><td>A|B|M|3</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>9</td><td>Electric winch</td><td>B|B|B|0</td><td>B|B|B|0</td><td>A|B|A|3</td><td>B|B|B|0</td><td>B|B|B|0</td><td>M|B|M|2</td><td>M|B|M|2</td><td>A|B|M|3</td><td>0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>10</td><td>Waste storage</td><td>B|B|B|0</td><td>M|B|A|3</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>11</td><td>Warehouse</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>12</td><td>Worker dormitory</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td><td>M|B|B|1</td><td>M|B|B|1</td><td>B|B|B|0</td><td>M|B|M|2</td></tr>
<tr><td>13</td><td>Canteen</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>M|B|B|1</td><td>0</td><td>M|B|M|2</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>14</td><td>Kitchen</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>M|B|B|1</td><td>M|B|M|2</td><td>0</td><td>B|B|B|0</td><td>B|B|B|0</td></tr>
<tr><td>15</td><td>Office</td><td>B|B|A|2</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td><td>B|B|B|0</td></tr>
<tr><td>16</td><td>Sanitary</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>M|B|M|2</td><td>B|B|B|0</td><td>B|B|B|0</td><td>B|B|B|0</td><td>0</td></tr>
</table>

Figure 6. Decision-making for the case study 1. This figure displays the relationship matrix completed by the first manager during the exploratory study.

Five relationships with a high need for proximity, eight of medium importance, and seven of low importance were chosen, showing twenty relationships with some need for proximity. The predominance of these relationships is balanced between elements of production, storage, transportation, and access to the site. In contrast, almost all the relationships of the elements of living are irrelevant or unimportant.

The real construction site was represented in BIM to calculate and compare its weighted distances with those generated by CSOF, using the manager's selected proximity preferences. CSOF then generated a construction site based on the mathematical formulation developed in Dynamo and the Genetic Algorithm. Figure 7 shows the floor plan of the current construction site and the site generated by CSOF.

Figure 7. Visualization of construction sites in the first study. This figure presents the actual construction site layout at the top, showing how it was executed in practice, and the optimized layout generated by the framework at the bottom.

Fixed installations were identified in green, production and stock areas in red, and living areas in yellow. Although there are walls in the drawing, the manager stated that these would only be erected in later stages of construction; therefore, the only restriction was the entrance to the staircase to the upper floor.

Using the calculation built into Dynamo, the distances between the elements were calculated and multiplied by the ratio value. Figure 8 compares the sum of the weighted distances in both cases.

Sum of weighted distances (m)		Total reduction
Real construction site	388.49	159.21m
CSOF construction site	229.28	40.98%

Figure 8. Comparison of results from the first study. The first box displays the sum of the weighted distances obtained in the real and optimized construction sites. The second box shows the reduction in distance achieved through optimization, along with the corresponding percentage reduction.

On the construction site generated by CSOF, there was a reduction of 159.21 m, equivalent to a 40.98% reduction in the total distance resulting from non-value-added activities. This means that CSOF made it possible to meet the proximity preferences indicated by the construction manager substantially better.

After the tool generated the optimized layout, a quick evaluation with the manager focused on functional aspects of the site planning. One limitation identified was the lack of integration with production management, as CSOF focuses solely on spatial optimization. Although it uses a static model, the layout was effective for the site's needs during the construction phase. The manager appreciated its flexibility and potential for adaptation as the project evolves, considering it a promising tool for improving productivity and aiding decision-making in space planning.

- Second case

The study was carried out on a housing project with a planned land area of 3458.62 m^2 and a construction area of 1457.99 m^2. The construction manager began by defining available and restricted areas, listing temporary facilities, access points, and fixed elements. This included gates for personnel, cars, material entry, an elevator, and a hoist. Figure 9 shows the relationship matrix completed by the manager for this study, encompassing 16 elements.

N	Proximity Relationships	People Access	Material Access	Car Access	Concrete mixers	Gravel and sand	Formwork and Framing	Cement storage area	Brick warehouse	Elevator	Electric winch	Warehouse	Worker dormitory	Kitchen and canteen	Sanitary	Waste storage	Office
1	People Access	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|A|3
2	Material Access	B|B|B|0	0	B|B|B|0	B|B|B|0	M|B|M|2	M|B|M|2	B|B|M|1	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	B|B|B|0
3	Car Access	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|A|3
4	Concrete mixers	B|B|B|0	B|B|B|0	B|B|B|0	0	A|B|M|3	B|B|B|0	A|B|M|3	B|B|B|0	A|B|A|3	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
5	Gravel and sand	B|B|B|0	M|B|M|2	B|B|B|0	A|B|M|3	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
6	Formwork and Framing	B|B|B|0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
7	Cement storage area	B|B|B|0	B|B|M|1	B|B|B|0	A|B|M|3	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
8	Brick warehouse	B|B|B|0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
9	Elevator	B|B|B|0	B|B|B|0	B|B|B|0	A|B|A|3	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
10	Electric winch	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
11	Warehouse	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2
12	Worker dormitory	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0
13	Kitchen and canteen	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	0	M|B|M|2	B|B|B|0	B|B|B|0
14	Sanitary	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	M|B|M|2	0	B|B|B|0	B|B|B|0
15	Waste storage	B|B|B|0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0
16	Office	M|B|A|3	B|B|B|0	M|B|A|3	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0

Figure 9. Decision-making for case study 2. This figure displays the relationship matrix completed by the second manager during the exploratory study.

Five high-priority proximity relationships were chosen, ten medium, and one low, totaling sixteen. Unlike the first study, most high-priority relationships involved production and storage elements. The hoist had one medium-priority relationship, similar to the material gate. The highest-priority relationship, between the "Office" and "People access", was emphasized by the manager. Living elements received less focus, with some combined into a single spreadsheet cell.

After defining element relationships, the tool replicated the real construction site. Unlike the first study, this site had an irregular shape, causing disorderly element placement that did not fully meet proximity requirements. The Dynamo routine was revised, adjusting how X and Y coordinates were identified. After refining the relationship matrix and ensuring proximity rules were respected, CSOF generated a new layout based on the manager's input. Figure 10 shows both the real and CSOF-generated construction sites.

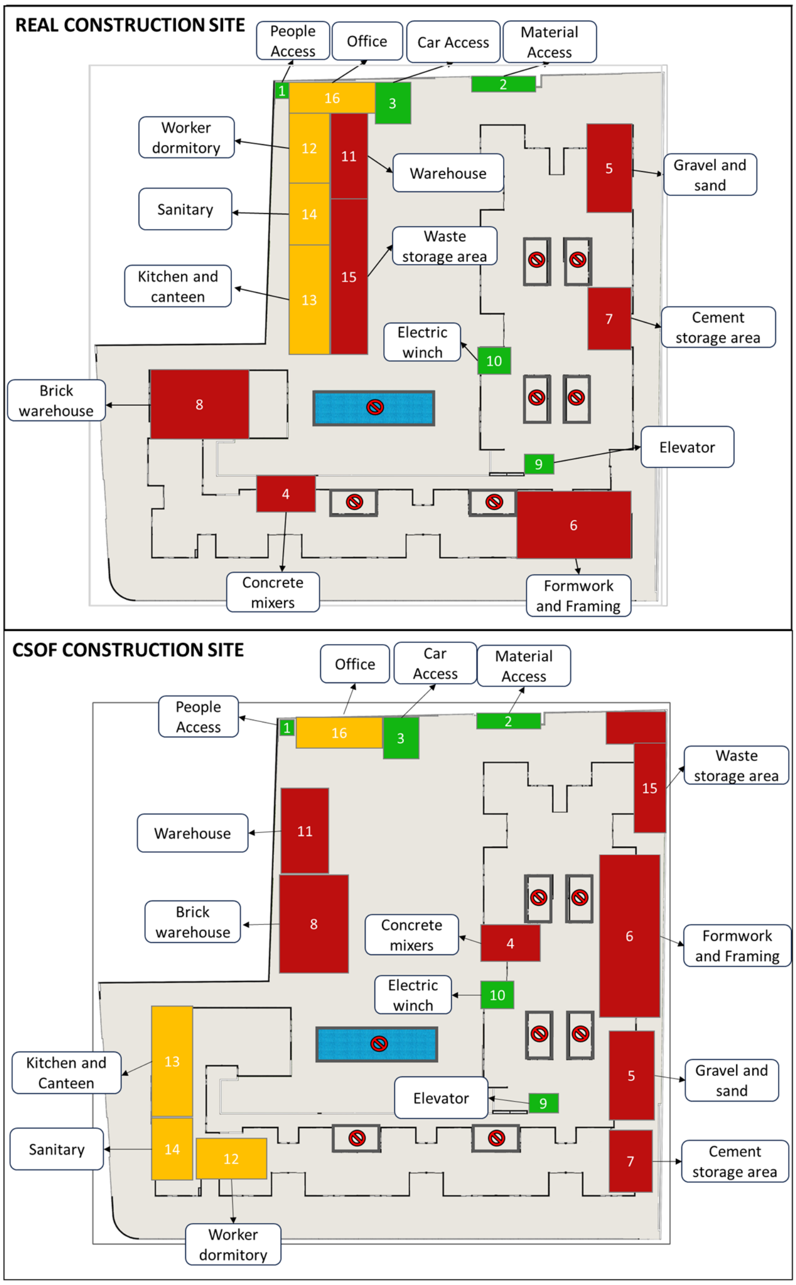

Figure 10. Visualization of construction sites in the second study. This figure presents the actual construction site layout at the top, showing how it was executed in practice, and the optimized layout generated by the framework at the bottom.

The weighted distances from both construction sites were combined, leading to a comparative analysis. As illustrated in Figure 11, the results showed a reduction of 291.17 m, which corresponds to a 31.63% decrease in non-value-added distances eliminated.

Sum of weighted distances (m)	
Real construction site	920.55
CSOF construction site	629.38

Total reduction
291.17m
31.63%

Figure 11. Comparison of results from the second study. The first box displays the sum of the weighted distances obtained in the real and optimized construction sites. The second box shows the reduction in distance achieved through optimization, along with the corresponding percentage reduction.

After generating the optimized layout, a discussion with the construction site manager validated its practical applicability. The manager commended the tool's improvement in recognizing unconventional terrain shapes, highlighting its potential to enhance operational efficiency. He emphasized the need to integrate planning with production data for better material displacement quantification and operational analysis. Additionally, he suggested exploring integration with the work schedule to create a comprehensive site plan.

- Third case

The third case study focused on a residential project with three different-sized towers (Blocks A, B, and C). Block A has four floors, Block B has five, and Block C has six, covering a total built area of 1589.51 m^2 on a 3392.74 m^2 site. Construction was divided into two phases, with Blocks A and B built simultaneously and Block C following later. Due to its phase limitations, the CSOF tool was only tested for Blocks A and B. Two gates provided access: one near Block A and another near Block C, which led directly to the basement.

Materials and equipment, including steel, gravel, sand, concrete mixers, and steel cutting and bending equipment, were stored in the basement. These materials arrived via the gate near Block C, which provided direct access to the basement due to the site's level difference. Figure 12 shows the relationship matrix filled in by the manager.

N	Proximity Relationships	Gate A	Gate C	Rack lift B	Electric Winch A	Concrete Mixers	Gravel	Sand	Formwork Stork	Brick warehouse	Warehouse	Waste storage area	Office	Dormitory and Sanitary	Kitchen and Canteen	MEP	Framing location
1	Gate A	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|A|3	M|B|A|3	B|B|B|0	M|B|M|2	B|B|A|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
2	Gate C	B|B|B|0	0	B|B|B|0	B|B|B|0	M|M|B|1	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|M|1
3	Elevator B	B|B|B|0	B|B|B|0	0	B|B|B|0	A|B|A|3	A|B|A|3	A|B|A|3	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|M|1	B|B|M|1
4	Electric Winch A	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|A|2	B|B|A|2	B|B|A|2	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|M|1	B|B|B|0
5	Concrete Mixers	B|B|B|0	M|M|B|1	A|B|A|3	B|B|A|2	0	A|B|A|3	A|B|A|3	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
6	Gravel	B|B|B|0	M|B|M|2	A|B|A|3	B|B|A|2	A|B|A|3	0	A|B|A|3	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
7	Sand	B|B|B|0	M|B|M|2	A|B|A|3	B|B|A|2	A|B|A|3	A|B|A|3	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
8	Formwork Stork	M|B|A|3	B|B|B|0	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
9	Brick warehouse	M|B|A|3	B|B|B|0	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|M|1
10	Warehouse	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|M|1	B|B|B|0
11	Waste storage area	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
12	Office	B|B|A|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0
13	Dormitory and Sanitary	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0	M|B|B|1	B|B|B|0	B|B|B|0
14	Kitchen and Canteen	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	M|B|B|1	0	B|B|B|0	B|B|B|0
15	MEP	B|B|B|0	B|B|B|0	B|B|M|1	B|B|M|1	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|M|1	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0
16	Framing location	M|B|A|3	M|B|M|2	M|B|M|2	M|B|M|2	B|B|B|0	B|B|B|0	B|B|B|0	B|M|A|2	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	B|B|B|0	0

Figure 12. Decision-making for case study 3. This figure displays the relationship matrix completed by the third manager during the exploratory study.

Nine relationships with a high need for proximity were chosen, fifteen of medium importance, and five of low importance, for a total of twenty-nine relationships with some need for proximity. As in the first study, most of the relationships that were considered important refer to elements of production, transportation, and storage.

The tool recreated the real construction site, designating gates A and C, the elevator, and the hoist as fixed elements. Restrictions included the staircases in Blocks A and B, with Block C's area on both the first and basement floors.

To make the computational tool more robust and realistic to real planning, we sought to incorporate the functionality of allocating elements to multiple floors.

The most feasible solution, which would not significantly increase computer processing, was to treat the two floors as one. Thus, the basement and first floor plans were combined on the same level, and a rule was imposed for allocating elements. With the exception of fixed elements, those that needed to be allocated had to choose only one of the floors to be positioned according to their priorities.

Considering that some installations need to be close to each other, even though they are on different floors, a way for the tool to account for these distances needed to be developed. Thus, the new rule imposes that if elements that have been allocated to different floors have a relationship, the distance between them will be the sum of the paths of each one to the fixed element connecting the floors. Figure 13 shows both the real and CSOF construction sites.

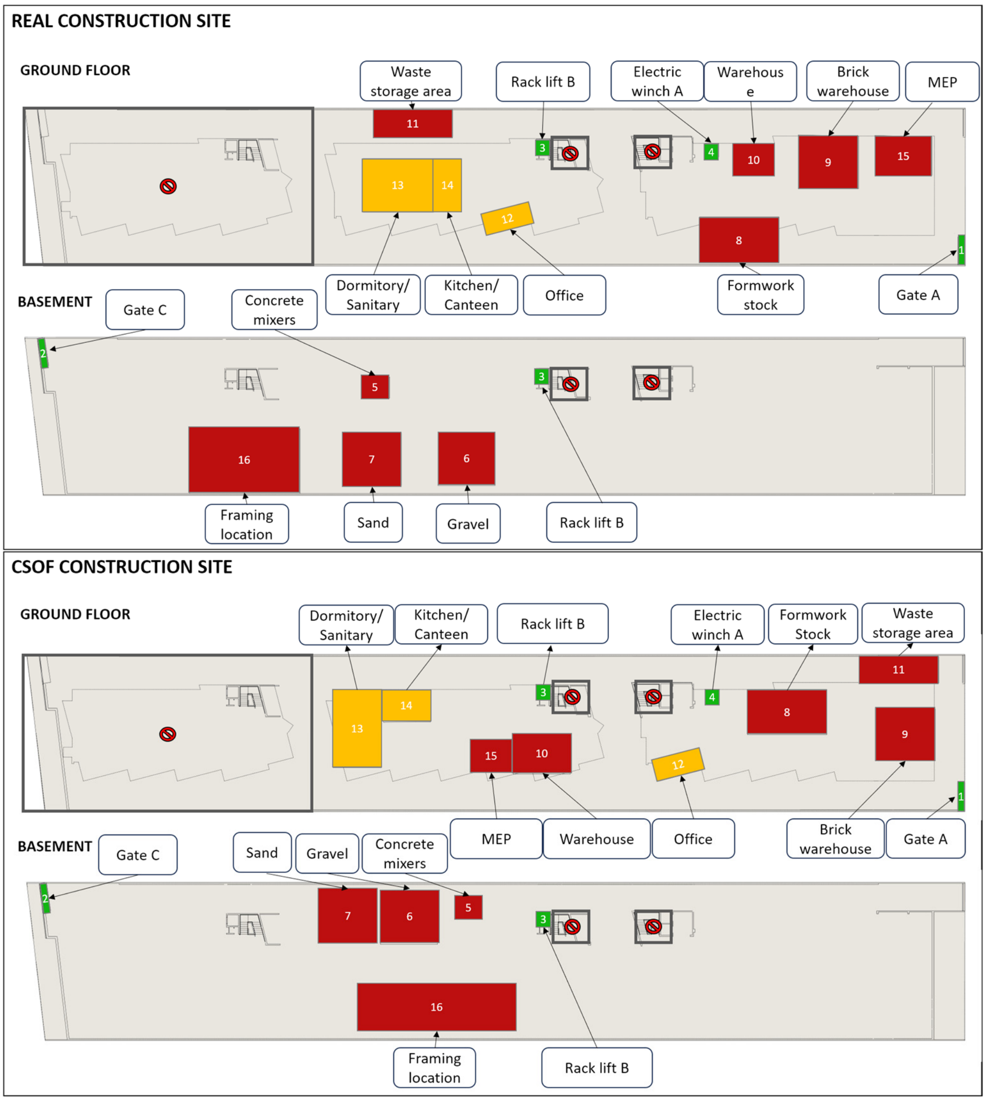

Figure 13. Visualization of construction sites in the third study. This figure presents the actual construction site layout at the top, showing how it was executed in practice, and the optimized layout generated by the framework at the bottom.

Figure 14 compares the results obtained on the real construction site and the site generated by CSOF. Once again, the tool developed to plan the construction site layout proved efficient in reducing distances that do not add value, even with the higher level of logic required. There was a 30.79% reduction in weighted distances on the optimized site, which means that the planning carried out using CSOF could better meet the proximity rules assigned by the user.

Sum of weighted distances (m)	
Real construction site	2017.01
CSOF construction site	1395.8

Total reduction
621.21m
30.79%

Figure 14. Comparison of results from the third study. The first box displays the sum of the weighted distances obtained in the real and optimized construction sites. The second box shows the reduction in distance achieved through optimization, along with the corresponding percentage reduction.

The site manager validated the layout generated by the tool, noting that the positioning of elements made sense and led to a reduction in material movement, improving logistics and productivity. However, he raised a concern that using Euclidean distances might not reflect actual on-site paths, which can be longer due to obstacles. This limitation was highlighted as an area for future improvement to enhance planning accuracy. Overall, the validation confirmed the effectiveness of CSOF in creating both theoretically sound and practical solutions for construction site planning.

4.3. Discussion

Adapting SLP procedures for CSOF required fundamental changes to fit the dynamic nature of construction sites, unlike the static layouts of manufacturing facilities. In manufacturing, SLP organizes fixed elements with moving products, while in construction, temporary facilities shift as the project evolves. CSOF enhanced the SLP relationship matrix to improve usability, automating the process and using color to simplify proximity analysis, making it faster and more intuitive. Additionally, CSOF considers workflow intensity and safety concerns when determining element proximity, creating more efficient layouts tailored to construction dynamics.

Regarding the decision-making process, it is important to notice that this framework offers flexibility for construction managers to make informed decisions based on their understanding of key factors such as safety, workflow intensity, and other project-specific needs, and its main objective is to reduce non-value-adding distances by optimizing logistics through decision-making processes that consider these three factors. In this way, BIM is utilized primarily as a visualization and data management tool rather than directly enhancing safety or reliability.

While safety is indeed a priority, it is integrated as part of the manager's input rather than an explicit output driven by the BIM platform. When managers consider safety as a decision factor, they can specifically decide, for each pair of facilities, whether to bring them closer or keep them apart due to potential risks associated with their proximity. Regarding reliability, unlike automated solutions that impose predefined proximity rules, the proposed framework optimizes layouts based on the manager's input, thus supporting their strategic decisions. This personalized approach increases trust in the tool, as it reflects the manager's planning choices rather than rigid, pre-set criteria.

Unlike earlier studies that integrated SLP and BIM using predetermined locations, the CSOF continuous-space approach enables elements to be positioned flexibly within the construction site while respecting set constraints. Post-generation adjustments to the layout are simplified, and BIM plays a key role by providing detailed visualizations that enhance problem detection and adjustment. Integrating a Genetic Algorithm further expands layout possibilities by offering multiple potential solutions and optimizing based on weighted distances. Although dynamic changes in project phases are not yet accounted for, this approach significantly enhances operational efficiency and minimizes unnecessary displacements. The combination of SLP with BIM and Genetic Algorithms maintains the optimization logic, adapting it effectively for construction site planning.

Regarding layout solutions, the comparative analysis of the three case studies highlighted that several factors, such as terrain shape, number of facilities, and spatial constraints, directly influence a reduction in non-value-adding distances. Figure 15 summarizes the results.

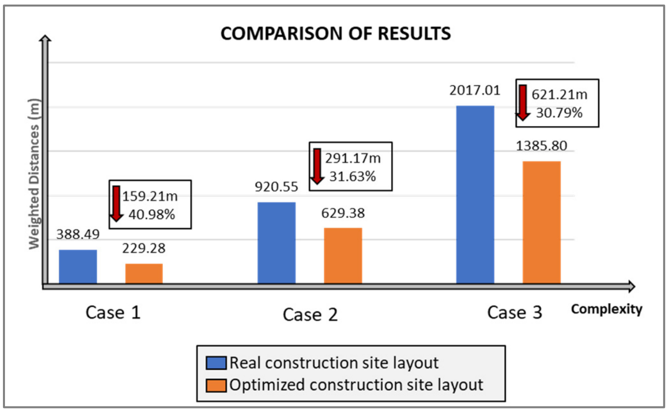

Figure 15. Comparison of results from the third study. The first box displays the sum of the weighted distances obtained in the real and optimized construction sites. The second box shows the reduction in distance achieved through optimization, along with the corresponding percentage reduction.

In the first case study, a rectangular layout resulted in a 40.98% reduction, benefiting from fewer restrictions and a more straightforward optimization process.

In contrast, the second case, involving a non-conventional site and more fixed elements, was reduced by 31.63%. The irregular terrain and increased restrictions led to a minor optimization, showing a 9.35% difference compared to the first case due to stricter limitations in flexibility and planning.

In the third case, which incorporated two-floor planning, the reduction was 30.79%. Although the terrain and structure were more similar to the first case, the added complexity of multi-floor planning slightly reduced the tool's efficiency in minimizing distances. However, the result still reflects effective optimization, given the added challenges.

Overall, the results suggest that as the site complexity increases, the tool's ability to reduce non-value-added distances decreases. A pattern emerged where smaller, more constrained sites allow for better optimization as fewer options exist for element allocation, simplifying the search for optimal solutions. The tool faces more possibilities and more significant computational effort to find an efficient layout on more significant sites, often yielding less significant improvements.

The algorithm's current setup tests the same number of solutions regardless of site size, favoring optimization in smaller sites. While increasing the number of tested solutions could enhance results for more significant sites, it would also increase computational time, raising the need to balance efficiency and processing costs.

Future studies are recommended to confirm these findings across different types of construction projects and offer insights into how the tool can be adapted for more complex scenarios. This would help generalize the results and further improve the CSOF performance, particularly in multi-floor and high-restriction environments, maximizing the reduction in non-value-added distances even in challenging conditions.

4.4. Construction Site Layout Planning Framework

Figure 16 shows the structure of the final version of CSOF, improved after carrying out case studies and validated in focus groups. Several limitations were overcome, providing new functionalities and a better representation of a real construction site. Its development also focused on the efficient automation of SLP and ensuring flexibility in the manager's decision-making.

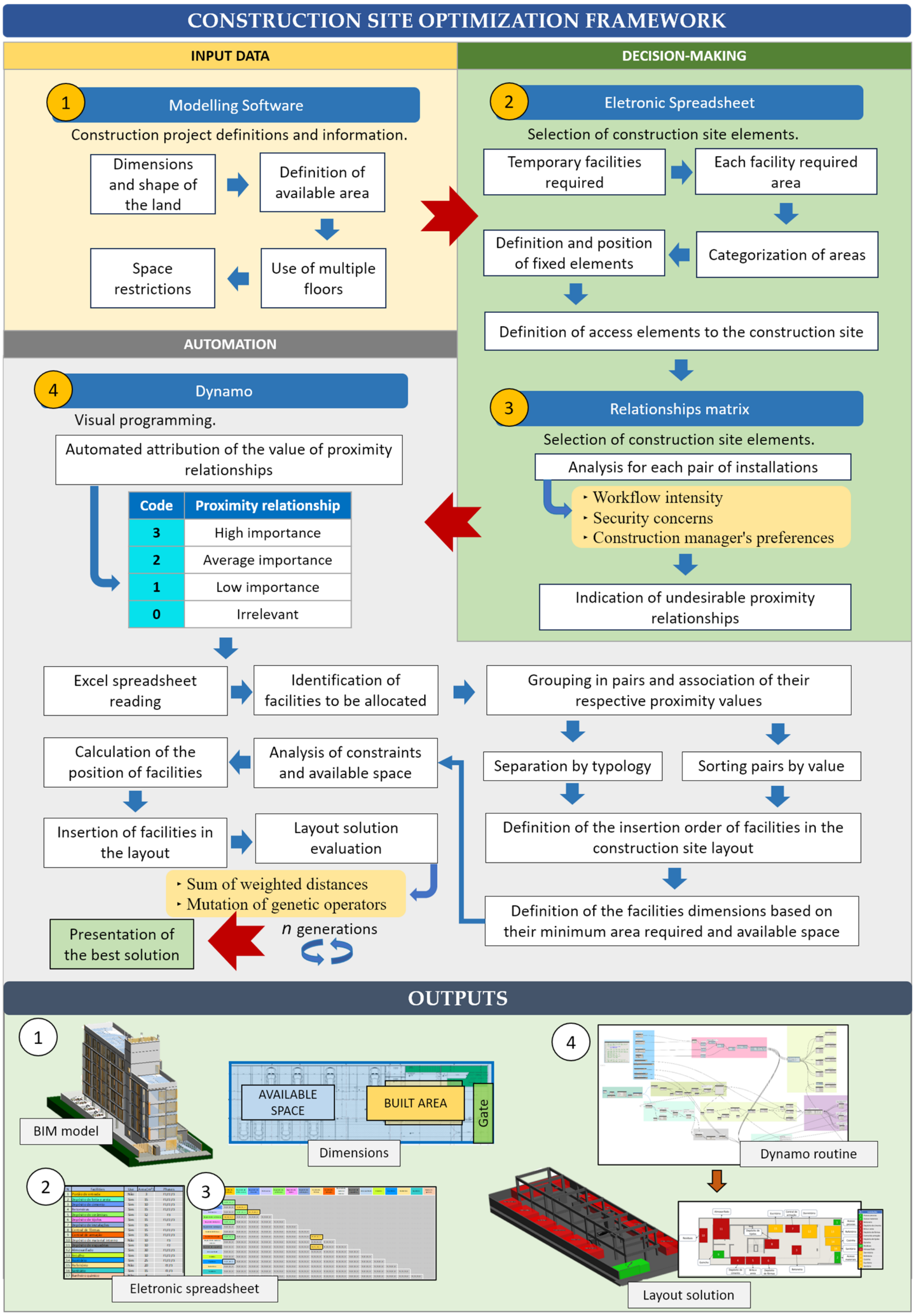

Figure 16. CSOF structure. This figure represents the final design of the CSOF developed in this research. Colors differentiate the backgrounds of the three stages: input data are yellow, decision-making is green, and automation is grey. Blue arrows indicate the flow of steps within a stage, while red arrows represent the transition between stages, leading to the final solution. Numbers are associated to indicate the graphical outputs at the figure's bottom.

The artifact was structured in three stages. The first is inputting data using Revit modeling software. The model is inserted by activating the CSOF plugin, and terrain information, such as dimensions and shape, is obtained. Then, the user defines the available area on the construction site and the built area. The latter is an area unavailable for allocating construction site elements. Unlike a restriction area, this one allows the circulation of people and materials. Moreover, at this stage, the possibility of using multiple floors to allocate the elements and identify space restrictions, where facilities cannot be positioned for any reason, must be addressed.

The second stage is where decisions will actually be made. In a spreadsheet linked to the CSOF, all the elements required on the site must be entered, including temporary facilities, production storage and living areas, vertical transportation elements and access to the site. They must all be included because they are related to each other, and their location directly influences the efficiency of the work.

In the spreadsheet, each element must have its minimum required area entered and then be categorized into two groups: storage and production areas and living areas. This categorization serves to differentiate the elements by color in the final solution. Afterward, the elements with a fixed starting position must be listed and positioned correctly in the layout. The same procedure applies to access elements to the site, such as the material entrance gate and access for people, which are automatically considered fixed. In the final solution, these fixed elements appear in green, while storage and production areas are highlighted in red and living areas in yellow.

The next step in the decision-making stage is to fill in the relationship matrix. The elements listed in the previous spreadsheet automatically appear in the matrix, ready for the proximity needs between each pair to be assigned. The proximity analysis is based on three factors: workflow intensity, security concerns, and the manager's preferences. Each factor must be assigned a level of importance ("low", "medium", or "high"). Combining these criteria will determine the need for proximity between the elements. Only the relationships that have some importance need to be filled in; the rest are automatically considered irrelevant. Finally, it is necessary to inform whether any relationships with undesirable proximity between the elements exist.

The automation process carried out by Dynamo then begins. GA runs the routine several times, and each time, it changes three parameters during the optimization process which are the order of distribution, distances between elements, and dimensions of elements.

- Order of distribution: The sequence in which the elements are arranged on the construction site. This order is critical, as it influences how efficiently the layout meets proximity and space requirements.
- Distances between elements: The algorithm adjusts the distance between facilities to minimize unnecessary movements and optimize the overall workflow while considering safety and manager-defined preferences.
- Dimensions of elements: The dimensions of each facility are adjusted, respecting the minimum area requirements specified by the manager. This ensures that the layout complies with practical constraints while allowing flexibility in the optimization process.

These parameters allow the Genetic Algorithm to iteratively search for an optimized construction site layout that effectively balances workflow, safety, and other constraints. By varying these aspects, the algorithm performs a comprehensive exploration of possible configurations, resulting in a layout that enhances site efficiency.

As with the preliminary version of the artifact, the objects in the construction site are arranged using a continuous-space approach, allowing the algorithm a more comprehensive search range.

To significantly reduce processing time and the need for advanced equipment or infrastructure, factors that can make it difficult to adopt more complex methods, the objects are represented as stationary elements with approximate geometry, differing only in size. The distinction between their dimensions is made based on the minimum area defined by the user and the space available on the construction site, which is another difference from previous studies.

GA searches for the best solution among those generated and identifies whether it also meets the distance between elements in undesirable proximity. Its operation is divided into the following five stages:

- Generation of layout solutions:

GA generates multiple layout configurations guided by calculations embedded within Dynamo. This ensures that the initial generation of layouts considers proximity needs and spatial constraints from the outset, aligning with the structured logic of SLP.

- Fitness evaluation:

The evaluation of the solutions is similar to that of SLP, which is measured by the sum of the weighted distances. GA uses a fitness function, which measures the efficiency of the layout based on proximity requirements. This is quantified by calculating the sum of weighted distances between all pairs of facilities for each layout. The distance between two elements is multiplied by their proximity value (0, 1, 2, 3). A lower total score indicates better adherence to proximity needs, meaning that elements requiring closer proximity are placed nearer to each other.

- Undesirable Proximity Check:

In addition to minimizing distances, the algorithm evaluates whether elements are too close to those they should be kept distant from. Solutions receive a penalty if such conditions are detected, lowering their fitness score.

- Selection and Optimization:

The GA iterates through multiple generations, selecting the best-performing layouts, combining them, and introducing small mutations to generate new solutions. This iterative process continues until an optimal or near-optimal solution is found.

- Visual feedback:

Visualization of the best solution is generated in Revit, allowing stakeholders to review the layout in a visual format. Also, a report with location data, dimensions and areas of the facilities, and the weighted distance score are generated. Minor adjustments to the positioning of elements can easily be made after the final result and the score is recalculated to confirm the impact of those changes.

An efficiency indicator works after GA's operation. Its primary function is to quantify the efficiency achieved by optimizing the construction site layout, serving as a validation tool. However, the indicator is not utilized when the goal differs from comparing to a previous layout. It calculates the percentage reduction in the distances traveled between the main elements of the construction site compared to the original layout. This value objectively expresses the gain regarding reduced displacements, providing a clear metric for assessing the impact of space restructuring. By being associated with the score generated by the tool, the indicator acts as an additional parameter in the quantitative analysis, facilitating decision-making based on the actual improvement achieved in site planning.

The created performance indicator played a crucial role in objectively measuring the efficiency of the optimized construction site layout. Comparing the percentage reduction in distances traveled between the main elements of the real and optimized layouts provided a clear metric of the actual impact of the optimization. This allowed managers to visualize the gains made by reorganizing the space directly, facilitating comparisons and justifying changes, resulting in the practical validation of the artifact developed.

5. Conclusions

This study contributes to CSLP by developing a hybrid computational framework integrating SLP principles with the BIM platform. The framework provides a visual approach to planning, focusing on efficiently positioning temporary facilities while evaluating critical factors such as workflow, safety, and managerial preferences. An essential contribution is its capacity to embed decision-making processes into spatial planning, potentially increasing operational efficiency by optimizing on-site logistics. The framework's hybrid approach blends automation with professional expertise, allowing for the quick generation of multiple layout options while requiring minimal initial data input. It facilitates rapid decision-making without the extensive processing times demanded by other methods.

The core innovation of this study lies in developing a highly flexible and manager-driven framework that surpasses the limitations of existing methods. Unlike previous studies that rely on rigid grid-based or predetermined layouts, this framework employs a continuous-space model, allowing the algorithm to position facilities freely. This approach accurately reflects real-world conditions, with approximate geometry based on minimum required areas for object representation. Managers are given comprehensive control over defining constraints, available spaces, and access points, which is an uncommon level of flexibility in the existing literature.

Another key differentiator is the framework's unique integration of automated processes with human expertise. Decisions regarding workflow, safety, and other proximity factors are directly informed by the manager's practical experience and professional judgment rather than being constrained by fixed criteria. This manager-driven approach ensures that the outcomes align closely with actual site strategies and priorities, fostering trust in the framework's adaptability and reliability.

By simplifying the planning process, the framework addresses a significant gap in the literature regarding the complexity of advanced Construction Site Layout Planning methods, which often deters their adoption. The exploratory case studies validated the framework's flexibility and simplicity, demonstrating its ability to optimize layouts while minimizing the input data and effort required. This simplicity makes the framework accessible to practitioners without advanced technical expertise, empowering construction managers to optimize site layouts effectively.

Based on the analysis of the three case studies, the CSOF demonstrated varying degrees of effectiveness in reducing non-value-adding distances, influenced by the site's complexity and constraints. For instance, with a straightforward rectangular layout, the first case achieved a 40.98% reduction due to fewer spatial restrictions. Conversely, the second case, involving irregular terrain and more fixed elements, saw a lesser reduction of 31.63%, highlighting the impact of increased constraints on optimization. The third case, which included multi-floor planning, resulted in a 30.79% reduction, reflecting the additional challenges introduced by planning across multiple levels.

The observed pattern suggests that smaller, more restricted sites are optimized more efficiently due to fewer allocation options, while larger sites require more significant computational effort to achieve similar results. As project complexity increases, factors such as limited space, the number and type of facilities, proximity needs, spatial restrictions, fixed-position elements, multi-floor allocations, and irregular site shapes diminish the tool's effectiveness in minimizing non-value-adding distances. Despite these challenges, the framework significantly improves efficiency across simple and complex scenarios.

However, the tool has limitations. Its accuracy depends on the input data and active participation from construction managers in defining proximity relationships. As a decision-based framework, managers must have prior experience to avoid errors. There is also potential for bias, as the framework reflects the managers' opinions who contributed insights during its development, particularly in determining proximity relationships. To mitigate this, and given that the managers are specialists in vertical construction projects, the framework is most suitable for similar contexts. For other scenarios, such as modular construction, gathering input from domain-specific experts is recommended.

Future research could enhance the computational framework by integrating optimization algorithms that balance precision and processing speed, especially in complex scenarios. Investigating machine learning techniques to predict workflow patterns and automatically establish proximity relationships could further minimize manual input. Expanding the study with additional case studies across various layout types and spatial constraints would validate the framework and enhance its applicability in diverse construction settings.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author because they are part of an ongoing doctoral research project. The data will be made publicly accessible after completing the doctoral course.

Conflicts of Interest: Author Ari Monteiro was employed by the company Dharma Sistemas. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

This section refers to the operationalization of the Systematic Literature Review. The strategy adopted for the SLR is illustrated in Figure A1.

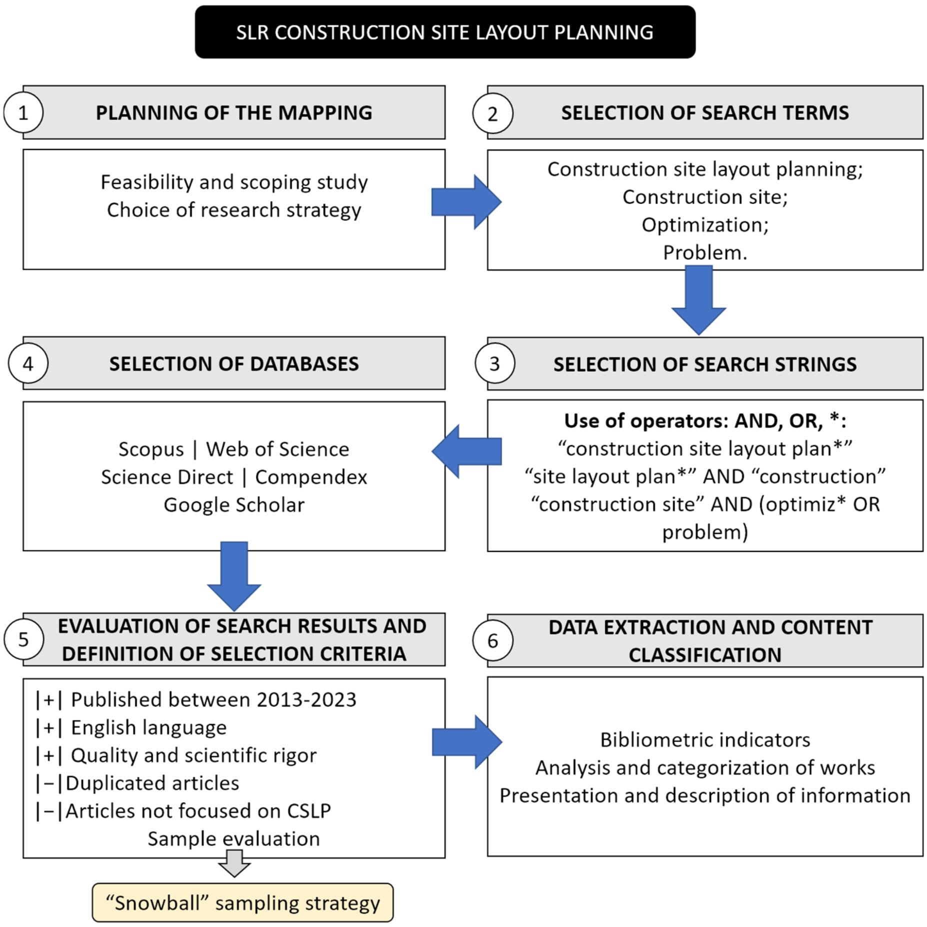

Figure A1. Systematic Literature Review strategy.

The SLR was limited to articles published between 2013 and 2023 in the English language. The articles were collected in Scopus, Science Direct, Web of Science, and Compendex. At first, the search terms were "construction site layout plan*", which should appear in the title, abstract, or keywords.

Publications that did not directly address the topic in question were subtracted. Next, a critical analysis of the chosen sample was carried out. From this, the Snowball strategy was conducted, in which it identified other relevant publications that were not identified in the initial search.

After analyzing these studies, it was decided to perform a new search, but with different terms, as it was seen that some of them did not use the chosen search terms. Thus, the terms "site layout plan *", "construction site", "optimiz", and "problem" were included.

In a more critical analysis of the quality of the studies, 69 articles were selected. In the data extraction and classification stage, bibliometric indicators were established to characterize the state of the art. The bibliometric indicators will be presented in the following topics.

- Temporal evolution

The temporal evolution of the articles is illustrated in Figure A2. It can be observed how the subject has gradually gained more attention over the last decade.

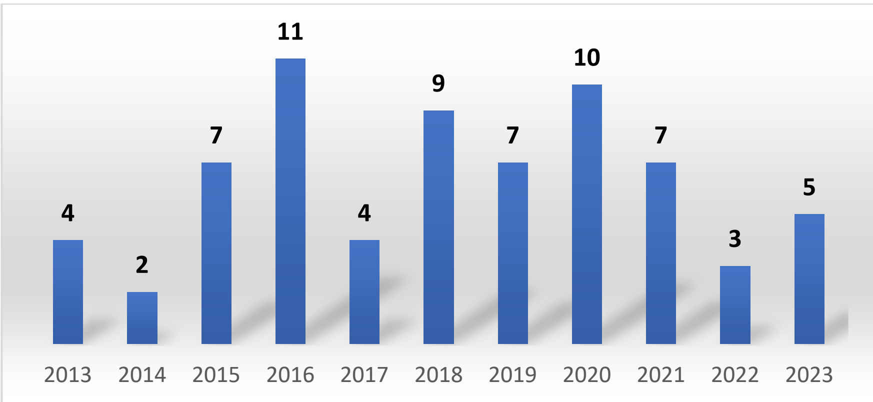

Figure A2. Temporal evolution of publications.

- Most used publication vehicles

A total of 33 different publication vehicles were recorded, of which 39 were journals and only 3 were scientific events. This shows that the complexity of site layout optimization leads authors to disseminate their research in media with more scientific rigor and credibility. Figure A3 illustrates these results.

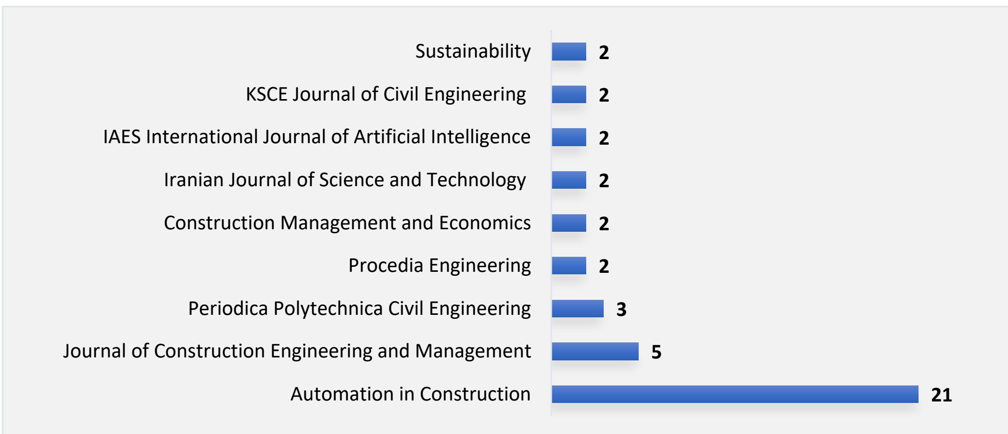

Figure A3. Main publication vehicles.

In addition to these, the others that had one publication are shown in Table A1.

Table A1. Other publishing vehicles.

Title	Type
Advanced Engineering Informatics	Journal
Alexandria Engineering Journal	Journal
Journal of Algorithms	Journal
Applied Sciences	Journal
Asian Journal of Civil Engineering	Journal
Computers and Operations Research	Journal
Construction Innovation	Journal
Construction Management	Journal
Engineering with Computers	Journal
Evolutionary Intelligence	Journal
Infrastructures	Journal
International Journal of Civil and Environmental Engineering	Journal
International Journal of Civil Engineering	Journal
Journal of Building Engineering	Journal
Journal of Cleaner Production	Journal
Journal of Computing in Civil Engineering	Journal
Journal of Construction Engineering and Management	Journal
Journal of Infrastructure Systems	Journal
Ksce Journal of Civil Engineering	Journal
Neural Computing and Applications	Journal
Organization Technology and Management in Construction	Journal
Safety Science	Journal
Scientia Iranica	Journal
Structure and Infrastructure Engineering	Journal
4OR—A Quarterly Journal of Operations Research	Journal
Canadian Society of Civil Engineering Annual Conference	Event
Computing Conference	Event
Construction Research Congress	Event
International Conference on Construction and Real Estate Management	Event
International Symposium on Automation and Robotics in Construction	Event

- Most chosen keywords

The authors used 236 different keywords in the articles. The most frequently used are presented in Figure A4.

- Technologies for CSLP

The use of technologies for data collection and processing was identified in some studies. Figure A5 shows these data.

- Main optimization approaches

Researchers widely selected Genetic Algorithms (GAs) for tasks such as solving mathematical models, supporting rule-based decision-making, finding solutions using

GIS data, or evaluating layouts. Additionally, Knowledge-Based Reasoning (KBR) and Particle Swarm Optimization (PSO) were each applied in eight studies, while seven other algorithms were used, individually or in combination, to generate layouts in various research contexts. Figure A6 visually represents these data. Meanwhile, Table A2 provides the full names of all algorithms applied in the studies reviewed.

- Publications by objective function

The most covered topics in studies are shown in Figure A7. It should be noted that the sum of these values is greater than the number of papers, as some of them have multiple optimization objective functions.

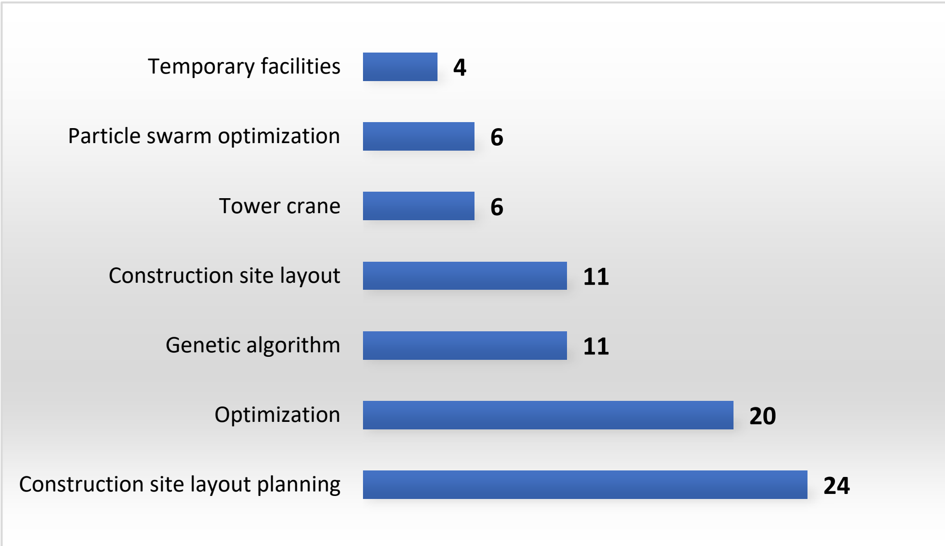

Figure A4. Most frequently used keywords.

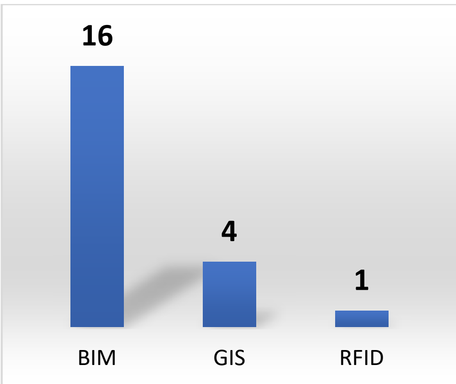

Figure A5. Technologies for CSLP.

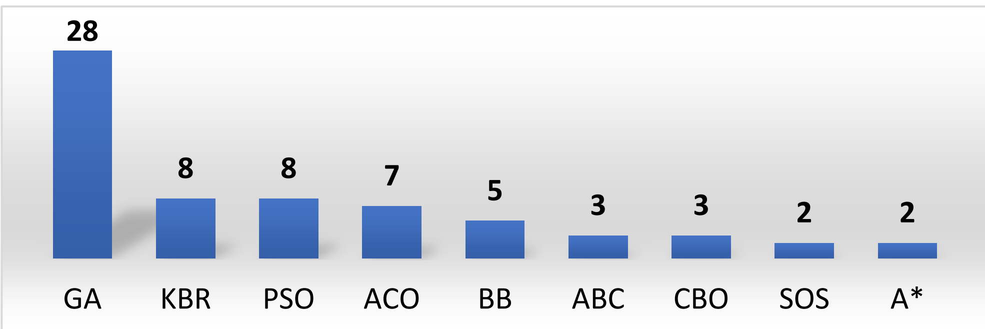

Figure A6. Main optimization approaches.

Table A2. List of optimization approaches.

Abbreviation	Method
A*	A* Search algorithm
ABC	Artificial bee colony
ACO	Ant colony optimization
ADP	Approximate Dynamic Programming
ANP	Analytic network process
BB	Branch-and-bound algorithm
CBO	Colliding bodies optimization
CCM	Cardinal class method
CPA1	Cutting plane algorithm
CSA	Cuckoo search algorithm
CSS	Charged System Search
DEA	Differential evolution algorithm
.	Dijkstra's algorithm
ECBO	Enhanced colliding body optimization
EVPS	Enhanced vibrating particle system
FA	Firefly algorithm
GA	Genetic Algorithm
GPAWOA	Guided Population Archive Whale Optimization Algorithm
MCSS	Magnetic Charged System Search
MTPE	Minimum total potential energy
PSO	Particle Swarm Optimization
KBR	Regras baseadas no conhecimento
SA	Simulated Annealing
SCA	Sine Cosine Algorithm
SOS	Symbiotic organisms search
VPS	Vibrating particles system
EO	IBM CPLEX Optimizer
EO	SCIP Optimization Suite
EO	Mixed-integer programming
EO	Método augmented ϵ-constraint

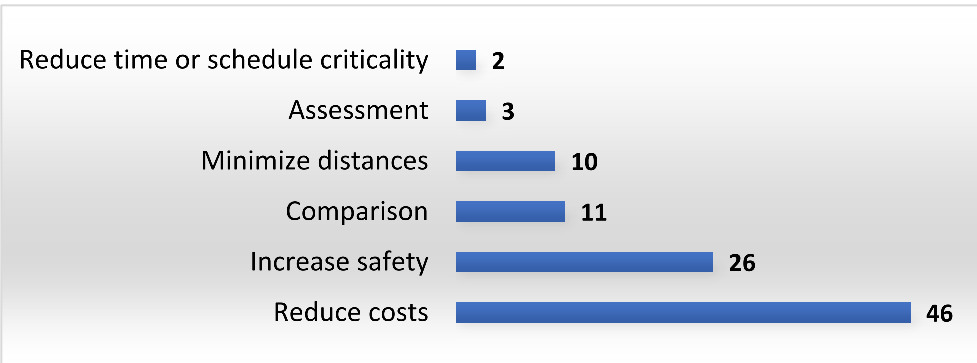

Figure A7. Most popular objective functions.

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