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GENERATIVE DESIGN FOR SITE LAYOUT OPTIMIZATION

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Abstract

Construction site layout planning (CSLP) is a strategy and decision-making process for the placement of temporary facilities and areas within a construction site. CSLP initiates and affects the direction and productivity of projects. CSLP often encounters several challenges brought about by uncertainties and unquantified decisions. Research efforts to automate CSLP have evidently faced insufficient field validation and adaptation. In literature there has also been difficulty in considering three-dimensional spaces and movement for site layouts. The study aims to contribute to the automation and applicability of quantified three-dimensional layouts in CSLP. Generative Design is a technological tool that intakes numerical inputs and produces computational and model outputs in real time. A realistic consideration of construction projects requires dynamic layouts that consider three dimensional spaces. Grasshopper Generative Design software was utilized to optimize layouts minimizing an objective function in a quadratic assignment problem. It optimizes using the Genetic Algorithm, and its effectiveness was demonstrated by testing against benchmark results. A site layout optimization case was conducted on a 12-storey educational building with three phases. Furthermore, a qualitative interview with the site planner was conducted to establish a contrast between industry practice and theory. The use of benchmark data in this optimization process produced a decreased minimum cost by 17% compared to the original publication. Results produced rapid generation of *three-dimensional* models and layouts for exploration and visualization. The case study demonstrated the applicability of the technique by producing an optimized three-dimensional layout for distinct phases of the project. Aside from this, the outputs were found to be readily interpretable by an industry professional due to its visuals and objective driven layouts. Future works may use Generative Design plug-ins for multi-objective optimization and physics simulations such as obstacle detection.

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Keywords: facilities, generative design, layout, and optimization.

1. Introduction

Construction Site Layout Planning (CSLP) is a planning process that decides on the appropriate site facility layout to be employed. This involves the strategic placement of construction elements such as lot and building footprint, temporary facilities, obstacles and access points. This planning process is purposed to find the optimal layout while considering complexities and conflicting alternatives through optimization [1]. In construction planning, CSLP is recognized as a crucial component of effective project management and control. The importance of CSLP lies in its subsequent effect on succeeding phases of the project.

Appropriately chosen facility layouts, affect several aspects of construction such as productivity, mobility, safety and other aspects. CSLP is a crucial initiating aspect which optimizes construction efficiency and placement of resources and processes [2]. Even though site layouts significantly affect the productivity and success of construction projects, it is difficult to quantify and isolate the impact of site layout on construction activity efficiency [3]. This planning aspect also has implications on safety and cost and time savings [4]. The construction industry suffers from diminished productivity due to its resistance to

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adopt technological advancements [5]. As a specific area of construction planning, CSLP retains a significant gap between theoretical and technological advancements and industry adoption.

There exists a wide array of research efforts to quantify, enhance and thoroughly understand CSLP. Various models, algorithms, simulations and objectives have been applied for the automation of CSLP. Despite this, the application and adoption of these techniques or technologies has lacked applicability and usability. A significant emerging technology called generative design has the potential for CSLP applications. The implementation and intensive investigation of this technology is yet to be explored thoroughly [6]. 2D approaches to CSLP are incapable of presenting dynamic and complex spatial information which in turn reduces the accuracy of information and support for project planning [7].

Since CSLP requires the accurate assignment of facilities to respective locations, conflicts on use and spatial assignment tend to occur and cause inefficiencies. Strategic facility planning for the creation of optimal layouts could be computed through the quadratic assignment problem (QAP) [8]. QAP introduces two variables and indices for consideration in assignments producing inherent interdependencies. Considering important factors in an objective function throughout all assignments, the Koopmans-Beckman QAP [9] is applicable. This study optimizes the computational complexities of QAP while providing crucial visual information to the user throughout the entire process.

Despite its importance and significant implications on project success, CSLP is often strategized and conducted informally using expert experience or preference of project planners. This customary practice in the industry, creates evident inconsistencies and inefficiencies in chosen layouts [10]. The inherent variety and wide scope of construction projects hinder the implementation of automation and well-informed strategies. Highly specific project conditions have been the cause of significantly estimated CSLP practices. Improvised strategies and implementation fail to consider and include crucial factors that affect the process. Complexities and a wide range of considerations in real-world site planning emphasize the importance of knowledgeable decisions. As an initial stage of planning, its optimal choice potentially dictates the direction or success of the project. Technological adaptations in theory, have encountered a lack of field application.

This study aims to contribute to the application of automation in CSLP through optimization and visualization. Techniques and methods employed in this study utilize Generative design to create a practical layout exploration process producing perceptible and quantifiable information. The computational aspect of this study deals with CSLP as a quadratic assignment problem (QAP) using the Genetic algorithm. Alongside this, a highly visualized model representation of the layout exploration process could promote its simpler technological comprehension for industry professionals. The significance of developments in this study lie in the applicability and convenient comprehension of a visualized optimization method. Research gaps in section 2.2 were also the focus and consideration of in this study.

2. Related Work

Various works of literature focused on CSLP have investigated and proposed various automation techniques for potential adoption. As a guide for this study, research trends, direction and gaps identified in literature have been a general guide for this study.

2.1. Categorization of CSLP

The highly specialized and complex field of CSLP has developed through the years in literature. Unique construction projects are another motivation for the categorized development of CSLP literature. Starting as early as the 1970s as a simple mathematical problem, it has progressed significantly alongside technology [11]. Throughout the progression, diverse aspects have been explored including facilities, objectives, facilities and time and distance aspects. Objectives typically involve construction elements such as distance, flow, cost, noise and safety. Among the parameters considered for published works, the most important parameters include choosing an appropriate algorithm considering movements and flows and placement of temporary facility requirements.

In a social network analysis of seventy unique approaches to CSLP, the most common algorithms were visualized based on frequency and simultaneity of use. The visualization in Figure 1 by Salah, Khallaf, Elbeltagi and Wefki sees the Genetic algorithm as the most common algorithm used, and Generative Design used alongside it [12]. Sizes of the nodes indicate the frequency of use.

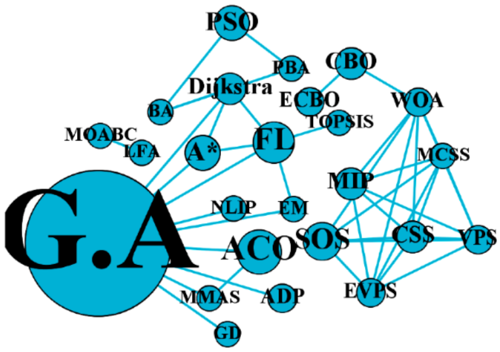


Fig. 1. Common Algorithms Used for CSLP (Salah 2023)

Spaces within construction sites have been classified in the past. Micro, macro and path spaces were related to one another to further understand the CSLP interactions. Micro spaces were considered work areas that require less space, macro spaces were larger spaces for temporary facilities and paths were spaces for mobility within the site. The study demonstrated a significant relationship between workspaces and temporary facilities [13]. This study considers spatial relationships and important aspects of CSLP tackled in literature through an integrated visual optimization approach within a Generative Design platform.

2.2. Trend of CSLP Publications

The progression of CSLP publications has provided significant insight into effective trends and directions of CSLP development. In its earliest developments in the 1970s, CSLP was solved as a simple static problem with minimal analytical considerations. Eventually, it was innovatively solved as an optimization problem in the 1990s. Important advancements in optimization were the use of the Genetic algorithm [14] and Artificial Neural Networks [15]. These optimization methods were Heuristics or approximations for solving CSLP as a static problem. Modelling and visual methods were introduced in the 2000s through computer aided design considering distance and safety [16] [17]. Optimization methods also experienced further developments using methods such as the Ant colony optimization [18], Particle swarm optimization [19] and Colliding bodies optimization [20]. The maximization of safety and minimization of cost was tackled simultaneously using the Max-min ant system [21]. It is evident that the importance of optimization use catalyzes the automated computational approach for CSLP.

The development of technological applications for CSLP started with simple graphical displays without optimization objectives [22]. Advancements in computer aided design and building information modelling promoted the visual understanding and simulation of CSLP. Challenges for upscaling CSLP from a two-dimensional problem to a three-dimensional problem with time considerations has been a consistent challenge for models [23]. The recurring theme for modelling approaches for CSLP has focused on realistic replications of real-world construction projects. This study builds on both the computational and visual developments of CSLP in an integrated process with Generative Design optimization and responsive three-dimensional modelling.

2.3. Generative Design as a tool

Through Generative Design, alternatives and designs are exhaustively explored using artificial intelligence and optimization. For construction, it has been used for initial planning and exploration due to its capabilities in rapid exploration of various possibilities [24]. GD generally follows a sequence of defining design goals and constraints then running an optimization based on this. Alongside this, building information modelling (BIM) has also been utilized alongside GD for modelling and processing data. The coupled use of GD and BIM for an intuitive design has proven to be a more holistic approach in design exploration and data management. Generally, GD design exploration processes follow a flow illustrated in Figure 2.

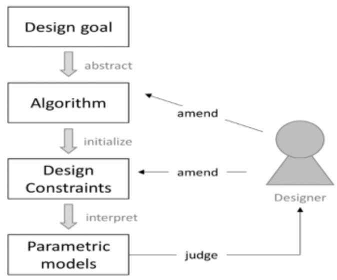


Fig. 2. General flow of GD (Salah 2023)

In the context of CSLP, the BIM-GD coupled tool has been used to solve an existing QAP in literature. Using the visual programming approach in GD, each required facility was assigned to an appropriate location. Conditions and spatial requirements were introduced to enhance the computational complexity of the problem. Fixed facility requirements and spatial requirements for larger facilities were introduced to the computational exploration of layouts. Violations of the programmed restrictions invalidated the proposed layout [25]. The proposed use of the BIM-GD tool was demonstrated through a comparison with benchmark results. The same exact problem was solved borrowing inputs on facilities, distances, setups and frequencies from the original publication [26]. This problem has been tackled in literature previously in seven unique occurrences, with improving results throughout the years.

Continuing the use of BIM-GD, the same author used Dynamo-Revit GD to solve CSLP as a multi-objective problem. The objective aimed to maximize site safety scores and minimize cost. The product was a trade-off of analysis showing that minimizing cost to an extreme, deters safety while maximizing safety may increase costs significantly [27]. The same tool was also used to analyse site safety through the optimization of crane positioning. Computation and visualization techniques were used to improve lift scores by 40% while other alternatives were ready for viewing. Furthermore, a Likert scale questionnaire among twelve participants showed that the software use could improve decision-making. Dynamo GD could potentially be an attractive tool for industry professionals with knowledge on BIM due to its direct connection.

Another GD tool called Grasshopper was used to create a freeform representation of site elements. Actual travel distance was also estimated through grid pathing using the “ShortestWalk” tool within the software. However, the high flexibility of freeform geometries leads to approximate solutions that do not guarantee complete optimization [28]. The more visual inclination of Grasshopper GD makes it more interpretable and attractive to industry professionals without previous knowledge to information modelling techniques. A focus on more advanced modelling than BIM makes Grasshopper a suited tool for a visual approach to optimization. Grasshopper uses visual programming illustrating processes as nodes taking inputs and producing outputs from left to right with wires as connections.

3. Methodology

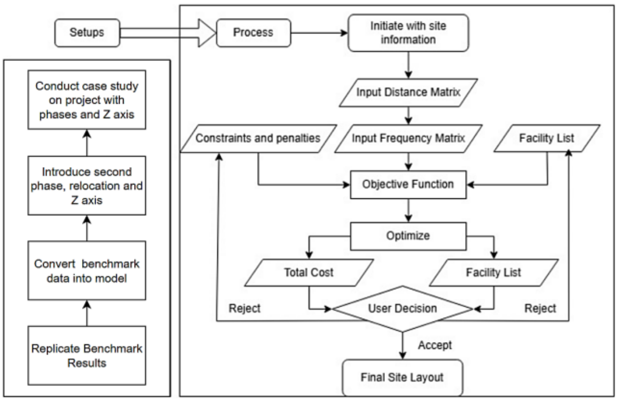


Fig. 3. Setups and Process

The experimentation of the study involves several setups to promote the applicability and transition of theoretical CSLP to actual site planning. Figure 3 illustrates the setups and process for each procedure all in Grasshopper GD. Starting with the theory, benchmark problems were solved and improved upon. The improved procedure was then applied in a real-world project case study. Throughout all applications of the framework the same setup was employed in terms of computation. The objective function in Equation 1 served as the computational setup for all cases, only varying modelled elements. Equation 1 is the equation for optimization which minimizes the double summation of cost products over all assignments through indices *i* and *j.* Variables D, F and C are the distance between locations, frequency of trips between facilities and unit cost per meter of travel, respectively.

$$Total\ cost = \sum_{i}^{n-1} \sum_{j=i}^{n} D_{ij} F_{ij} C_{ij} + 20{,}000 \times (N_1 + N_2 + N_3) \quad (1)$$

N_1, N_2 and N_3 are the number of violated restrictions for the assignments preventing facilities from being assigned to multiple locations, insufficient spaces and restrained locations. These values are multiplied by 20,000 or any other large arbitrary number to invalidate the solution and identify violations for optimization. This value exists to identify an error in the layout and could be adjusted to identify other user defined restrictions. This constant could be increased to infinity while having the same effect.

3.1. Literature-Based CSLP

The first setup for the theoretical development of the integrated framework was the optimization of benchmark data to test against benchmark results. The facility requirements, distance matrix, frequency matrix and assignment restrictions were borrowed from a benchmark publication [26]. The distance matrix was the pairwise distances between all eleven locations. Pairwise facility relationships were identified in the frequency matrix. The assignment of eleven facilities to eleven locations in a QAP was minimized through the Genetic algorithm to a value of $15,160 [26]. In cases where the distance matrix was model defined, the “cross reference” node in Grasshopper provided all pairwise distances.

The inputs from the benchmark publication were used to initiate the problem as a QAP. The distance and frequency matrix files were inputted through the “file path” node which isolated the matrix file in comma-separated variable (CSV) format. This was then read and parsed through the “text split” node where each cell was isolated using comma separators. The number matrices were then inputted to the objective function node.

The objective function node was programmed through the “GHPyhton” program node. The double summation and permutations were coded in this node using the *for* and *while* functions. A “gene pool” or adjustable sliders for facility assignments was also inputted in the “GHPyhton” node. The Galapagos solver optimized the output of the “GHPython” node as the fitness function altering the facility assignments.

The restriction for duplicated assignments was identified through the “shift list” and “equality” nodes. Identified equalities between the original and shifted list identified duplications. Fixed facilities in locations were verified using the “list item” node and checked for equality. This was then identified and numerated using the “dispatch pattern” node. Unfit facilities for insufficient areas were programmed similarly in Figure 4, but with multiple equalities for sufficient spatial possibilities.

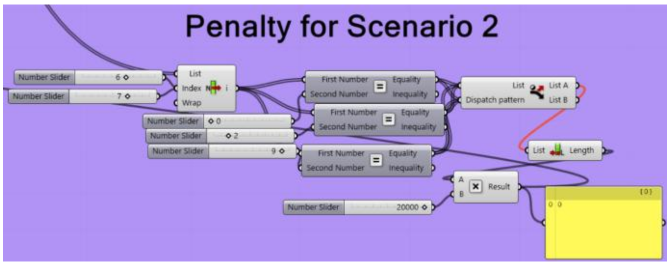


Fig. 4. Visual Program for Violation Detection

The facility assignment list and objective functions were optimized in the Galapagos solver through the Genetic algorithm until one hundred stagnant populations. Generated index lists were optimized rapidly through iterations starting with an initiated population genome. The fitness or probability of selection of succeeding solutions is based on the proportion of the singular objective function to the sum objective function of the population. The contributions of parents have a proportion based on fitness and mutations were introduced throughout the iterations to ensure widespread exploration.

After the testing against benchmark results, the inclusion of a visual model approach was included. This was done by converting the distance matrix into a model through multidimensional scaling. The modelled distance matrix was minimized for difference with the benchmark matrix. The model-based distance matrix was optimized in the same way. Modelling was done through indexed “text tag” and “rectangular box” nodes” Figure 4-a shows the model setups and succeeding phases.

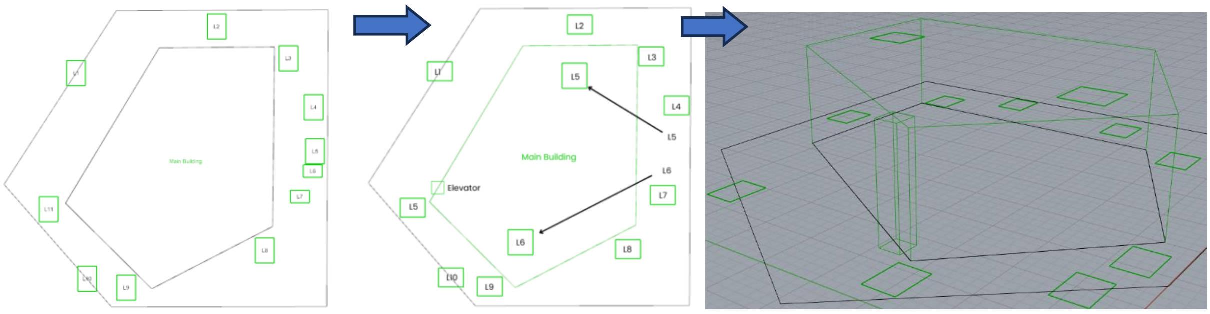


Fig. 5. (a) Model setup; (b) Second Phase Relocation; (c) Second Phase Setup

As construction projects possibly require multiple phases or facility relocations, a second phase was considered in this study. In this phase, the Z-axis was considered to allow the modelling of three dimensions. The main building footprint was assumed to be constructed ten meters high where locations 5 and 6 were relocated. The linear distances between the centroids of these locations were then used to form the distance matrix inputted for optimization. With this, the same optimization method and setup was conducted for Figure 5-b and Figure 5-c.

3.2. Application

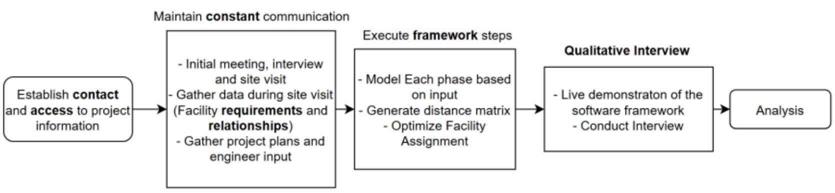


Fig. 6. Methodology for Application of Framework

The holistic procedure in Figure 6 was then tested in a real-world case study conducting multiple phases of CSLP for the construction of a 12-storey educational building. The selection of the singular case study was due to in-depth investigation and limitations in access to data and time constraints. The project engineer responsible for the site planning for the project was the primary participant and source of information. Data for CSLP was gathered through constant communication, meetings and interviews with the project engineer. Site documentation during visits and project plans provided by the project engineer provided the data used for the CSLP framework testing. Figure 5 illustrates the procedure for framework application. The case demonstration used the Philippine Peso as unit cost (Php).

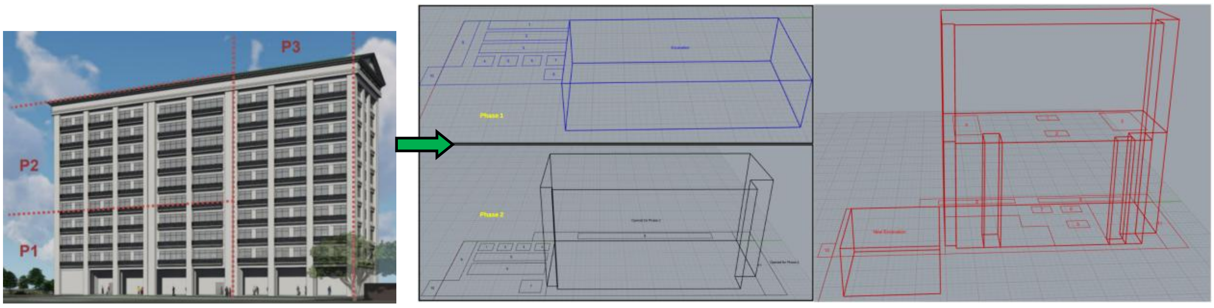
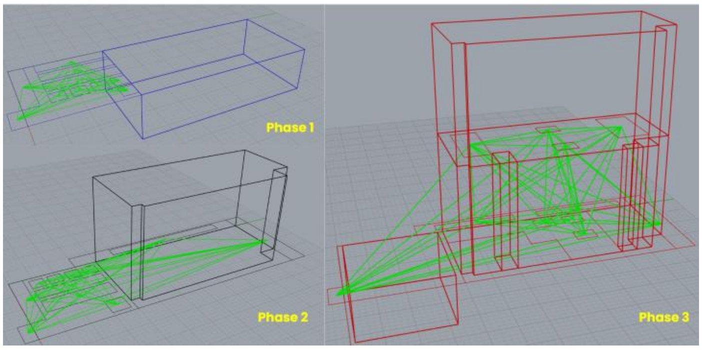


Fig. 7. (a) Render for Phases; (b) Model for each Phase

The project was divided into three phases with varying site setups, facility requirements and predefined locations as illustrated in Figure 7-b. The approximate models of each phase were created considering instances right before the construction of each phase. Potential locations for facility placements were discussed with the site planner and the site geometry was based on site documentation and the site plans provided. The facility requirement lists and lines representing each entry in the distance matrix are illustrated in Figure 8-a and Figure 8-b respectively. The optimization process remained the same.



Phase 1	Phase 2	Phase 3
Main Gate	Main Gate	Main Gate
Site Office	Site Office	Site Office
Rebar Handling	Rebar Handling	Rebar Handling
Concrete Handling	Concrete Handling	Rebar and Scaffolding Storage
Rebar Storage	Rebar and Scaffolding Storage	Worker's Barracks
Worker's Barracks	Worker's Barracks	Warehouse
Warehouse	Warehouse	Staging Area
Crane Generator	Crane Generator	Delivery Area
Operations Generator	Operations Generator	Finishes Storage
Backup Generator	Backup Generator	Tool Storage
	Staging Area	Fabrication Area

Fig. 8. (a) Linear Pairwise Distances; (b) Facility Requirements

Following the CSLP conducted for the case study, a live demonstration and interview with the project engineer was organized. A demonstration of the visual and optimization features of the framework were shown to the project engineer to contrast and determine the applicability of the visual framework. Prompts were used to guide the interview, and a thematic analysis was conducted to analyze findings.

4. Findings and Discussion

4.1. Literature-Based CSLP Results

The testing of the benchmark QAP resulted in a total cost minimized to $12,606 with a revised facility assignment list compared to the original publication. This result matched exactly the publication in 2024, which also used Generative Design to solve the problem computationally. Compared to the original publication by Love and Li in 2000, there was a reduction in minimum total cost from $15,160 by 17%. Each facility was assigned to one location each without duplication, confirming the restriction previously set in Section 3.1. The main gate and side gate were also assigned to their fixed locations, and larger facilities were all assigned to large locations capable of accommodating them. All these conditions in the minimum cost layout were met, demonstrating that user-defined restrictions were considered in the computation. The GD process outputs are illustrated in Figure 9.

Fig. 9. Optimized Cost and Facility Assignment Result

The multi-dimensional scaling done to convert the benchmark data to model resulted in a discrepancy in total distance by 1.56%. The total cost optimization resulted in the same exact facility assignment list, but with a 1.79% increase in cost to $12,836 due to the discrepancy in model scaling. The result of the indexed modelling was the rapid generation of three-dimensional visual models. These models were interactive and responsive in real time to each iteration of the optimization. Any layout alternatives were readily available for viewing and analysis with a displayed model and objective function value upon the adjustment of the user. Figure 10-b shows the optimized visual layout.

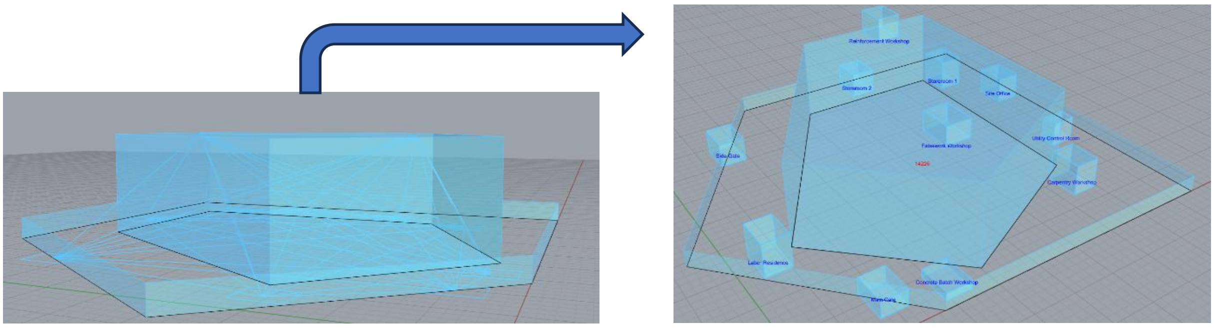


Fig. 10. (a) Linear Pairwise Distances; (b) Optimized 3D Visual Layout

The second phase and relocation resulted in an increase in total cost from $12,836 to $14,226 by 10.82%. Three-dimensional models for the cross-referenced distances, layouts and objective function were displayed. Figure 10-a illustrates the matrix of linear distances and the optimized layout with displayed objective function. Similarly, any layout the user applies through the gene pool would alter the model and objective function value in real-time.

4.2. Case Results

CSLP conducted on each phase of the project resulted in an optimized layout in Figure 11. These layouts were based on the minimization of the objective function and the compliance with the restrictions. Throughout all layouts achieved the main gate was assigned to location 10 which was the single fixed access point to the site. Each facility was assigned to one location respectively with large facilities only assigned to large locations. Phase one was optimized to Php 5,062, Phase two to Php 10,072 and Phase three to Php 12,575. The worker's barracks, site office and warehouse were assigned to large locations in all phases as they were assumed to require significantly larger areas as described by the project engineer. The optimization method's selection for optimal layouts considered all user defined restrictions. The automated layout exploration and model responsiveness was demonstrated to the project engineer.

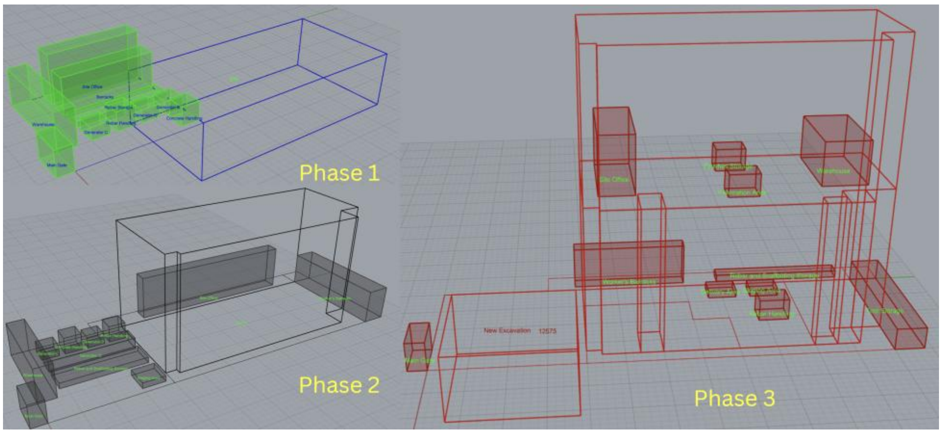


Fig. 11. Optimized 3D Layout for the Three Phases

The qualitative analysis of themes and highlights of the interview highlighted important responses. According to the engineer, CSLP for the project was conducted using only his expert opinion and priority on the building footprint and insufficient area allocations. Factors, requirements and priorities were said to rapidly change throughout the project. According to the engineer, the framework is beneficial for simulation, prediction and visualization. Improvements may be enforced through flexibility in accommodating user-defined restrictions without complex technological use. With inputs taken from the plans and engineer's opinion, the optimized layouts were aligned and similar with the actual plans. Overall, the project engineer expressed his interest and enthusiasm in the potential application of the framework.

5. Conclusion

The Generative design procedure partially automates CSLP. Using both computation and modelling for intuitive layout generation, the process could promote applicable tools and techniques. Optimization using the Genetic algorithm demonstrated efficient computation with desirable results. Matching the best results in literature and improving on the original publication shows the computational capabilities of the Grasshopper GD. The three-dimensional responsive models highlight the visual approach that also promotes simpler comprehension. Visual information in the form of the model layout, linear distances and objective function provide crucial information for decision-making. The interview demonstrated the potential of the framework for eventual industry applications.

Important limitations to the study include the requirement of predefined locations and exclusion of actual travel paths and relocation costs. The singular case study due to data access and time limitations could be addressed in future works. Construction phases were also considered as isolated phases with a limited extent of automated responses to changes. Site models were also user-defined and approximated based on plans.

A continual development to the process may include considerations for obstacles and actual travel paths. The use of the Opossum multi-objective solver plugin in Grasshopper GD may further imitate realistic conditions that require a high level of flexibility and consideration of numerous variables. Physics simulation plugins such as Kangaroo could allow automatic detection, generation and simulation of physical elements and interactions within a site.

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