GENERATIVE DESIGN FOR
CONSTRUCTION SITE LAYOUT PLANNING

by

Raj Birewar

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Clark Cory, Chair

Department of Computer Graphics Technology

Prof. Bradley Benhart

Department of Construction Management Technology

Dr. Soowon Chang

Department of Construction Management Technology

Approved by:

Dr. Yi Jiang

Dedicated to my Professors, Family, and Friends for their incessant love and support

And to

Everyone Aiming to Simplify the Construction Processes

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
GDP	Gross Domestic Product
VDC	Virtual Design and Construction
CSLP	Construction Site Layout Planning
Pre-Con	Pre-Construction
GD	Generative Design
TCP	Tower Crane Planning

ABSTRACT

The construction industry contributes significantly to the GDP of the United States, attributing to its growth at an unprecedented rate. Efficient planning on all stages of construction is the only way to combat dynamic obstructions and deliver projects on time. The first element involved in the planning phase deals with the layout of the Construction Site. It significantly regulates the pace at which construction operations function and directly affects the time, cost, and safety linked to the successful delivery of the target project. Hence, it is paramount to ensure that every component of the construction site maneuvers with the utmost productivity. One such equipment that occupies significant attention while carrying out the CSLP process is Tower Crane. Tower crane optimization is pivotal to ensure proper lifting and handling of materials, and warrant conflict-free work zones. This research, therefore, aims to optimize its position by maximizing the lift ability. To achieve the goals, Generative Design- a paradigm that integrates the constructive features of mathematical and visual optimization techniques, is used to develop a relatively comprehensible prototype. The first part of the research, thus, utilized Generative Design on two construction sites- one from the United States and one from India. After implementing the visual programming algorithm, an improvement of 40% was warranted in the lift score. A pool of potential alternatives was explored and supplemented by the trade-off illustrations. The concept of trade-off was substantiated by allowing a framework for prioritization of lift cycles, and facilitating a holistic decision-making process. To evaluate the usability, 12 participants were chosen based on their previous experience with tower crane operations. The participants witnessed a live demonstration of the algorithm, answered a Likert scale questionnaire, and appeared for an open-ended interview to provide feedback about the proposed Generative Design technique. After carrying out narrative analysis for the usability aspect- it has been unanimously observed that the technique has extreme efficiency of usage and can evidently prevent the occurrence of errors. The study concludes by providing recommendations to augment the significance and usability of Generative Design for tower crane position optimization.

CHAPTER 1. INTRODUCTION

1.1 Introduction

The construction industry is one of the key contributors that constitutes significantly to the economy of the United States. As of December 2019, it is documented to be worth $1.3 Billion, showcasing a rise of around 5% per annum (United States Census Bureau, 2019). To ensure that the targeted statistics are achieved, it is paramount that construction projects are delivered successfully. In lieu of the same, Construction planning has been identified as a pivotal factor that considerably affects the quality deliverables of a construction project(Laufer & Cohenca, 1990). It can be defined as a process that "Involves the choice of construction technologies, the definition of work tasks, the estimation of required resources and durations for individual tasks, and the identification of any interactions or constraints among the different tasks" (Hendrickson et al., 1987,p.253).

Within the realm of Construction Planning, Construction Site Layout Planning (CSLP) is recognized as one of the most noteworthy elements for successful project control (Song et al., 2018). It a nutshell, it essentially refers to the placement of tangible resources within the given project space (Pheng & Hui, 1999). An effective CSLP is paramount to optimize space and provide a well-defined route for the safety and security of the construction site and subsequently decrease the costs and material re-locations that accompany(Zolfagharian & Irizarry, 2014). To enhance and ease the CSLP process, a plethora of breakthrough technologies like 4D WorkPlanner(Akinci & Fischer, 2000), max-min ant system(Ning et al., 2010), Fuzzy random environment(Xu & Li, 2012) and Simulation (Razavialavi et al., 2014) have been used over the past years. However, each of them has demonstrated specific loopholes, in terms of applicability and usability, as discussed subsequently. A major emerging technique, which is yet to be utilized extensively for an efficient Construction Site Layout Plan is 'Generative Design'.

Generative design is defined as a methodology to interact with the end-product without having direct (hands-on) intervention with the results, but through employing abstract definitions by exploring the multiple design variations and then displaying and producing the elements of design products(Fischer & Herr, 2001). It has been manifested that this technology offers a wide array of design paths to the architects by breaking the obvious correlations that exist between the form and representation and using computationally generated complexities to create unexpected topologies (Agkathidis A., 2015).

The concept of generative design has demonstrated its applications in various industries -- independently and in conjunction. It has been used in additive manufacturing for honeycomb structures (Jihong et al., 2017), editable and watertight boundary representation (Marinov et al., 2019), jewelry design applications (Kielarova et al., 2013) and imprinting personalities in consumer products (Beghelli et al., 2017). One of the major applications it has posited in the architectural industry is, in exploring the multitude of exploring shape variations (Khan and Awan, 2018). Generative design has been adopted to extensively exploit AEC Conceptual design innovation(Abrishami et al., 2014), design space navigation(Chien & Flemming, 2002), and also as a selection tool for novice designers (Chase, 2005).

Automation and Artificial Intelligence in construction have been utilized extremely sporadically for the purpose of CSLP. Despite having the presence of designated frameworks concentrating on superior decision-making system (Ning et al., 2010), BIM enforced rule-based checking (Schwabe et al., 2016) and BIM-based hybrid approach for temporary facilities (Phuc Long et al., 2019) -- no substantial study, directly revolving around the implementation of Generative Design Concepts has been carried out to enhance the CSLP process. This thesis deals with extending the potential applications of Generative Design to augment and sharpen the CSLP process.

1.2 Problem Statement

A construction site layout plan is paramount to accomplish several predefined project goals. It is pivotal to not only ensure safety in the workplace and efficiency in the operations but also to optimize the site efficiency and satisfy the requirements of schedule (Elbeltagi et al., 2001). Despite of manifesting robust potential consequences, construction site layout planning has failed to garner the attention and importance it essentially deserves. Various reasons like ad hoc determination of the plan, subjective decisions by designers, and sticking to the conventional thumb rules for problem-solving have attributed to a failed encapsulation of vital factors that accompany this process (Chau & Anson, 2002). This lack of consideration has ultimately resulted in conventional, unorganized, and disorderly construction sites, leading to improper planning and execution of the construction project, as a whole (Lam et al., 2007). Thus, in order to augment the utilization of resources and increase the productivity of the entire cycle -- it is vital to have a well-developed and comprehensive construction site layout plan.

One of the most important components on a construction site that directly affects the majority of material movement in the shortest period and holds a key position to minimize the initial cost of construction is a Construction Crane. A proper selection, placement, and optimization of the crane is hence inevitable while making the design decisions in the construction process (Gray & Little, 1985). It is also necessary to ensure that the allied factors like material characteristics, site configurations, and building shapes and sizes function optimally within the purview of multifaceted layout strategies and approaches (Abdelmegid et al., 2015). Considering the breadth, scope, and complexity associated with meticulous planning and the level of scrupulousness that the process demands, industry practitioners tend to resort to previous experiences and pre-defined prototypes for formulating a well-defined approach to accurately encapsulate the intricacies associated with Crane Planning (Huang et al., 2011). The problem addressed by this study is therefore *Improper Planning of Construction Crane Conformations while developing the Construction Site Layout Plan.*

Cranes, in general, can be regarded as devices that facilitate the displacement of material in the horizontal and vertical direction, essentially by a mechanized operation for performance. With an increase in the number of specialties associated with crane, the major decision-making factors still happen to be the weight of the loads, target distances, time period for lifting operations and mobilization degree (Chudley & Greeno, 2006). Based on the specified characteristics, Cranes are usually classified into Tower Cranes and Mobile Cranes.

> Mobile cranes are typically self-powered and can be set up in multiple locations on the job site. Fixed cranes are placed at the beginning of the job and typically do not move for the entirety of the project. The most common fixed crane is the tower crane. (Rapp and Benhart, 2015, p. 198).

However, Tower Cranes have significantly demonstrated several advantages over mobile cranes when it comes to increased production rates, reduced requirement for daily management of operations (Ji & Leite, 2018), and high level of ensured safety on the job site (Shapira & Lyachin, 2009). Increasing research has thus majorly been revolving around broadening the efficiency of a construction tower crane.

While evaluating the best position of a tower crane on a construction site, several factors like range and reach of the crane, avoiding probable conflicts and clashes (Sullivan et. al., 2010), material movement to and from trucks and space available for crane placement (Rapp and Benhart, 2015) have been identified. To efficiently account for all of these aspects—the purpose of this research is to *Optimize the Position of a Construction Crane in a Construction Site Layout Plan.*

For better decision making when choosing from the best option from the pool of alternatives, visuals and shapes have ubiquitously exhibited significant importance for arriving at better and informed solutions (Lurie and Mason, 2007; Javurkova et al., 2012; Jaenichen, 2017). Pictures, shapes, symbols, and signs substantiate the process of Visual Thinking, which in turn aid in numerous processes like abstractions, developing perceptions, better understand the pressing issue, and form a verdict on the same (Arnheim, 1997). To expand the same concept, Generative Design is one such paradigm that helps users select the best option from the plethora of prototypes developed. Generative design has been progressively utilized: as a selection tool for novice designers (Chase, 2005), to indirectly represent grammar-based design system (Granadeiro et al., 2013), in parametric design in glue-laminated-timber industry (Monizza and Benedetti, 2016), as a technique to explore shape variations (Khan and Awan, 2018) and even Earthbag projects (Santos and Beiratildeo, 2020) -- making it one of the most pervasive and emerging techniques to address the problems in the construction industry. However, neither Generative Design nor any of its close allies have been directly used to report the specific issue of CSLP, as discussed herewith.

With the implementation of every novel technique, it is paramount to ensure that the primary users of the deliverable can easily access the benefits associated. To better decide the applicability, it is thus critical to test-run the model by its past, existing, or future personnel (Castronovo et al., 2013). This study thus evaluated the usability aspect of Generative Design on Tower Crane Planning (Faizal Omar et al., 2014; Ku & Taiebat, 2011)

The framework of this study therefore consisted of four sections: 1) Testing the applicability of Generative Design in CSLP 2) Identifying the prospective locations of Tower Crane on construction site and generate design prototypes for the same 3) Optimizing the crane position and 4) Evaluating the response based on utilization aspects of Generative Design.

1.3 Research Questions

Following an extensive literature review, the research problem has been postulated through the following question:

1. How significant is Generative Design in optimizing the Tower Crane Position?
2. What criteria affect the utilization of Generative Design for Tower Crane Planning?

1.4 Scope

The premier aim of this study is to augment the Construction Site Layout Planning Process. It has been observed that Tower Crane, in specific, has imparted a huge effect on this activity, and hence an attempt will be made to optimize its position on a construction site. In order to do so, the process of Generative Design was extensively employed. Construction site layouts from various construction industry professionals were collated and an optimization of crane position was carried out for the received plans.

In order to perform the optimization procedure, Generative Design scripts from the database and guidelines from Autodesk University's website, blogs, and lectures were referred and manipulated as per the site conditions. Finally, a set of demonstrations followed by questionnaires and interviews were conducted to identify the factors affecting the usability of Generative Design for Tower Crane Planning.

It is envisioned that this study will help develop a prototype that encapsulates site-specific conditions and generates probable locations for crane positioning—returning the most optimal location for placement. This study will benefit academicians and industry practitioners working in the field of Construction Site Planning and Logistics as well as researchers focusing on multi-disciplinary applications of Visual Programming and Generative Design.

1.5 Significance

An efficient construction site layout is extremely important to attain all the site-specific goals pertaining to site safety, productivity, and even the schedule specific requirements (Elbeltagi et al., 2001; Ning et al., 2010). The construction site layout plan, in itself, is an amalgamation of numerous components like free space availability, space allocation, location of existing buildings-- to name a few (Rapp and Benhart, 2015). CSLP is therefore a crucial step that has demonstrated its returns in reducing the material handling and storage costs, and minimizing construction waste considerations (Kumar and Cheng, 2015).

A key constituent of an effectively planned Construction Site Layout Plan is a perfectly positioned and appropriately utilized crane. The lifting and material handling capabilities, in addition to enormous initial and recurring costs (especially if not handled properly), have delineated construction crane as a pivotal factor to be considered throughout the construction process (Dalalah and Hayajneh, 2010). As stated by Emsley in 2001, in addition to delivering the most economical solution for materials handling and clearance of obstructions (Harris, 1994), tower cranes facilitate conflict-free load handling (Proctor, 1995), space management (Chalabi and Yandow, 1989) and deal with diverse characteristics of distinct materials. In order to ensure an unencumbered achievement of stipulated goals, it has been largely proven that computer applications and technological breakthroughs act as key actors—in supplement to 'rules of thumb' and anecdotal pieces of evidence perceived by experienced industry practitioners (Emsley, 2001).

Considering that the optimization procedure consists of exploring a plethora of suggested options and validating the best-suited alternative, the technique of Generative Design has been sought after. It has been used to not only explore the variations in the shapes (Khan and Awan, 2018) but also as a selection tool for novice designers (Chase, 2005). It has been integrated with Building Information Modeling to explore form generation and exploit innovations in detailed design procedure (Abrishami et al., 2014). To enforce better decision making and explore the multitude of variations that persist, Generative Design has also been used for shortlisting the designs of Brickworks (Afsari et al., 2014).

In order to achieve the anticipated outcomes of Generative Design, the tool of Visual Programming was widely utilized. Visual programming tools have portrayed a glut of applications in environmental studies, energy analysis, and enhancing sustainable construction. It has been used for green wall system design (Briscoe, 2014), energy and shading analysis (Kensek, 2015) visualization of KPIs (Wiberg et al., 2019), and energy simulation and optimization in pre-design phase (Hao et al., 2019). Within the other realms of construction, it has manifested applications to incorporate applications of BIM in precast concrete fabrication (Jeffrey, 2016), evaluate impacts of construction change orders (Likhitruangsilp et al., 2018), enforce parametric modeling and cost management (Bi and Li, 2018) and quantitatively assess steel structure deconstructability (Basta et al. 2020). However, specifically for Crane Optimization, Generative design has been used disparately and intermittently. This thesis aims to integrate two independently powerful spheres—CSLP through Crane Optimization and Generative Design using Visual Programming to address the issues discussed above.

1.6 Definitions

Analysis: Process of breaking a complex topic or substance into smaller parts in order to gain a better understanding of it. (The Stanford Encyclopedia of Philosophy, 2012).

Building Information Modelling: "Creation and use of coordinated, internally consistent, computable information about a building project in design and construction" (Cory, 2018, p.23).

Construction Crane: Cranes are "lifting devices designed to raise materials by means of rope operation and move the load horizontally within the limitations of any particular machine" (Chudley and Greeno, 2013, p. 167).

Construction Site: A construction site is a location within which the construction, creation, or erection of buildings or structures take place; in addition to structural modification, renovation and deconstruction that takes place within the perimeter of the marked location (as defined by the website Construction Laws, 2019).

Construction Site Layout Planning: Construction Site Layout Planning (CSLP) "is a decision-making process, which involves identifying problems and opportunities, developing solutions, choosing the best alternative, and implanting it" (Ning et al., 2011, p. 459).

Decision Making: It is the process of surveying a known and fixed set of alternatives, weighing the likely consequences and repercussions of each and then making a choice—based on the set goals, purposes, or values by assimilating all the available choices. (Orsanu et al., 1993).

Design Model: "A model of those aspects of the project that have reached the stage of completion that would customarily be expressed by an Architect/Engineer in two-dimensional construction documents” (Cory, 2018, p. 25). For this study, each prototype that represents one of the possible alternatives of the crane location would serve as a design model for that specific arrangement.

Generative Design: Generative Design is a design method that assists human designers to explore an array of design possibilities for the entire domain of problems by stimulating designer’s creativity and routing through viable design spaces within the defined performance criteria (Krish, 2010).

Optimum Crane Position: An optimum crane position on a construction site is one which has the maximum amount of liftable elements within the reach of the truck, avoids spatial conflicts, and eases the movement of material across various structures on the temporary site. (Emsley, 2001; as defined in Autodesk University, 2016).

Visual Programming: Visual Programming is a tool that creates an environment for architects to create, modify, and implement the designs created via direct manipulation. It eliminates redundant and unnecessary tasks by modeling the parameters rather than just the final design, as a whole (Graham et al., 1995).

1.7 Assumptions

The underlying assumptions that precede this study are:

1. The respondents are precisely aware of the process, implications, and scale of the study and have a consensus ad idem with the researcher.
2. Various factors like organization type, performance methodology, and work culture do not have an impact on the process of optimizing the crane position.
3. Respondents’ approach to the study is impartial and free of inherent bias.
4. Participation is voluntary and free of coercion.

1.8 Limitations

The limitations that are associated with this study are:

1. Participants' previous experience with similar kinds of technology might restrict or enhance their openness to adoption.

2. The study is limited by company officials' cooperation and openness to sharing the site-specific data of the organization.

3. The study is conceptually constrained by time parameters. Time taken by respondents to provide the requisite data might affect their inclusion in the study.

4. The samples would be garnered using a convenience sampling technique.

1.9 Delimitations

The delimitations that refine and narrow the scope of this study are:

1. Of all the facilities, equipment, and structures associated with a Construction site, Tower Crane has been identified as an essential factor. This study will, therefore, focus on just the aforementioned parameter(s).

2. The samples are limited to construction industries located within the US and India. Other international construction companies are excluded from this study.

3. To facilitate the implementation of Generative Design, majorly Visual Programming tools, and its associated plug-ins would be executed.

4. Factors like the type of crane and the number of cranes that affect crane optimization would not be considered.

1.10 Summary

This chapter developed a basic framework for the study and emphasized the essential aspects that surround the research. The problem statement has been concisely developed, followed by the specific purpose of the study and its significance. Important conceptual and operational definitions have been developed for a better understanding of the nuances surrounding the study. Finally, important assumptions, limitations, and delimitations that better hone and route the scope of this study are highlighted.

CHAPTER 2. REVIEW OF THE LITERATURE

2.1 Overview

Construction Site Layout Planning (CSLP) has demonstrated remarkable implications on the overall planning of construction project, by affecting numerous characteristics like time, cost, productivity, and safety-- concerning the ultimate deliverables (Song et al., 2018; Zolfagharian and Irizarry, 2014; Elbeltagi et al., 2001). In order to resolve the issues that persist, optimization of the tower crane is inevitable to ensure efficient material handling, minimize spatial conflicts and facilitate a clash-free construction site layout (Abdelmegid et al., 2015; Chudley and Greeno, 2006; Sullivan et al., 2010). In order to better choose from the design alternatives that stem as a result of probable locations across which a tower crane can be placed, the technique of visual programming that facilitates Generative Design will be utilized, considering the advantages it holds (Jaenichen, 2017; Chase, 2005; Khan and Awan, 2018). The literature review is structured to first highlight the importance of CSLP, followed by analyzing the importance that Construction Crane holds in a Construction Logistics Plan. Succeeding to this, existing techniques pertinent to optimize the crane configurations will be reviewed and inter-linked with capabilities of Generative Design and Visual Programming. An in-depth review to posit the benefits of the potential collaboration will be analyzed.

2.2 Literature Review Methodology

In order to ensure that the target outcomes are achieved by following all the links that lead to the end goal, the concept map, as shown in Figure 1 was followed. This warranted a comprehensive coverage of the relevant modules associated with the study and an in-depth literature review encompassing all the crucial steps.

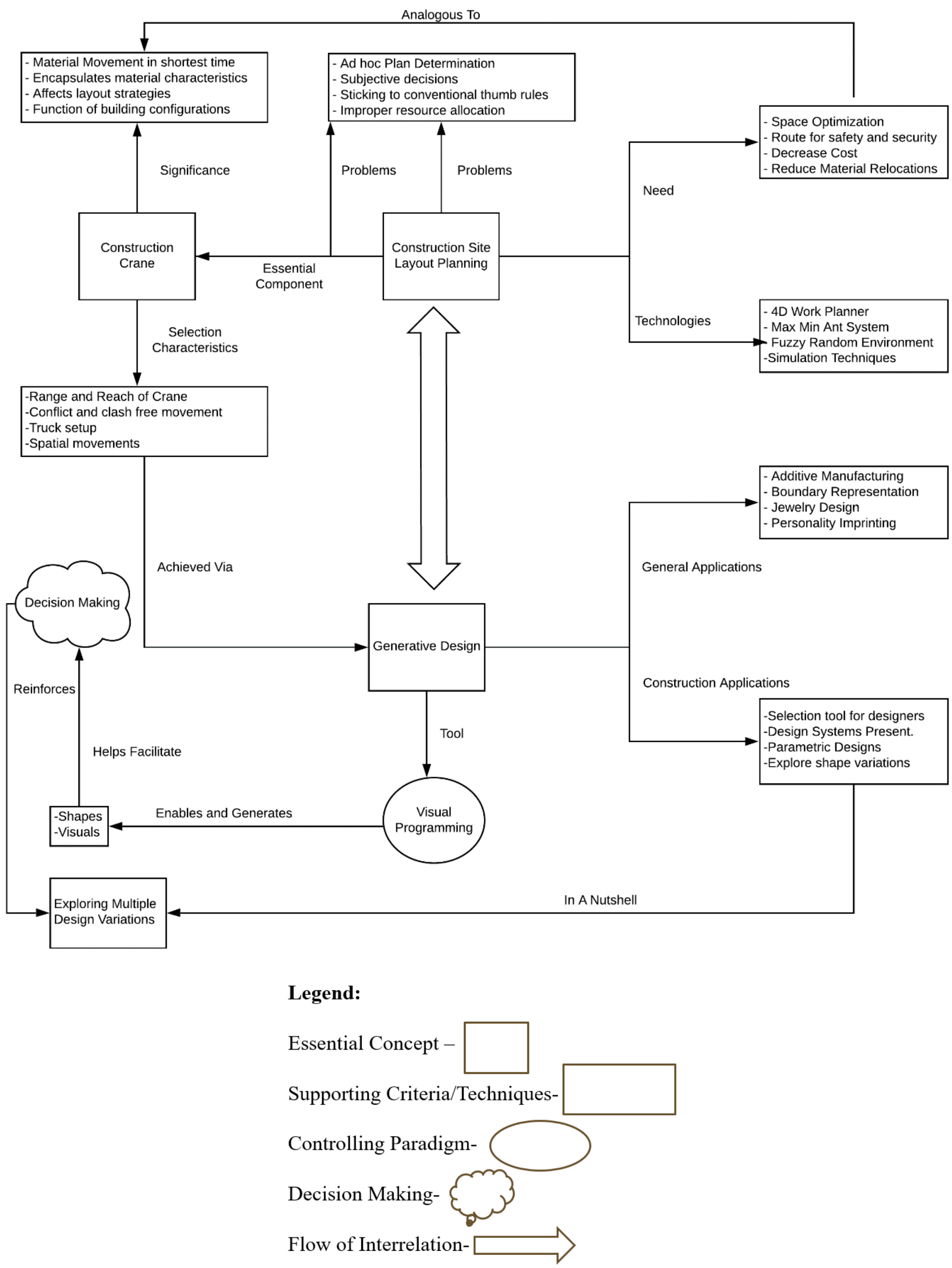


Figure 1: Concept Map for Literature Review. Developed by the researcher to ease the process of literature review.

A Venn Diagram is essential to direct the search strategy associated with the literature review. It ensures that a proper combination of search terms is used—while keeping a direct eye on the specified outcomes of the searches. To ensure the same, Three Set Venn Diagram—as shown in Figure 2 was used.

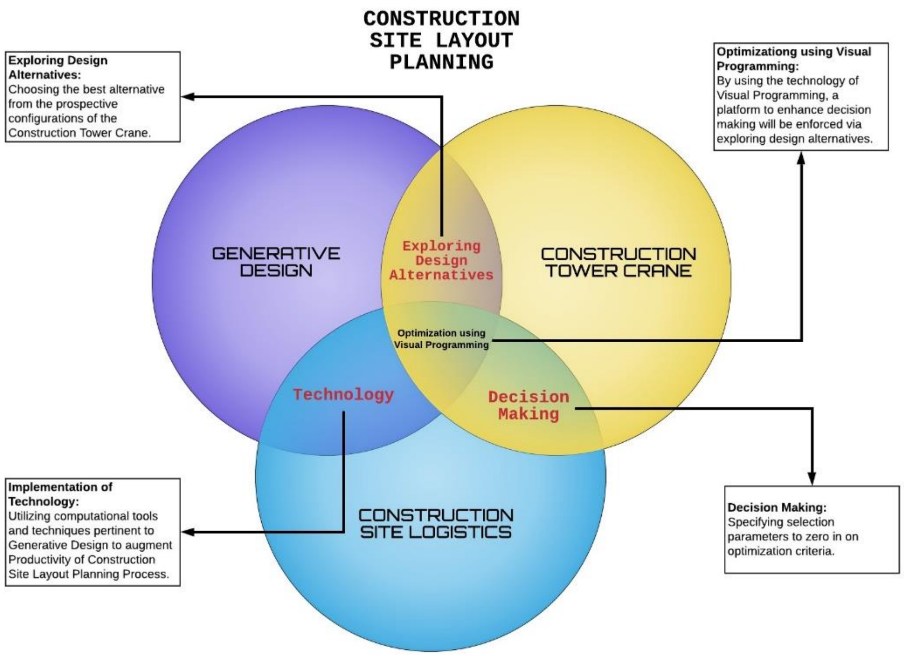


Figure 2: Venn Diagram to Optimize Search Results. Developed by researcher for combining search terms and keywords.

2.3 Databases and Search Characteristics

Crane Optimization and Generative Design are two independent realms—studies on which have been distinctly carried out. To comprehend the level of integration expected, several masters and doctoral thesis were sought out for. ProQuest was the sole database used, owing to its vast repository of maintaining diverse dissertations from across the globe. After doing the initial search, it was discovered that numerous thesis that did not satisfy the search requirement were indicated in the results. After preliminary screening of abstracts and table of contents: 17 relevant dissertations on Crane Optimization, 9 dissertations on Generative Design, and 4 dissertations on Visual Programming were obtained (exclusively). Personally, the researcher was benefitted the most by the dissertations on Visual Programming—the key reason being lack of direct and preliminary journal and conference proceedings based on the topic. Applicable review of the literature is presented in the respective sections.

Two databases that were primarily searched for the literature review were Engineering Village and Scopus. Engineering Village is an amalgamation of Compendex and INSPEC databases. It consists of a wide range of available material that includes journals, conference proceedings, trade publications, dissertations, patents relevant to the subject matter. Scopus, on the other hand has similar features with over 20,000 titles and over 6500 international publishers. Both the databases consist of materials on a broad array of topics like scientific, technical, medical, and humanities. Although both the databases consist of similar topics and encompass all the requisite material, Engineering Village has more content of direct relevance and easy to navigate search engines. Therefore, it can be regarded as the most appropriate database for literature review. However, numerous other databases will also be explored throughout the literature review process to incorporate diverse material and bolster multi-disciplinary references.

Both Scopus and Engineering Village provide navigation and search criteria that are analogous in nature. They have the search criteria based on the title, author, and author's affiliation, abstract, and subject/title/abstract. Several parameters can be added into the fields and be used in conjunction or exclusively by using AND and OR. Based on specific criteria like the year of publication, accessibility of article, the portal that hosts publication, etc. the searches can be limited and excluded. The only feature that distinguishes Engineering Village and Scopus is the search rate and spheres. Engineering Village enables Quick Search, Expert Search, and Thesaurus that facilitates specific search for precise sections of the dissertation. For example -- Expert Search enables the utilization of selective criteria and generates specific results. Similarly, Thesaurus is useful for the definitions section of research. In order to better understand the functioning of the database, various searches were carried out on both the portals with applicable filters to simplify the search route. Explicit elements from Venn Diagram were selectively combined to evaluate the accuracy of searches. To aid in the acquaintance and reliability of databases, similar searches were carried out in Engineering Village and Scopus. Results of which are tabulated, in Table 1.

Table 1: Search Results as per Database

Keywords and Search Criteria	Number of Results: Engineering Village	Number of Results: Scopus
(Generative Design) AND (Architecture) OR (Construction)	2,861,150	965
(Generative Design) AND (Construction Site) AND (Architecture)	1157	12
(Crane Optimization) AND (Construction Site)	114	88
(Generative Design) AND (Construction Site Layout Planning)	142	0
(Visual Programming) AND (Crane Optimization)	24	10

The search strategy applied was going from 'whole to part'. By including various filters for search strategies -- the results have been narrowed down and have yielded more directed outcomes. Depicted above are just some of the keywords used to direct the literature review. Engineering Village, in my opinion, has generated more expected and relevant results. By making the keywords more specific -- that will aid in garnering content for various sections of the proposal, Engineering Village has delivered more promising results. It cannot, however, be said that Scopus returned an unacceptable quantity of searches. For criteria in which Engineering Village had ten-times the results as compared to Scopus, it was discovered that the latter had more specific results, without any further refinement. Results from Scopus were thus used on certain occasions, if not on several! Post the preliminary searches, search results were downloaded for applicable concepts, and abstracts have been downloaded for directly relevant and applicable studies. Overall, the results of this exercise can be treated as effective. One small indicator being—generation of limited searches when applicable delimitations were introduced, and a more channeled set of keywords was used.

2.4 Construction Site Layout and Planning

2.4.1 Overview and Significance

Owing to the uncertainties associated with a typical Construction Project, it is imperative to develop coherent plans that surround any construction activity. The goal of achieving an ultimate timely-delivered construction project begins by ensuring a well-developed construction site plan—which is the base on which any and every activity is scheduled to be incorporated. Construction Site Layout Planning can be defined as the process of assigning tangible resources to the target construction site, by considering the spatial constraints (Pheng & Hui, 1999). Tangible resources is an extremely broad term that encompasses several components, not limited to Temporary facilities, material, scaffolds or heavy equipment-- details of which have been discussed in the subsequent sections. An efficient functioning of these resources is crucial to ensure that the site development and logistics function in harmony.

The presence of a well-developed construction site plan is, further inevitable to enhance site safety and security and optimize space to reduce the costs associated with material re-location (Zolfagharian & Irizarry, 2014). Additionally, by having a well-defined layout for a fair period of time when the construction begins-- a relatively efficient site operations schema is obtained, that in turn, aids in the optimal achievement of anticipated schedule milestones (Elbeltagi et al., 2001b). The process of Construction Site Layout Planning thus demonstrates a direct substantial effect on all the three aspects that surround the golden triangle of construction management—Time, Cost, and Safety to achieve the predetermined quality. A developed system architecture is thus sort after for avoiding the time-space conflicts and facilitate proactive space management (Akinci & Fischer, 2000). A typical site-layout planning process for construction is shown in Figure 3.

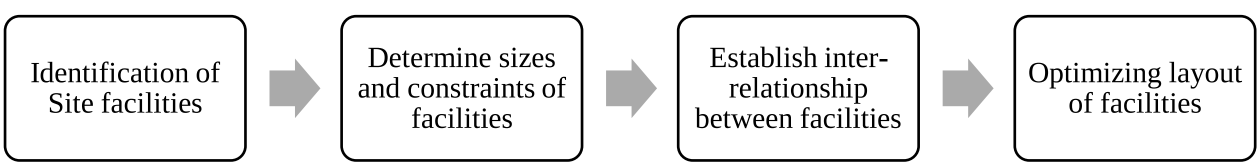


Figure 3 Construction Site Layout Planning Process. Based on the website information: Designing Buildings, UK.

2.4.2 Time

Delivering a construction project as per the anticipated schedule is one of the key factors that directly affect the decision-making process. Failure to account for the changes that might arise throughout a construction project in the initial site plan will incur significant losses in terms of precious project time(Ning et al., 2010a). It is thus imperative to have a construction site layout monitoring system that allows room for real-time site layout and equipment monitoring (Liang et al., 2018). Liang, Kamat, and Menassa (2018) classified planning into off-site and on-site and attempted to establish an interface to transfer the captured on-site data pertaining to layout and equipment—in real-time, by extensively utilizing BIM technologies. Scale-Invariant feature transform and Viewpoint feature histogram were developed to determine accuracy based on an excavator-truck configuration.

Time becomes a more crucial aspect when congested sites are dealt with, in practice. The challenge stems from the fact that limited resources would be used simultaneously owing to spatial and geographical constraints. Simulation models have proven significant in capturing time-based data from construction sites for active monitoring in such cases (Akbas, 2004). Pradhananga and Teizer in 2014, used real-time data and a cell-based simulation model to mobilize resources on-site and visualizing the congestion-on site by providing a framework for comparing alternative site layout plans and permutations associated with varying number of resources.

The time dimension of construction site layout planning is roughly classified into static and dynamic study. However, a new dimension in the name of phased models was introduced as a transition between completely static and dynamic models (Sadeghpour and Andayesh, 2014). As the literature indicates, several mathematical and visual techniques have been extensively used to enable the generation of an Optimum construction site layout plan and save time. Some of them include 3D-Planning of equipment (Horenburg et. al., 2010), UAV and 4D BIM (Hamledari et al., 2018) in the visual optimization realm, and harmony search algorithm (Dongmin et. al. 2016), global optimization models (Said and El-Rayes, 2013) and application of Electimize (Abdel-Raheem and Khalafallah, 2012) in the mathematical optimization sphere. Selected techniques directly affecting the problem statement of the study have been discussed in subsequent sections.

2.4.3 Cost

In addition to time, cost is another such equally important metric that determines the success of construction project delivery. Lack of an efficient construction site-layout plan increases the expected cost of the project beyond the anticipated contingencies (Abdel-Raheem and Khalafallah, 2012). This, in turn, affects the multi-stakeholder interactions (Song et. al., 2019). Song, Pnetildea-Mora, Shen, Zhang and Xu developed an interaction model of Construction Site Layout Planning with i) Construction Material Logistics Planning and ii) Security Planning, at the bi-level model involving logistics planner and safety manager.

To properly deal with the gravity of construction cost based on construction site layout plan-- workplace usage, and construction conflicts minimization is ensured based on project-specific constraints and practitioners' guidelines (Zolfagharian & Irizarry, 2014). Cost moreover has a direct correlation between other accompanying factors that control the flow of project execution. It demonstrates a strong correlation between potential risks arising from interaction flows as well as hazardous sources that demand a tri-objective optimization model (Ning et. al., 2018). This significance magnifies when dealing with a type of construction that is typically classified as 'crucial'. For example: due consideration needs to be given when hazardous material needs to be transported in a hydropower construction project, to minimize site layout costs and economic losses (Xu et. al., 2016). A clear demarcated relation between cost and site layout plan thus becomes vital in these ever-changing circumstances.

As mentioned, cost becomes an extremely crucial factor when directly comparing it to another aspect of similar or equal weightage. More advanced optimization techniques need to be adopted in such scenarios to judiciously deal with the cost aspect and establishing relative priorities. Ning and Lam in 2013 used a Multi-Objective algorithm to carry out a comprehensive cost-safety trade-off. Random-grids recognition strategy was employed without increasing computational complexities and validated using a residential building project. Another such crucial aspect that can affect the cost-based decision on CSLP is an environmental parameter. A multi-objective algorithm is thus a solution in such cases. To encapsulate a similar eccentric scenario-- Hammad, Akbarnezhad, and Rey (2016) incorporated a mixed-integer nonlinear programming model to minimize noise pollution and simultaneously the transportation costs.

2.4.4 Safety

In addition to time and cost, one of the premier aspects that determine the configuration of a construction site layout plan is its safety. With ever-changing considerations in the construction industry—safety has garnered increasing attention owing to its moral and public policy facets. In order to properly account specific safety features while planning a construction site layout plan, the alternatives should be considered beyond, yet in conjunction with the singular umbrella of cost (Ning and Liu, 2015). In this research, multi-objective functions of safety level and safety cost were planned to use the ACO algorithm to determine an accurate trade-off relationship.

In 2018, Ning, Qi, Wu, and Wang further sharpened the framework by including the aspects of detailed risk factors. Facility safety relationships and geographic safety relationships were derived by imposing cost as a critical barrier and implementing tri-objective ant-colony objectives. Potential risks arising from interaction flows and hazardous sources were established by connecting temporary facilities to solve the pertinent problem. Such problems are usually dealt with by using optimization techniques and heuristic methods (Haythman et al., 2008). In the study, Hayman, Mohammad, and Moheeb considered safety and environmental aspects a developed a genetic algorithm model and incorporated the number of trades and interrelated planning constraints.

Risks, however, cannot be necessarily classified into the above mentioned two categories. Thus, to account for a holistic risk factor, Ning, Qi, and Wu (2018) developed another study based on a quantitative safety risk assessment model that incorporated a myriad of possible hazards surrounding a construction site. The likelihood and linear attenuation law were incorporated to develop a model that was later verified via a case study on the proposed model.

Construction safety becomes more significant when concerning temporary facilities—owing to their dynamic, fragile, and volatile nature. Ning, Qi, Wu, and Wang in 2019 incorporated the effects of noise pollution via a multi-objective optimization model. Special emphasis was laid on environmental protection, economic efficiency and occupational safety to develop framework revolving around industrial layout facilities. Back in 2008, emerging technologies like GIS were extensively used to dynamically assess the safety of construction site layout around the temporary facilities construction and placement (Karan and Ardeshir, 2008).

2.4.5 Components

Construction Site Layout Plan, in its easiest terms, is a well-developed and comprehensive setup that augments utilization of all the on-site available resources, and thereby increases productivity through the entire life cycle of the construction process. One of the key indicators of a well-planned construction is the placement of temporary buildings and facilities. The process of developing an optimal layout for temporary facilities "involves the planning of temporary construction facilities within the boundaries of the restricted sites so that the materials transportation and rearrangement costs are minimized and distances between various departments are optimized" (Xu & Song, 2015, p.30). The umbrella of temporary facilities incorporates a number of elements: right from fabrication shops, batch plants and accommodation facilities to reinforcement places, maintenance areas, and warehouses—thereby making this planning process extremely crucial to deliberate upon. It is imperative to generate a full-bodied, durable, and sustainable configuration. The CSLP process thus deserves proper scrutiny and time investment to achieve the targeted productivity and obtain a framework that sharpens as the project progresses (Kim et al., 2012).

This process, however, has been facing a plethora of problems for several years now. Some of the problems identified in accurately determining an optimum temporary facility site layout include Incomplete design with ill-structured information, extreme labor and manual intervention coupled with subjectivity, lack of diversity and structured approach, and lack of rigorous analysis (Cheng & O'connor, 1994). Another obstacle that significantly reduces the value of utilizing temporary facilities is exceptionally high travel times of material with respect to its host equipment and hence the waiting times that stem out of the same. Thus, in order to generate an efficient layout—the optimum location of site facilities with minimal travel time needs to be taken into account (Tommelein, 1999).

One of the most important pieces of equipment on a construction site is a Crane. It is a device that affects the material movement and minimizes the initial cost of construction. A well-optimized crane position is principal to facilitate the informed decision-making process (Gray & Little, 1985a) and efficient performance of its complementary factors like material characteristics, site configurations, and building layout strategies (Abdelmegid et al., 2015). It is also enormously central to highlight that Cranes have the ability to showcase a conflict-free load handling and space management setup (Emsley, 2001). The main focus of this study is thus narrowed down to Crane

(Tower Crane, as explained subsequently). Numerous optimization techniques and their detailed insights are highlighted in the succeeding section.

A typical construction site layout showcasing all the requisite components is shown in Figure 4.

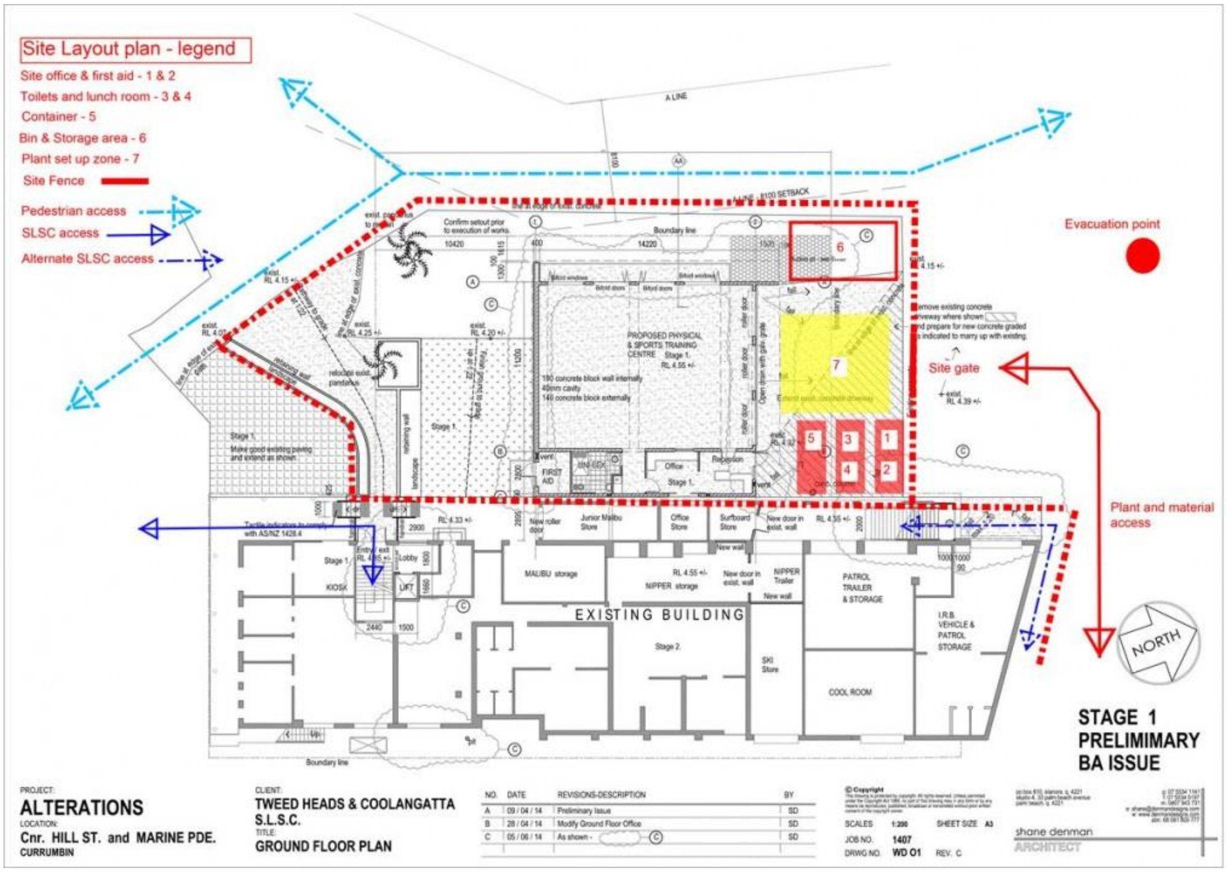


Figure 4 Typical Construction Site Layout Plan. Retrieved from the website: Construction Tuts. https://www.constructiontuts.com/construction-site-layout-planning/

2.5 Tower Crane Optimization

2.5.1 Overview and Significance

One of the most important pieces of equipment that exerts a direct significant impact on a construction site layout is Crane. Owing to its role in facilitating the majority of material movement during the construction phase—proper selection, placement, and optimization of the crane are extremely important while making decisions in the preconstruction phase (Gray & Little, 1985).

Cranes are generally classified into mobile and tower cranes. Based on the factors listed above, Tower Crane has demonstrated higher importance while considering the above mentioned CSLP aspects – Time, Cost, and Safety. Owing to increased production rates, reduced requirement for daily management of operations (Ji & Leite, 2018a), and increased safety (Shapira & Lyachin, 2009)—this research has been directed to the optimization of Tower Crane position.

As stated, an optimum position of tower crane can be of huge significance to various key performance indicators and evaluation metrics of a construction project. In fact, it has evidently showcased its impact on reducing the cost and increasing the overall productivity of the construction operations (Hasan et. al., 2013). This impact multiplies when the scope of the work increases, and the number of direct crane-based operations proliferate. Especially in high rise buildings where a tower crane is used to "lift various components including prefabricated elements, steel beams, ready0mixed concrete, and large-panel formwork" (Moussavi Nadoushani et. al., 2017, p.1).

Another prominent impact that a tower crane manifests—is by sharpening its primary function: material conveyance and transportation. An optimum position of the tower crane is thus a prerequisite for handling bulky materials, transportation of heavy prefabricated units, and allocating initial configuration of temporary facilities based on tower crane position (Kaveh and Vazirinia, 2018). This study further elucidates how an optimized tower crane can reduce operating costs based on material quantity between supply and demand points on a construction site. By further combining heuristics and mathematical optimization algorithms with visual models, layout optimization of sites can be used to minimize travel times and even enhance labor efficiencies. Gomez, Samrah, and Almullaali in 2016, for example, used GIS to create service area polygons to reduce the travel time per service area by incorporating the impact of decision variables. These decision variables were temporary facilities and tower crane (as equipment).

Finally, a group of tower cranes if used on a construction site—need to be dealt with utmost scrupulousness. An elaborate analysis of whether the benefits and improvements outweigh the problems pertinent needs to be incorporated to reach a more sound solution. More than one tower crane when used- engenders more flexibility to meet stipulated demands, reduce the net duration for overall task-set, and higher coverage area under the preview. However, care must be taken to avoid collisions of the crane, pay due heed to the safety aspects, and diligently study the overlapping regions in congested areas (Hattab et al., 2017). Moreover, using multiple tower cranes might contradict efficient operations and lead to a more detailed demand for functioning of crane jibs at different levels—making the entire process exceedingly arduous and complex(Zhang et al., 1999). Figure 2.5 shows the work-area of a single tower crane on a construction site.

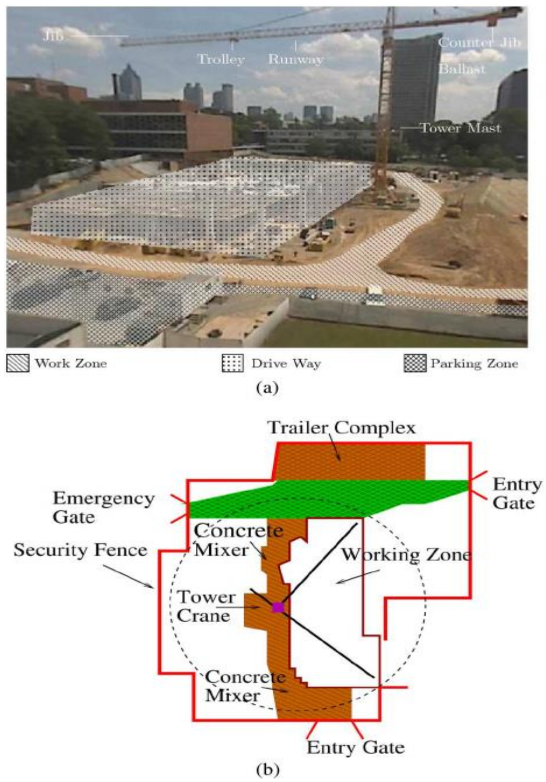


Figure 5 Accessibility of Tower Crane on Construction Site. A visual and 2D representation of working areas of a tower crane (Yang et al., 2014)

2.5.2 Optimization Techniques for Tower Crane

Over the past several years, numerous techniques have been used to optimize various aspects pertaining to a Tower Crane. This optimization can be centered around the location of the selected tower crane, a number of tower cranes, or even the type of tower crane. The techniques for each aspect, although specific, can be roughly classified into: Mathematical and Visual Models. These techniques have been used independently, and in conjunction as discussed subsequently.

2.5.2.1 *Mathematical Optimization Techniques*

One of the most primitive yet efficient methods for crane optimization is by using flow charts. These flow charts can be later transformed into a computational algorithm for multiple analyses and iterations. Gray and Little in 1985, used what they said as 'systematic approach' for crane selection. Depending on the forms of material handling and specified workload-- the requirement of the crane and the number of cranes were calculated. Further, depending on the site-specific conditions, specific crane configurations were looked out for. A logic-based iterative program can thus pave the way for examining a wider research and craneage requirements (Gray & Little, 1985).

Another pervasive technique used for optimizing specific characteristics of tower crane involves utilizing Genetic Algorithm and optimization models. Back in 2001—Tam, Tong, and Chan used Genetic Algorithm (GA) for Optimizing Supply Locations around Tower Crane. A GA model was used to investigate and analyze the key storage areas and tower crane by taking into consideration the complexities extending beyond shape, size, and space constraints of the facilities present on the site. The GA model was applied to optimize tower crane outputs and supply point locations for various trades (Tam et al., 2001). Further in 2015, Abdelmegid, Shawki, and Abdel-Khalek used GAs to minimize total transportation time on construction sites. Various novel factors like vertical velocity of tower crane jib, number of cycles for each task considering capacity for each location to deal with, and spatial constraints of the crane were considered for development and validation of the model(Abdelmegid et al., 2015).

Genetic algorithms can also be used in collaboration with techniques like mixed-linear-integer-programming (MILP) problem using solvable by standard branch and bound technique for certain optimal results (Huang et al., 2011a). Huang, Wong, and Tam used constraint sets to linearize the quadratic problem and demonstrated an improvement of 7% for facility and location considerations by ensuring design flexibility.

In addition to the above-mentioned factors, one important choice that might arise while making a decision pertaining to the crane is choosing the right type of crane. Dalalah, Oqla, and Hayajneh used the Analytical Hierarchy Process (AHP) in 2010 to determine multi-criteria analysis while selecting the cranes. Knowledge-based evaluation and assessment were embedded in Expert Choice Software followed by sensitivity analysis to ensure confidence and bolster precision in the validity of the study.

In order to complement the shortcomings of a specific mathematical technique, a supplementary algorithmic tool might be used to enhance the decision-making process. For example – in the study conducted by Tam and Tong in 2002, "artificial neural networks are used to model the non-linear operations of a key site facility: a tower crane — for high-rise public housing construction. Then genetic algorithms are used to determine the locations of the tower crane, supply points, and demand points by optimizing the transportation time and costs." (p.257). This collaboration yielded a more comprehensive and quantitative way to assess the effectiveness of site layout. (Tam & Tong, 2003)

2.5.2.2 *Visual Techniques for Optimization*

Considering that construction site professionals with minimal programming knowledge would be the front-end users of the developed model, it is imperative to have models that can be easily construed, and the weightiness of the issue be easily interpreted. The process of selecting an optimal plan should hence provide a pool of alternatives to the user rather than a definite solution—in order to better facilitate the decision-making process. Using visual models for any such processes can hence enable the development of better perceptions and substantiate abstractions involved (Arnheim, 1997). Thus, the ubiquitous dimension of visuals and shapes should be used to better arrive at informed solutions (Jaenichen, 2017).

One of the most significant obstructions that visuals help in obviating is spatial conflicts and collision detection. Han, Shafiul, Zhen, Altaf, and Al-Hussein in 2013 used a matrix-based visualization model to facilitate a collision-free crane operation path. More than 40 factors were used for simulation and the proposed methodology was tested for boiler house structures in Germany to lift a 102-ton load—resulting in accurately deciding the two tower cranes from the database. When multiple tower cranes are required on the site, the probability of collisions and conflicts increases exponentially (Sleiman et. al., 2016). In this study conducted by Sleiman, Zankoul, Khoury, and Hamzeh—in addition to carrying out an extensive study on sensors and their locations of the site, the data was integrated on the 4D schedule. This groundbreaking simulation not only reduced clashes (and hence the duration) but also highlights the concerns associated with joint crane operations.

Over the years, Building Information Modelling (BIM) has been demonstrated as one of the strongest visual-based simulation technologies, as highlighted in the subsequent section. It is thus used heavily to moderate tower crane operations, as well. The hard-pressed issue of conflicts, as discussed above, exacerbates when blind lifts come into the picture (Ghang et. al., 2012). In this research, 3D BIM data was merged with sensors to obtain real-time visual data and thereby demonstrated an ease of system usage from 3.2 to 4.4 on the Likert scale to deal with similar situations. The capabilities of BIM, however, extend beyond the general modeling and visualization applications. Ji and Leite in 2018 leveraged 4D BIM and rule-based checking to automate the tower crane planning process. By developing a prototype that can embed US-based rule-checking schemas—manual intervention was reduced to review more alternatives and thereby increase the efficiency of the associated process in the pre-construction phase (Ji & Leite, 2018a).

BIM, moreover, possesses the capability of encompassing several salient features associated with Tower Crane optimization. Outlooks of hook travel time, travel distance, and length of jib can be coupled with IFC data to obtain a workload curve. By incorporating the coordinates and parameters, different positions are identified to corroborate the safety and constructability of the developed model (Funtik and Gasparik, 2016).

In order to augment the capabilities, just like mathematical optimization techniques, BIM has been used in conjunction with GIS to enhance the spatial competencies of the completed model(Irizarry & Karan, 2012). BIM's potential is utilized for digital visualization in the pre-construction phase whereas GIS provides a platform to incorporate huge chunks of spatial data and enable topographic geometry. In the collaborative research conducted by Irizarry and Karan, feasible locations identified by GIS, based on demand and supply points are linked with BIM to obtain 3D Views and simplify the decision-making platform for optimal tower crane position.

2.5.2.3 *Collaborative Optimization Techniques*

As discussed above, 'mathematical' and 'visual' is the most broadly accepted classification for the optimization of the tower crane. However, both of them have their independent advantages and disadvantages. For example, mathematical models have extreme computational capabilities and data synthesizing proficiencies but require lots of manual data input and lack visual representations. The visual models, on the other hand, lack in-built computational and optimization skills- as required for the operation. Thus, several research efforts have been carried out to integrate the individual advantages of both these techniques and generate a wholesome resultant model.

BIM has largely been used in conjunction with Firefly algorithm for specific optimization needs of Tower Crane. In 2014, a four-step procedure was followed by the team of Wang, Liu, Shou, Wang, and Hou to optimize the target layout for tower crane. As stated by the team in the documented work:

> Firstly, BIM technology is utilized to automatically generate the quantity of materials that need to be transported. Then firefly algorithms are used to determine the locations of tower cranes, supply points, and demand points according to transportation requirements, time, and cost. Thirdly, the optimal tower crane layout scheme will be visualized by 4-Dimension (4D) BIM to verify its constructability and safety based on computer simulation and individual experience. Finally, a practical case is selected to evaluate the developed approach. In addition, some lessons learned and issues are highlighted that help direct future research and implementation (Wang et al., 2014, p.321).

An extended study has also been carried out, where BIM acts as a data-input tool and the Firefly algorithm is used to decide the best-fit location as per the supply points (Wang et al., 2015). In this study: Wang, Zhang, Shou, Wang, Xu, Kim, and Wu developed a three-module system to efficiently handle parametric data. The details of the workflow adopted is best represented via a pictorial framework as shown in Figure 6.

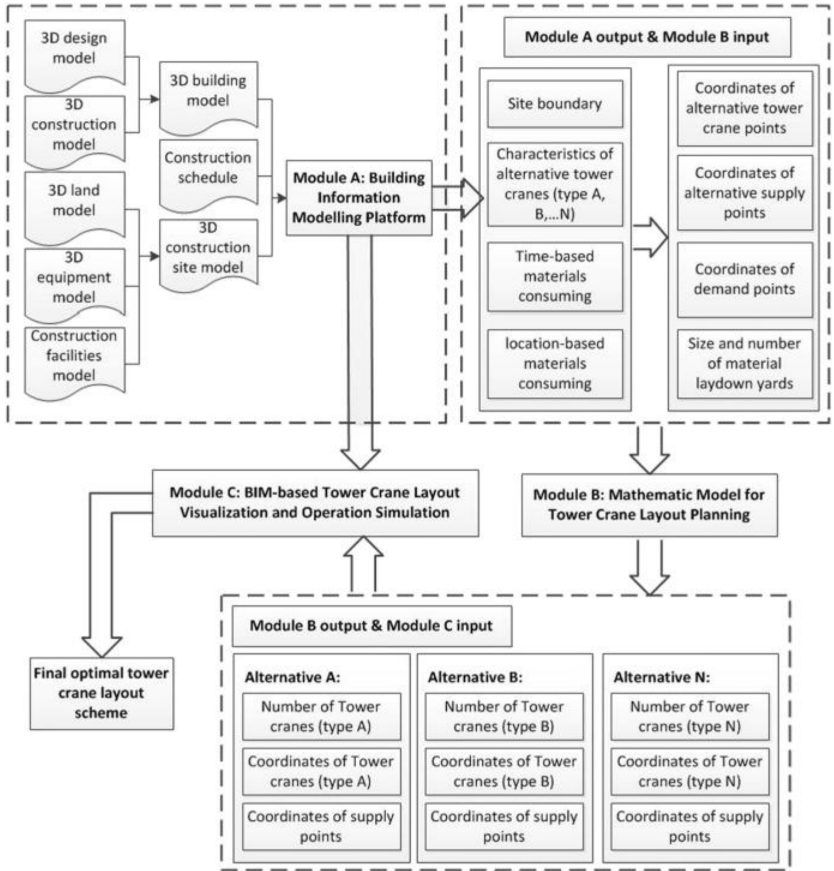


Figure 6: Framework for BIM automated tower crane layout planning system. Wang et al. (2015)

As stated above, one of the premier motives of tower crane functioning is to avoid clashes and conflicts. BIM and genetic algorithms can be unified to ensure safety and attain this motive (Marzouk & Abubakr, 2016). A three-step study was carried out for developing a decision-making model to choose the correct tower crane, and then perform optimization to decide on the ideal number and locations of tower crane. Finally, the 4D simulation model for operations was carried out to delineate the potential action of the developed framework. In 2017, a more generic study was further carried out by Ji, Sankaran, Choi, and Leite to formalize tower crane planning criteria by incorporating industry-based standards and guidelines. The knowledge of industry experts was synthesized to use BIM and optimization methods to generate a model, in compliance with regulatory institutes (Ji et al., 2017).

2.5.2.4 ***Miscellaneous Techniques***

Sparsely and minorly, methodologies extending beyond the above-mentioned techniques have been used for tower crane optimization. Selected research that addresses or is indirectly associated with either the mathematical or visual optimization techniques is discussed in this section.

For high-rise building construction, BIM has been used in conjunction with automation for identifying potential areas where the latter primarily augments the crane performances (Heikkila et. al., 2013). The execution, planning, and control measures of BIM have been incorporated specific to an infrastructure construction project and mapped with possible benefits associated with automation. The control system so developed after integration claims to sharpen the construction site operations and logistics.

A radical approach to robotize the tower cranes in a dynamic BIM environment was undertaken by Dutta, Cai, Huang, and Zheng in 2020. BIM was used in data management for discrete and continuous collision detection and path planning. Computer-Aided Lift Planning (CALP) was proposed as an intelligent decision-making system for graphical simulations. A Decision support system and Path Re-planner was used to validate the effectiveness of specific tower crane on two different real-world models of construction sites. Optimum real-time re-planning system was ultimately delivered as a product of this work (Dutta et al., 2020).

Younes and Marzouk utilized a relatively novel concept called Agent-based simulation to avoid crane clashes by considering activity conflicts. This study aimed to quantify the effect of conflict among tower cranes and map the effects on time and cost calculations. Operations and interactions between agents in the models help compare several layouts and decide the best fit as per the required specifics—with emphasis on time and cost (Ji et al., 2017).

Based on the techniques discussed above, it can be said that specific techniques need to be adopted to achieve direct goals. If achieving multi-dimensional goals is the aim of the study, the most commonly selected route is using the above-mentioned techniques in conjunction. However, various problems like mathematical and computational abilities of on-site personnel, interoperability between software, and complexities associated with compatibility and collaboration-- hinder a free combination of techniques. Generative Design, is one such technique that is proposed as a solution to this problem, as discussed subsequently.

2.6 Generative Design

2.6.1 Evolution of Technologies in Construction

Generative Design is a term whose definition, significance, and applicability in the construction has been well-demarcated only in the recent years. Construction Industry has witnessed a sharp yet subtle change in the myriad and diversity of the technologies-- to cater to several needs and ease an array of job responsibilities. Herewith, an extremely concise overview of this evolution has been presented to inform the reader about the growth of technology, specifically, in the construction sector.

As cited by Cory (2019), the construction management process "is fragmented as individuals from different organizations which are geographically and temporarily dispersed are involved" (Luck, 1996, p.1). The earliest technique for design collaboration and information exchange dates back to hardbound paper illustrations. Bi-dimensional graphics and visual representations were used to represent plans, elevations, and sections by using core paper-based data (Santos and Ferreira, 2008). The next step, i.e. Digital representation of this data was what turned out to be 2D Computer-Aided Design (CAD). This digital interface made provisions to easily workaround with the drawings and make frequent yet dynamic changes without any significant time being elapsed (Ye et. al., 2006). The need for enhanced visualization along with spatial perceptions and judgments gave birth to 3D CAD. It enabled the information to be viewed in 3D i.e. Length, Height, and Breadth (Azhar, 2011).

BIM followed next as an improvised version of 3D CAD. BIM-enabled the representation of functional and physical characteristics associated with every entity in the model (NBIMS, 2017). By representing these characteristics, BIM provides a platform to recognize, analyze and even solve multifaceted problems of construction including, but not limited to—architecture, structure, HVAC (Heating, Ventilation, Air Conditioning, and Cooling) and even MEPF (Mechanical, Electrical, Plumbing, and Fire) (Cory and Jenkins, 2008). BIM, furthermore, expanded the technological scope by improvising in the form of operating with the database, working with design disputes and RFIs, and easy collaboration and sharing plug-ins (Rowlinson et. al., 2010). Today, BIM actively continues to add a new dimension on its existing foundation in the form of Schedule (4D), Cost (5D), Sustainability (6D), location-based systems (7D), and even disaster management systems (8D)—as explained by Cory (2019).

The breadth and realm of BIM is ever-increasing as per the current research trends. What started out as 3D modeling has now provided the AEC industry with a multitude of technologies to choose from. As per specific goals set by the AEC firm—there exist realms like Computational BIM, Augmented and Virtual Reality, Laser Scanning to name a few (Cory, 2019). Lately, all of this has been roughly grouped nowadays into the cluster called Virtual Design and Construction. Computational BIM, adopted as Dynamo, is one such branch that stems from this tree and is transforming into what is known as—Generative Design.

2.6.2 Applications of Generative Design in Construction

Generative Design is a design method that assists human designers to explore an array of design possibilities for the entire domain of problems by stimulating designer's creativity and routing through viable design spaces within the predefined performance criteria (Krish, 2010). It can be treated as a framework that allows an interaction with the end-product without having direct (hands-on) intervention with the results. Instead, it employs abstract definitions to explore multiple design variations and then displays and produces the elements of the finished design products (Fischer and Herr, 2001).

"The power of generative design tools is that these can guide a novice down an exploratory path" (Chase, 2005, p. 689). One of the premier motives of this research is to help construction site planners optimize site performances without having to go through the complex procedures of understanding mathematical algorithms. Chase attempted to develop a formal methodology for generating several designs—based on predefined rules and procedures, but not including the building codes. Based on the study carried out to characterize generative design tools and methods, perform computer programming and using samplers as a premium tool for Generative Design, Chase concluded and recommended the following points:

i. Generative Design accurately represent key forms of design generation – "geometry, spatial relations, and transformations, recursion, reiteration, procedures, and encapsulation" (p.697).

ii. Generative Design can leverage an assortment of benefits depending upon the first user. Right from contemplating on basic design paradigms to exploring complex designs to developing insightful theories of design and computational and software design—Generative Design can nurture each one of them!

iii. Provided appropriate teaching tools are used to enter the realm of Generative Design, it allows exploration of the pool of design alternatives, rich representation of forms, generating and testing of models, and compatibility with other methods to understand the theoretical framework of a methodology.

Back in 2000, Chien and Flemming developed a navigation space for Generative Design Systems by obtaining power from explicit depictions of design requirements and add to the information generated by the system. Their approach took into account "studies dealing with human spatial cognition, wayfinding in physical environments, and information navigation in electronic media" (p.1). The developed prototype was tested on five aspects of usability: Ease of learning, efficiency of usage, ease of remembrance, prevention of errors, and subjective pleasing.

Generative Design has also paved the way for multi-disciplinary collaboration of robotics in construction and human factors for generative architectural design (Ameijde, 2018). The research discussed "a series of small projects that explore new scenarios for the creation of architectural structures, experimenting with mobile and low-cost fabrication devices, connected to generative design algorithms driven by sensory technologies" (p.523)

Generative Design has furthermore elucidated its applications on several occasions in developing sustainable environments from an architectural viewpoint. Chang, Saha, Castro-Lacouture, and Yang developed a study in 2019 utilized Generative Design for multi-criteria performance analysis of Urban Designs. An algorithm was developed that generates site requirements and developed requirements of the campus and was later tested for sky openings, solar radiation, and energy consumption. The study proposed a "data-driven urban design approach that connects generative design and multi-criteria performance analyses. The relationships between urban geometric forms and performance criteria function derive guidelines for a sustainable and green campus" (Chang et. al., 2018, p.3994).

In order to augment the capacities of Generative Design, it is usually coupled with several other design and non-design-based techniques. Abrishami, Goulding, Rahimian, and Ganah integrated Generative Design with BIM in 2014 to exploit computational design methods and provide a base framework for implementation and increasing the ‘level of automation’ in AEC. Based on surveys and modeling form generation—virtual generative design workspace was developed using BIM as the key element (Abrishami et al., 2014).

Furthermore, Abdullah and Kamara in 2013 integrated Parametric Design Procedures (PDPs) to address the specific issue of recreating configurations and parameters pertaining to topography and geometry. The model encapsulated the factor of changing parameters and tested the prototype using Grasshopper – a visual programming tool (Abdullah and Kamara, 2013). The potential of Visual Programming has been in several dissertations and research studies in the past, as discussed in the subsequent section.

2.6.3 Visual Programming

Visual Programming is a tool that creates an environment for architects to create, modify, and implement the designs created via direct manipulation. It eliminates redundant and unnecessary tasks by modeling the parameters rather than just the final design, as a whole (Graham et. al., 1995). It has demonstrated its applications by not only acting as an alias and attaining goals specific to Generative Design but also independently, as one of the most powerful plug-ins for Revit. Considering the multitude of capabilities Visual Programming possesses and its applications that extend beyond just information visualization—it exists in the literature by taking several other names. Some of them include: Representational Programming (Stouff and Chang, 2010), Graphics Programming (Roozbeh and Soderman, 2018), Computational BIM (Nezamaldin, 2019) and even Algorithmic BIM (Heist, 2016)—depending on the specific function served.

As described above, Abdullah and Kamara used Grasshopper to facilitate the effective utilization of PDPs in Generative Design. Stouffs and Chang (2010) used the term representational programming to illustrate the flow of data along with network nodes while performing design analysis. Using Grasshopper graphical algorithm editor and Autodesk Maya, representational structures called Sorts were developed, applications of which were exemplified in building design analysis and implemented via primitive design analysis tool.

In May 2016, for her master’s dissertation in Architecture—Sofia Heist utilized the term Algorithmic-based Building Information Modelling (A-BIM) and compared A-CAD, A-BIM, and Manual BIM. An extensive evaluation was carried out on the basis of automation of repetitive tasks, propagation of changes, exploration of design alternatives, building information, optimization, parametric and associative capabilities, and geometric modeling. The study concluded by demonstrating the recovery of time and efforts based on the initial investment carried out while implementing A-BIM—especially while dealing with repetitive structures, masses, and forms.

A similar master's dissertation was carried out by Nezamaldin in 2019 in the name of Parametric Design. The research establishes a workflow from 2D CAD to 3D BIM and further performs analysis and automation using Dynamo. The research used default Dynamo scripts to automate the repetitive tasks and provided a strong base to illustrate the working potential of this Visual Programming tool.

The utilization of Dynamo as a Visual Programming tool is in fact widespread and prevalent—more dominantly in the field of Automation in Construction. For example, Shishina and Sergeev (2019), used Dynamo to address one of the most cumbersome tasks in BIM – the geometry of complex objects. In this study, a toolkit is considered alongside a developed script to accelerate the process of project geometry creation and incepting paradigms for the design of non-standard construction objects—based on specific project needs (Shishina and Sergeev, 2019). Dynamo has furthermore successfully shown indications of mitigating one of the most widespread issues in VDC and BIM: Interoperability (Sandzshiev et al., 2018). Considering an Open BIM perspective, data from IFC was procured to present "itself with the best open standard and neutral alternative to facilitate the exchange" (p.75). Dynamo was successfully highlighted as an effective tool to address problems revolving around rectifying problems associated with importing IFC format via an automated framework.

Based on the literature reviewed above, it won't be hyperbolic to say that Generative Design implemented via a Visual Programming tool- holds the potential to address all the issues that this research targets. By readily generating a pool of alternatives, mitigating problems pertaining to compatibility, collaboration, and interoperability, providing a platform for optimization and allowing automation of repetitive tasks—Generative Design certainly demarcated bright likelihoods of optimizing Tower Crane position. Owing to the availability of open-source Dynamo scripts and user-friendly visual interface—it was worth the wait to obtain participant's responses to this inter-disciplinary theory.

2.7 Summary

This chapter presents a Review of Literature pertinent to the subject matter. The first section gives an overview of the topic, along with the databases referred to and search strategies. The next section describes the realm of Construction Site Layout Planning and explains its direct contribution to the cost, time, and safety of a construction site. The last sub-module concentrating on the components leads to an important piece of equipment on job-site: Construction Crane. The next section describes the need and significance of a Tower Crane and presents an exhaustive description of various optimization techniques used for optimization. Based on the flaws identified, the realm of Generative Design is explored and cursorily tested for proof-of-concept. Owing to the potential visual programming clutches, it is envisioned that this paradigm would help optimize the position of tower crane on the construction site.

CHAPTER 3. METHODOLOGY

3.1 Overview of Problem and Purpose

A construction site can be regarded as an instrument without which no construction can practically take place. It is thus inevitable to have a well-planned construction site that marks the beginning of the successful delivery of the final project. A construction site acts as a host to a variety of construction essentials like temporary facilities, temporary structures, heavy equipment, etc. to name a few (Rapp & Benhart, 2015). Construction Crane has been recognized as one of the pivotal elements of a construction site that directly affects decision-making in the construction process and ensures proper utilization of material characteristics associated with the construction site (Abdelmegid et al., 2015; Gray & Little, 1985). Cranes are roughly classified as Mobile and Tower. However, the latter ones have lately garnered more attention in recent researches owing to their increased productivity(Ji & Leite, 2018) and safety(Shapira & Lyachin, 2009). Of all the aspects associated with tower crane, it is critical to ensure that it is positioned correctly to facilitate the smooth flow of material and develop an easily accessible and liftable framework(Emsley, 2001). An optimum configuration of the tower crane is hence paramount to rationalize operational time cycles, enhance the supply chain process, and even generate a sustainable construction site environment (Dasović et al., 2019). The importance of a perfect tower crane's position has repeatedly insisted upon in history. However, owing to the extra time and efforts required to introduce a paradigm for optimization—conventional techniques are usually sought out for. These include ad-hoc approach, previous knowledge of professionals, and referencing previous construction site layouts—to name a few(Huang et al., 2011b). The problem addressed by this study is *Improper Planning of Construction Crane Confirmations while developing the Construction Site Layout Plan.*

While evaluating the best position of a given tower crane—several factors like crane's reachability, avoidance of conflicts, and easy transmission of material and elements on the construction site have been identified (Dalalah et al., 2010). Lift-ability of the tower crane thus needs to be augmented to identify the intersection area and lower the possibility of conflicts (Irizarry & Karan, 2012). The lifting assignments of the tower crane posit a huge significance in minimizing the idle time and thereby maximizing the utilization of tower crane(Marzouk &

Abubakr, 2016). The purpose of this study is thus to *Optimize the Position of a Tower Crane on a Construction Site by enhancing its lifting operations.*

Previous researches have implemented a myriad of techniques to optimize the position of tower crane as indicated in the last chapter. However, each one of them has manifested significant flaws that hinder an effective decision-making process—as indicated in the subsequent sections. To rule out and better treat the decisive factors that accompany, Generative Design was implemented for this research. The potential to visually present prototypes for arriving at informed solutions, combined with its documented applications in various realms of the construction industry—makes Generative Design the best pick for the planned methodology.

With the implementation of every novel technique, it is paramount to ensure that the primary users of the deliverable can easily access the benefits associated. In order to better decide the applicability, it is thus critical to test-run the model by its past, existing, or future personnel (Castronovo et al., 2013). This study thus evaluated the usability aspect—as applicability criteria to test the implementation of Generative Design on Tower Crane Planning (Faizal Omar et al., 2014; Ku & Taiebat, 2011). The various indicators to test the usability of this paradigm included: Ease of Learning, Efficiency of Usage, Ease of Remembrance, Prevention of Errors and Subjective Pleasing.

3.2 Research Questions

For the purpose of clarification and establishing a brief framework of what follows, the research questions have been restated as follows:

1. How significant is Generative Design in optimizing the Tower Crane Position?
2. What criteria affect the utilization of Generative Design for Tower Crane Planning?

3.3 Research Framework

A number of studies have been undertaken on optimizing the position of a tower crane. However, each one of them has demarcated specific drawbacks that have hindered its pervasive utilization. The major goal of this study is thus to utilize and work with open-source Dynamo scripts and develop a Visual Programming prototype to achieve the outcomes of Generative Design. It is intended that this model be easily interpreted by construction professionals without having the need and knowledge to rigorously comprehend complex computational algorithms. The framework of this research would be 'Conceptual Framework- Working Hypothesis'. The steps associated with carrying out this empirical investigation were as follows:

1. Collate and modify Visual Programming Scripts specific to optimizing the position of a Tower Crane on a given Construction Site.
2. Use the developed model to optimize the position of Tower Crane on various construction sites and evaluate the improvement based on the lift score.
3. Evaluate the usability of the model based on the participant's responses to the benefits of the Generative Design model.
4. Determine the potential barriers to implementation and readiness to adoptability of the developed Generative Design model for Tower Crane Planning.

3.4 Justification of Technique Chosen

It has been discovered through previous research that several optimization techniques have been utilized to plan the Tower Crane position on a construction site. As indicated in the previous chapter—these techniques can roughly be classified into Mathematical Models and Visual-based models (Ji et al., 2017). A classification of the same has been presented in Figure 3.1

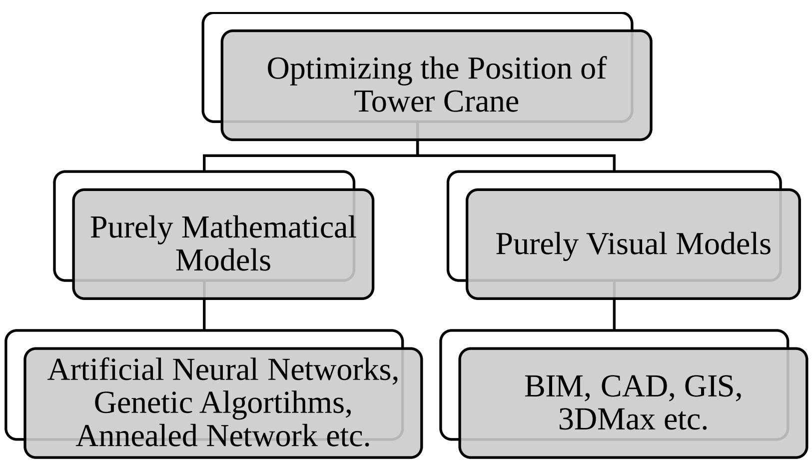


Figure 7: Classification of Optimization Models for Tower Crane

The left half of the tree i.e. Purely Mathematical models require a large amount of redundant data that needs to be fed manually(J. Wang et al., 2015). Moreover, there exist mathematical parameters that need to be dealt with, and developed from scratch- ultimately constituting several abstract inferences(Tam et al., 2001). The complexity and core computational sophistication demanded by these models make them extremely complicated and site-specific to be used by firsthand users and construction site planners. This set of technologies has therefore failed to perform optimization that facilitates 3D visualization and detect spatial conflict detection (J. Wang et al., 2015) and thereby hindering an opportunity to examine a broad range of feasible solutions (Marzouk & Abubakr, 2016). Construction Site Planners thus need a more directly relevant and easily construable model, that possesses a high level of similarity to the actual job site conditions (Tam et al., 2001; Wang et al., 2015).

Visuals in construction require less amount of tacit interpretations and are more readily comprehensible—thereby helping generate quality decisions in lesser time (Ji et al., 2017). Purely Visual Based Models are thus highly regarded by on-site professionals for the purpose of optimization (Marzouk & Abubakr, 2016). Of the technologies listed above, BIM has by far been demonstrated as the most superior in the group owing to several benefits it visibly posits. BIM successfully represents the functional and physical characteristics of every element associated with the target construction site by associating every possible characteristic to its actual magnitude or value (Abrishami et al., 2014). Furthermore, several characteristics associated with BIM like quantity extraction, parametricity, and clash detective measures make it easily compatible with additional computational models (Marzouk & Abubakr, 2016).

BIM, however, has not successfully resolved the problem pertaining to Optimizing the position of Tower Crane—independently. Despite of providing an interface to facilitate visualization, BIM does not have inherent capabilities for optimization of designs (Marzouk & Abubakr, 2016). BIM, furthermore, isn’t specifically meant to carry out spatial analysis—thereby requiring assistance from technologies like GIS. This integration of several visual interfaces, however, is not recommended-- owing to pivotal issues pertaining to interoperability, data transfers, software incompatibilities, and the end-user requiring knowledge of both system functionalities (Irizarry & Karan, 2012). Generative Design techniques, like Visual Programming, on the other hand, hold the potential to facilitate decision-making based on visuals, as well as inherently implementing Genetic Algorithm and Fractal to generate the best possible configuration

Both the above-defined categories cater to specific needs. However, their implementation might lead to workflow redundancies and create solutions that do not coincide with the predefined objectives (Ji et al., 2017). Generative Design is one such sphere that combines the capabilities of Pure- Mathematical and Pure-Visual Model and provides a plethora of opportunities to comprehensively exploit the possible design innovations (Abrishami et al., 2014). An attempt has thus been made to test its potential and applicability in the real construction world.

3.5 Research Type and Design

It is extremely crucial in research to determine the appropriate type of research and analysis, especially in construction, to make sound choices and arrive at informed decisions(Wing et al., 1998). In order to answer the first research question pertaining to analyzing the significance of Generative Design for optimizing the Tower Crane Position, an exploratory research using case-study design has been utilized. Whereas, a Descriptive Qualitative Study was carried out to determine usability of Generative Design to answer the second question.

An exploratory case study is vital to narrow the gap between concepts construed and the application of the theoretical approach to understand knowledge, practical and context-dependent realities (Pan & Scarbrough, 1999). This claim has been backed by literature to highlight the fact that whenever a proof-of-concept needs to be carried out—the most accurate way to test its applicability is by employing the said research design. Even previous studies, as indicated in Chapter 2, have resorted to applying the said research methodology. As a part of Case Study Design, the proposed technology would be henceforth implemented on selected construction sites to gauge the improvement on a specific parameter – lift score.

Generative Design has been sparsely and sporadically used in the Construction Industry. Furthermore, no direct application of Generative Design has been showcased yet in any realm of Construction Site Layout Planning. Thus, before developing an exhaustive framework, it is vital to test the applicability and response by the end-users of the technology. In order to facilitate the same, a Descriptive Qualitative Research had been incorporated. The study aims to address aspects pertaining to the technique and hence the aforementioned research helped analyze and interpret subjective data to better understand the designated situation (Padek et al., 2015). Specifically, to obtain answers on "why" people might or might not chose a technology—incorporation of a Qualitative study helped understand people's perceptions and enhance transparency, mechanicalness, and adherence to the specified evidence (Settipalle, 2018).

3.6 Research Procedure

In order to answer the first research question i.e. to demonstrate the significance of Generative Design in optimizing the position of Tower Crane on a construction site, an exploratory case study design had been followed. Literature pertaining to the utilization of a multitude of techniques pertaining to optimization of Tower Crane has revolved around a single methodology of developing the prototype and testing it on a sample construction site as a case study. In order to better validate and verify the applicability of the proposed research, one construction site sample from each country i.e. India and USA were taken-- totaling it to two, rather than just one. In order to garner these construction site samples, various construction professionals in both the countries were reached out. Only the companies that lay special emphasis on Construction Site Layout and Planning, and can provide with the Construction Site Plan that has a clearly identified position of Tower Crane were sought after. The sampling technique was therefore a combination of convenience and voluntary response sample. Once the samples were obtained, a basic 3D framework model was developed as a benchmark for optimization and visualization purposes. After the development of the model, visual programming techniques were applied to the model to generate a 3D Image of every possible location of Tower Crane on the Construction Site. The underlying principle of optimization was the lift score (Irizarry & Karan, 2012; Marzouk & Abubakr, 2016). The position of Tower Crane that corresponds to the lowest lift score was the one positing the optimum configuration. This entire process has been depicted in the following figure.

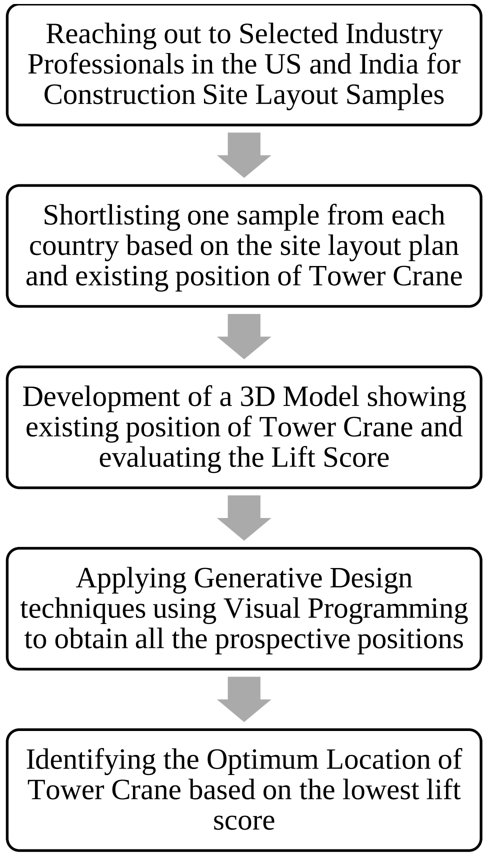


Figure 8: Developed Flow-Chart for Optimizing Tower Crane Position

The second research question aims to identify specific criteria that affect the utilization of Generative Design for Tower Crane Planning. The essential governing parameter in this case was thus the ‘Usability’ of Generative Design for the target problem. A sample size of twelve people consisting of interns, entry level associates, project engineers, project managers and executive level personnel (Managing Director, Vice President and President) was formed. In order to clearly demarcate the distinction in opinion based on previous experience garnered in this field—the first group consisted of Entry Level associates, people with contractual positions and interns. The second group subsequently consisted of project engineers, project managers and associates at executive level. Participants were expected to volunteer for this study and based on the responses, a final sample consisting of an assortment of various disciplines, education level and previous experience in this field was ultimately formed (Chien & Flemming, 2002).

A Pre-Test Demographic Questionnaire was further utilized to incorporate diverse yet multifaceted pool of participants. To specifically determine the usability component, participants then appeared for a questionnaire-- developed based on a literature review. The aspects to be analyzed included Ease of Learning, Efficiency of Usage, Ease of Remembrance, Prevention of Errors, and Subjective Pleasing (Chien & Flemming, 2002). The participants answered a Qualtrics survey on a 5-point Likert scale. In order to better encapsulate their subjective liking and experience with the developed algorithm—the participants also answered an open-ended interview. Based on the responses, potential barriers to implementation of Generative Design were obtained. Moreover, a correlation between previous knowledge plus direct experience and readiness to adaptability has been established. The entire procedure is as shown in the flow chart. Appendix A, B and C highlight the Pre-Demonstration Survey, Post-Demonstration Questionnaire and Open-Ended Interview Questions respectively.

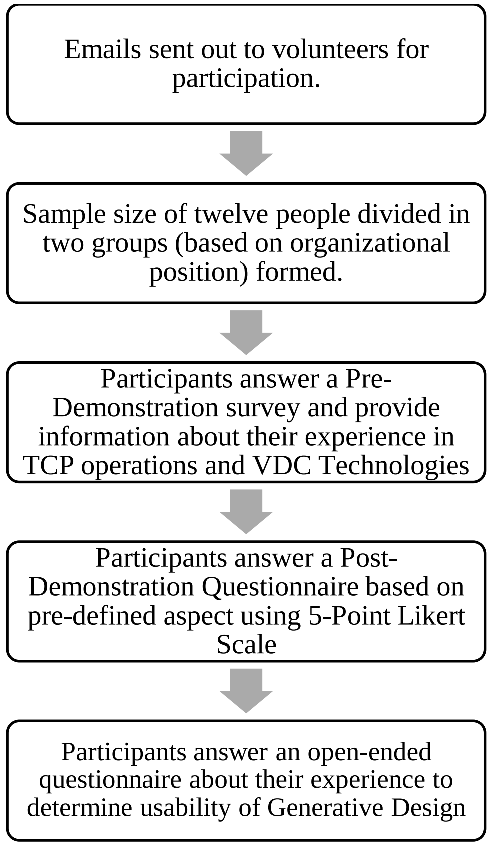


Figure 9: Developed Flow-Chart for Optimizing Tower Crane Position

3.7 Data Collection Instrumentation: Development and Validation

To answer the first research question pertaining to gauging the significance of Generative Design for optimizing the tower crane position, selected construction professionals from India and the US were reached out to. Construction site plans having clearly marked the location of Tower Crane were chosen for the study and later, the optimization. In total, two samples were diligently dealt with. Post the samples were obtained, details pertaining to target elements to be lifted, and potential crane positions were identified. If 2D Drawings or CAD plans would have been obtained, they were intended to be first converted to 3D BIM Model using Autodesk Revit as the software and raw files as an underlay. After the basic layout for transformation, the lift score was calculated for the basic configuration. The algorithm was later applied to obtain the optimized position of tower crane on the specific construction site. The key instrument to fetch site-specific data, here, was Autodesk Revit that captured and synthesized information from the raw files obtained. Visual

Programming Technique—Dynamo was heavily utilized for optimization and facilitate Generative Design.

In order to comprehend the criteria associated with the utilization of Generative Design for Tower Crane Planning, usability aspect was meticulously dealt with. A pre-demonstration survey aided in shortlisting a diverse sample size and gathering data about participant's pre-dominant notions about technologies in construction and experience with Tower Crane Planning operations. After deciding the sample for the study, as described in the subsequent section, the participants witnessed a brief demonstration by the researcher on how Generative Design can be utilized for Tower Crane Position Optimization. Based on their experience with the software, participants answered a short questionnaire—in person or telephonic. A semantic differential scale was used to capture responses and then converted to 5-point Likert Scale, with 5 being the "Most Likely" and 1 being the "Least Likely" output for the usability aspect. Finally, participants answered an open-ended interview questionnaire developed by the researcher to express their subjective opinion about adopting the technology and describing barriers to effective implementation.

In order to validate the instrument associated with answering the first research question, initially, 50% of the sample size i.e. 1 Construction Site Sample was chosen from the samples obtained for Pilot/Test Run and implement the complete methodology. Since the results were following what was anticipated i.e. a proper comparative study between the two lift scores, the study was further extended for the sample chosen. The conversion of CAD to BIM (if applicable) as well as the live run of the proposed optimization algorithm was reviewed by an expert panel of three members having previous experience in the relevant field. This panel consisted of academicians and industry professionals in the field of Construction.

To validate the instrument proposed for the second part of the study i.e. Usability, a pilot/test run with 6 participants (50% of the sample size) – and a rough analysis to answer the following questions was carried out: a) Can a fair comparison of anticipated training time be carried out? b) Can Barriers to training and implementation be identified? c) Is there a correlation between previous experience and readiness for adaptability? And finally, d) Is the developed Likert Scale suitable to obtain the anticipated results. The questionnaire prepared and the Likert Scale developed was reviewed by an expert panel of three members having previous experience in the relevant field. This panel consisted of academicians and industry professionals in the field of Construction.

3.8 Population and Sampling Procedure

For the first part of the study i.e. depicting the significance of Generative Design for optimizing the position of Tower Crane, construction site samples acted as key inputs. All the construction sites in the US and India thus constituted the population. Since the premier aim of this research was to optimize the position of Tower Crane, it is needless to say that only the construction sites utilizing the said equipment qualified in the final sample. As discussed in the literature, case-study analysis or proof-of-concept studies usually employ one sample to perform their study. However, to better validate the proposed technology, one sample each from India and the US was selected for this study. To garner these samples, a convenience sampling technique was incorporated. In case the number of samples having clearly identified the location of Tower Crane would have exceeded two, the concept of elimination would have been carried out to follow the Purposive Sampling technique. The samples that clear the above mentioned first criteria were then tested based on the availability of a 3D model. In order to eliminate the errors that stemmed while converting hard copy/blueprints of the construction site sample, the 3D model if used could be straightaway tested for optimization. If more than the required number of samples would have a had 3D Model as well, the complexity of the plan, in terms of, spatial areas would have been considered. Owing to the inherent errors persistent in congested or small-scale size that might have hindered an unencumbered achievement of the research objectives, construction sites with the largest site area would have been considered. If more than two samples qualify the set condition, as well, a simple random sample would have been obtained to carry out the final proposed study.

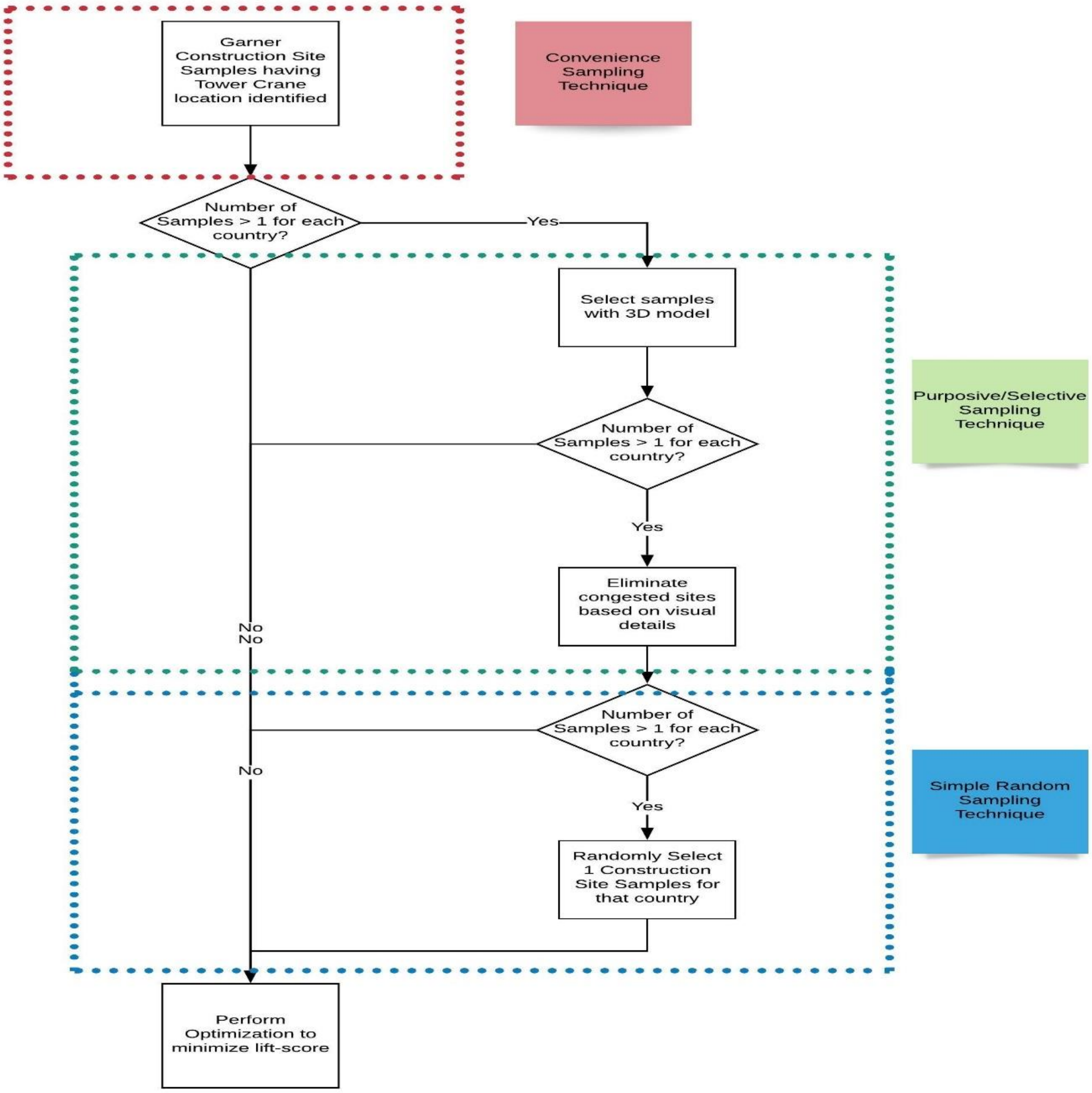
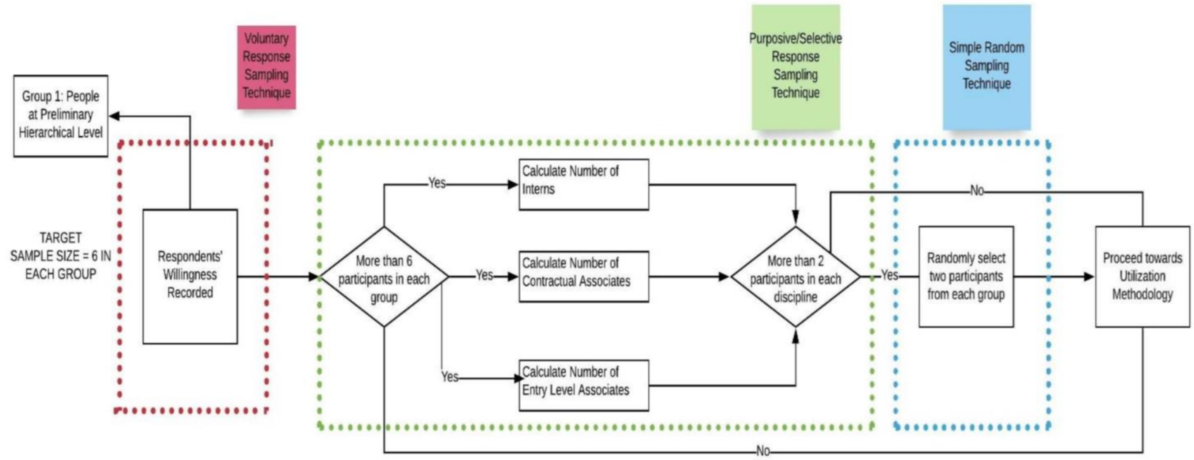


Figure 10: Sampling Procedure for testing significance of Generative Design

For the second part of the study—pertaining to criteria affecting utilization of Generative Design for Tower Crane Planning, a combination of stratified sampling and simple random sampling was used. In 2002, Chien and Flemming used an experimental design consisting of six graduate students to assess the Design Space navigation in Generative Design Systems. To better arrive at concrete results, this study employed two samples of six people each based on their previous experience in the relevant field. People placed at the intern, entry level or contractual associate level in the organization **and** having preliminary tower crane operations experience constituted the first sample. Similarly, volunteers possessing the designation of Project Engineer, Project Manager and Executive Level position constituted the second sample portion. The population of this study was thus all the students and/or construction industry professionals associated having exposure to construction site techniques. Post the call for volunteers, since more than six volunteers fit in each group, a stratified random sampling technique was then carried out. Participants in each group were classified first based on their exact designation. Ideally, two participants from each discipline were intended to be included in this study. If more than two qualified in each category, a simple random sampling technique would then have been employed to arrive at two participants from all the three disciplines.



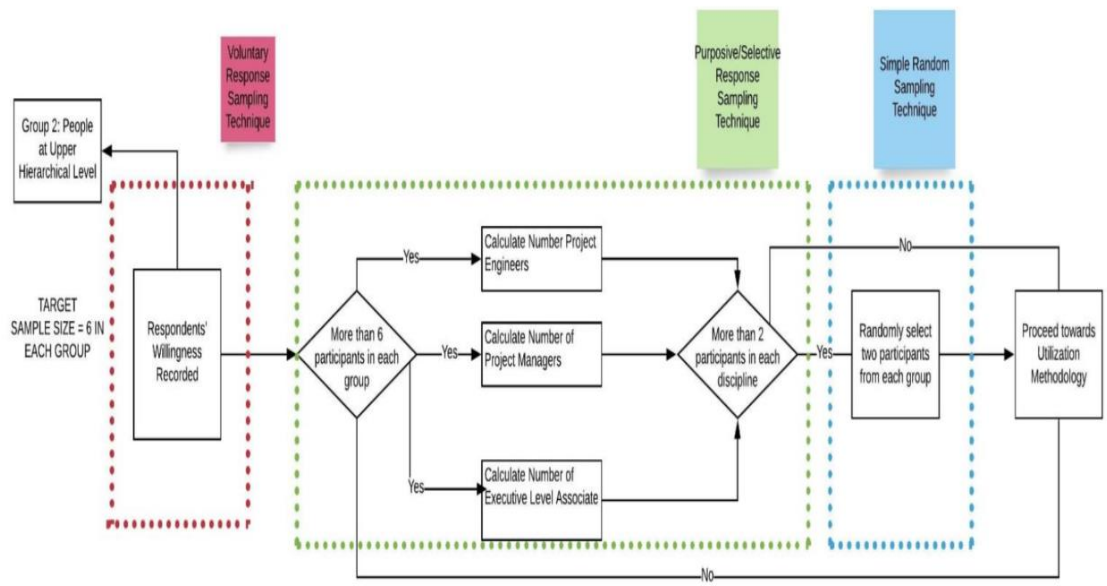


Figure 11: Sampling Procedure to test utilization criteria of Generative Design

3.9 Analysis Procedures and Tests of Significance

For the first part of the research i.e. testing the applicability of Generative Design in optimizing the position of Tower Crane, two construction site samples were chosen. Owing to the importance it possesses in ensuring effective operations, Lift score had been chosen as the target variable for the study (Irizarry & Karan, 2012; Marzouk & Abubakr, 2016). The lift score was first calculated for the existing configuration and then after the optimization algorithm was applied. In the literature, this study has generally been carried out on a single construction site—however, for this research, algorithms were wholly tested on both the construction sites. The change in the lift score was indicative of percentage improvement, owing to the application of the Generative Design technique. Consequently, the final result was manifested in terms of the percentage improvement, in terms of lift score.

For the second part of the study, the usability aspect was dealt with to determine the extent of utilization of Generative Design for Tower Crane operations. Initially, a Pre-Demonstration questionnaire aided in gathering relevant information about participant's background and experience with Construction technologies and Tower Crane Configurations. Two samples of six participants each— witnessed demonstration of the technique by the researcher. Specifically, for the usability aspect, the responses were converted to a 5-Point Likert Scale and further analyzed via the mean and standard deviation of both the groups. The sub-components that were essentially tested included Ease of Learning, Efficiency of Usage, Ease of Remembrance, Prevention of Errors and Subjective Pleasing (Chien & Flemming, 2002). Finally, the participants answered an open-ended questionnaire on their experience with the technology and their opinion on its efficacy for Tower Crane Planning operations.

Parameters like mean comparison and standard deviation have shown significant importance in determining user's responses to a technology and carrying out a primitive comparison to obtain a holistic view. These statistics have not only been used to test the applicability of Generative Design (Chien & Flemming, 2002) but also to construction technologies for design reviews (Castronovo et al., 2013) and assessing credibility and applicability in design and construction (Woksepp & Olofsson, 2008). It is thus definite that absolute values of these parameters, combined with subjective opinions of the participants helped understand several aspects of utilization like – Barriers in Training, Learning Rate owing to previous experience, potential barriers to implementation, and finally the correlation between previous experience and readiness to adaptability. Finally, in order to capture the viewpoints otherwise not addressed in the questionnaire, garner feedback on the experience with the implementation of Generative Design for Tower Crane Planning and know the front-end user's attitude and opinion on the efficacy of the novel technique—narrative analysis was carried out, after the transcription of data—and its fragmentation in parts for appropriate referencing. (Ashok, 2020).

3.10 Elimination of Biases

Bias in a broader sense can be defined as "tendency which prevents unprejudiced consideration of a question" (Pannucci & Wilkins, 2005, p. 1). Here's what they state about bias:

> In research, bias occurs when "systematic error [is] introduced into sampling or testing by selecting or encouraging one outcome or answer over others". Bias can occur at any phase of research, including study design or data collection, as well as in the process of data analysis and publication (p. 1).

Some of the biases that might have surrounded this study and the ways to minimize or eliminate them are listed as follows:

- As many construction sites and participant pools, that the researcher could have got access to were reached out. In other words, a broader relevant target frame was sought after to eliminate Sampling Frame Bias.
- To deal with non-response bias, participants and construction site professionals were sent recurring e-mails and continuous communication as reminders to ensure the quality and quantity of the sample so formed.
- The researcher has backed every substantial step with evidence from literature, sound knowledge and previous experience in this domain to completely obviate deliberate and intentional bias that may arise.
- A mixture of sampling techniques—especially the Purposeful Sampling Technique was employed to ensure that opinions of the uninformed do not shape the course of the study.
- Questionnaires were kept terse, brief as well as comprehensive to incorporate all the five usability characteristics. This was done to ensure that no unnecessary complexity existed on the interaction portal.

3.11 Reliability and Validity of Research

As stated by Cory (2019), Connelly (2016) identifies four components to ensure reliability and trustworthiness: Credibility, Transferability, Dependability, and Confirmability. Each of these factors were given due consideration in this study.

- To ensure Credibility, the same optimization algorithm was applied to all the final 3D models. The data was moreover collected from a variety of sources to encapsulate eccentric site features that might have come into the picture. Similarly, the same set of questions was be asked to all the participants to eliminate the occurrence of subjective opinions.
- Transferability was ensured by following a well-defined combination of sampling techniques. Purposive or Stratified sampling was carried out to only include diverse construction sites and construction professionals from various realms, respectively. It was done to reduce skew and potential biases that would have arisen, otherwise.
- In order to bolster the dependability, data obtained was reported as-it-is. For qualitative responses, the Likert scale was used to transfer subjective answers to numerical values in a well-defined manner.
- Confirmability can be achieved by replicating the research. To achieve the same, a well-defined methodology has been presented. This will enable future research in this field to be based on the same framework, shall the need arise.

Yin (2015), furthermore, as cited in Cory (2019) recognizes three qualities to ensure reliability and trustworthiness: Transparency, Methodicalness, and Adherence to Evidence.

- To ensure transparency, all the questions for the interview, garnered datasets and results, and verbatims of participants can be made available.
- Methodicalness was achieved by semantically organizing data and generating questionnaires that were not affected substantially by unanticipated circumstances.
- Adherence to Evidence was warranted by minimizing researchers' participation in the data transformation or conversion process and by repeatedly analyzing-- to ensure legitimate inclusion of actual information.

The above framework is roughly based on the procedure implemented by Cory (2019). Validity can be defined as "the correctness or credibility of a description, conclusion, explanation, interpretation or other sort of account" (Maxwell, 1996, p.87). Maxwell, further enlists seven strategies to combat threats that surround validity in a Qualitative Research. All these strategies, along with the specific aid to deal with it are as listed:

- ‘Comparison’ is a key attribute of this study and the results were explicitly compared across several settings, groups, and events.

- ‘Quasi-Statistics’ were incorporated in the form of Likert scale variations ranging from Strong Disagreement to Agreement—to aptly represent the adjectives, that the participants needed to determine usability and barriers to implementation.

- ‘Data triangulation’ was facilitated by collecting construction site samples from two different countries. Moreover, to include vast opinions about usability—construction personnel from different disciplines and on-site experience were included in the study.

- Negative cases for the implementation of Generative Design have not been cited in Literature—thereby obviating ‘Discrepant Evidence’ as a threat to validity.

- To ensure ‘Respondent Validation’, final numerical values and transcribed data was cross-checked and verified by the participant.

- A thorough literature review was conducted to prepare a comprehensive questionnaire and certify the collection of a ‘Rich Data’.

- In order to ensure that the maximum possible ‘Intensive involvement’ persists in this study, the researcher was in regular touch with participants during the training, post-training, interview, and post-interview phase to incorporate any change in the respondent’s opinion.

As an additional measure to ensure validity, the concept of construct validity and face validity was used to garner answers to research questions 1 and 2 respectively. The obtained result after optimization was compared to previous studies about the lift score to get an approximate idea of the validity of the research carried out. Similarly, respondents’ facial expressions and ease of thought flow were critically analyzed to test the usability of Generative Design.

3.12 Strengths and Weaknesses of Data Collection

Based on the procedure determined above, the following strengths have been identified:

- The data collection procedure is cost-effective and does not demand an external source of funding or a designated device for data collection.

- Since, the final sample pool was determined based on the broad pool of volunteers, the results would tout generalizability.

- Based on the expected group of volunteers, the respondents’ answers showcased a high level of versatility.

- In-Person intercepts allowed instant feedback, in-depth exploration of issues, observation of non-verbal responses, and higher probable survey lengths.
- Questionnaires and Interviews facilitated the usage of graphics and visual aids, obtain higher response rates, and ensure that all the questions are answered—in entirety.

The framework developed for data collection can posit the following points of weaknesses:

- Geographical limitations limited the accessibility of researchers to regions, far beyond practical reach.
- Technological advancements could have affected the participant's desire to appear for training or demand external resources and efforts for smooth conduct.
- Respondents might have inadvertently lost the feeling of anonymity and developed acquiescence with the researcher.

3.13 Ethical Considerations

To ensure the quality and integrity of the research, Cory (2019) identified the following six principles from the 'Economical and Social Research Council' (ESRC). Following efforts were to ensure optimum quality of research ethics:

- The responses were reported without any deliberations or fabrications.
- Companies' and participants' informed consent precluded the commencement of the study.
- The confidentiality and anonymity of every construction company and participant has been ensured.
- Participants had the provision to withdraw from the study without any reservations or obligations.
- Participants wouldn't have been subjected to any environment that poses a threat or harm to their well-being and safety.
- The research has been justified to be independent, impartial, reliable, and valid.

Furthermore, as stated by Orb, Eisenhauer, and Wynaden (2001), participants' observations, opinions, and feedback were given utmost importance and were treated with all due respect.

3.14 Summary

The chapter began by providing an overview of the problem, purpose, and significance that the research plans to undertake, and restating the research questions. The next part described the research type and design adopted to answer each of the research questions. To implement the same, the next section clearly explained separate procedures that would be carried out. An integral section that precedes an efficient data collection process is Instrumentation. The chapter therefore briefly explained the instrument associated and its development and validation through distinct pilot studies. Later, based on the applicable population to obtain an answer to each of the research question, the sampling process and sizing is described and justified. Following the same, how the researcher aims to ensure reliability and validity of the data is explained. Finally, analysis procedures including statistical tests of significance, for both the data sets are described along with the incumbent strengths and weaknesses. The chapter also supplements basic information needed with other relevant topics specific to this study that includes – Ethical Considerations, Elimination of Biases, and Time Action Plan for the specifics of the proposed research.

CHAPTER 4. ANALYSIS AND RESULTS

This chapter encompasses the data analysis and visual results portion of the study- obtained as a result of implementing the methodologies discussed in the preceding sections. The contents of this chapter can be roughly classified into two sections. The first segment introduces the Dynamo script and workflow, followed by a detailed analysis for both the chosen construction sites. It concludes by discussing the observations and results, pertaining to testing the efficiency of Generative Design in evaluating the optimal position of Tower Crane on a construction site.

The second module completely cores around the Usability of Generative Design for the intended purpose. It begins by reporting the raw Likert scale data obtained by interviewing twelve participants, followed by analyzing each aspect of usability, and cursorily observing each associated statement to distinguish the response of the two distinct target groups. Finally, an in-depth discussion on every aspect of the open-ended questionnaire is carried out to showcase participants' feedback and objective evaluation on the implementation of the technique on the construction site.

4.1 Overview

The problem addressed by the study was Improper Planning of Construction Crane Conformations while developing the construction site layout plan. To address the issues that stem as a consequence of the problem, the purpose of this research was to Optimize the position of Construction Crane in a construction site layout plan. Owing to demonstrated evidence of sharpened productivity, limited demands of repeated daily maintenance and management operations, and increased level of job-site safety- this study focused on the optimal positioning of the tower crane.

To better account for the Proof-of-Concept part of the study as well as the usability aspect- the following research questions were derived:

1. How significant is Generative Design in optimizing the Tower Crane Position?
2. What criteria affect the utilization of Generative Design for Tower Crane Planning?

To answer the first part of the research question- two construction sites, one each from the United States and India were chosen. Based on the BIM model, a situational analysis was first carried out to evaluate the lift score of the existing crane configuration. The dynamo-driven visual programming algorithm was then implemented to obtain the optimal position of the tower crane- and calculate the lift score associated with it. By utilizing the Beta Refinery platform of Generative Design, all the intermediate and possible positions were also sought after- to avoid the selection of an extreme position that was evidently not plausible on the construction site. The final result has been reported in terms of the percentage change observed in the absolute magnitude of the lift score. The study is similar to the one described on Autodesk Beta Refinery and medium platform.

To address the usability aspect, twelve participants were chosen through the Pre-Demonstration Questionnaire, to involve a diverse population having multiple experiences with tower crane. The participants were classified into two groups based on their organizational position/designation and previous experience with Tower Crane. The participants first witnessed a live demonstration of the functioning of the Generative Design algorithm and then filled out a Qualtrics survey to address five aspects of usability: Ease of Learning, Efficiency of Usage, Ease of Remembrance, Prevention of Errors and Subjective Pleasing. Likert scale was used to assign a number to the qualitative scale and later compare the 'mean' of both the groups to obtain the relative response to the adaptability of the technique. Finally, a narrative analysis was carried out via transcribed data of the open-ended questionnaire-- to identify potential barriers to the implementation of the technique in the actual construction industry practices.

The underlying and fundamental objective of the study was to develop a tested Generative Design optimization framework for Tower Crane optimization that is easily usable on the construction site, readily comprehensible by the construction site professionals, and can be reused on multiple projects with minimal mathematical alterations.

4.2 Workflow of Dynamo Script and Calculation of Lift Score

The Dynamo script utilized in this study was an open-source script available on the website of Autodesk University. The study was presented at the Autodesk University Conference in the year 2016 by Dieter Vermeulen for a small-scale construction site- largely positioned around steel erection. The entire script was divided into four parts- in the same order: Data Input, Initialization, Analysis (Analyze), and Evaluation. Each of these nodes was connected by wires that move from Data Input to Evaluation. The final output was then exported to Generative Design- to explore all the possible alternatives, based on chosen input variables that can be modified.

4.2.1 Input Structure

The foundation of the chosen Dynamo script lies in the input region of the script. It is extremely dynamic and intuitive enough to encapsulate the eccentric features of different construction sites. Clearly, the entirety of the changing results is an effect of the modified yet unique input structure of every construction site. Figure 12 explains the Input Structure of the script.

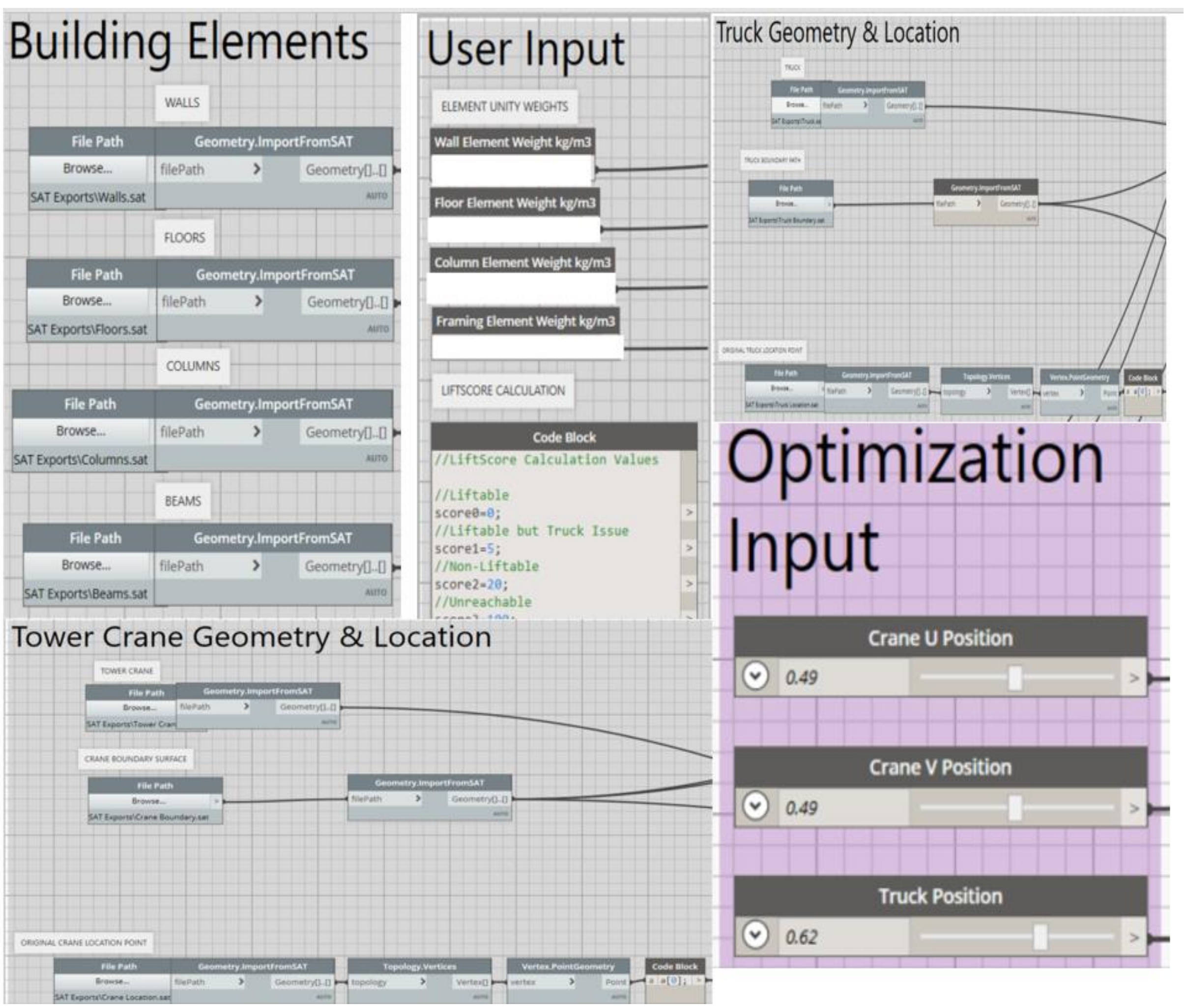


Figure 12: Input Structure of the Dynamo Script

The input structure of the script consisted of the following nodes for the initial entry of data:

1. Geometry of Building Elements: For both the construction sites- the geometry of elements to be target lifted by the tower crane included: Wall, Beams, Floors, and Columns. The geometry of all the elements was first fetched from Revit and then exported as SAT Files to be imported in Dynamo. Since all the elements have different weight densities- they are analyzed differently via separate SAT files.

2. Unit Weight: A number node is used to report the unit weight of all the target elements. This node is dynamic with the provision of being manipulated separately for different parts of the construction site.

3. Crane Specifications: The crane ranges and associated lifting capacity are captured via this node. If the crane has a specific load factor or factor of safety for a specific range, it can be included in this node, as well.

4. Geometry of target Tower Crane and the building pad across which it can be exactly positioned. If there are specific regions where the Tower Crane should specifically not be placed- it can be accounted for by making the changes to the geometry of the chosen, existing, or modeled building pad.

5. Geometry of Truck and Truck region- across which the truck is free to move. If there are specific regions where the truck should specifically not be placed- it can be accounted for by making changes to the geometry of the chosen, existing, or modeled building pad.

6. Variable Input: Coordinates of Tower Crane and Truck, and its ability to be modified is one of the most essential features of Generative Design. These nodes are usually marked as input- and can vary between the specified ranges. The building pads chosen in Step 5 – are divided in the coordinate system ranging from (0,0) to (1,1). For the initial configuration of the crane- Dynamo automatically detects its coordinates and returns results upon successful execution of the script. While exporting the study for Generative Design- it automatically takes variable numbers based on the range specified and the number of generations mentioned.

7. Lift score: Explained in detail, in section 4.2.5.

4.2.2 Initialization of Obtained Data

The initialization region of the script processes, consolidates and simplifies the data collected in the previous step. This is done- to ensure that collected elements can be easily analyzed and can be extracted to synthesize meaningful information to regulate the flow of data throughout the script. Figure 13 highlights the ‘Initialize’ region of the script.

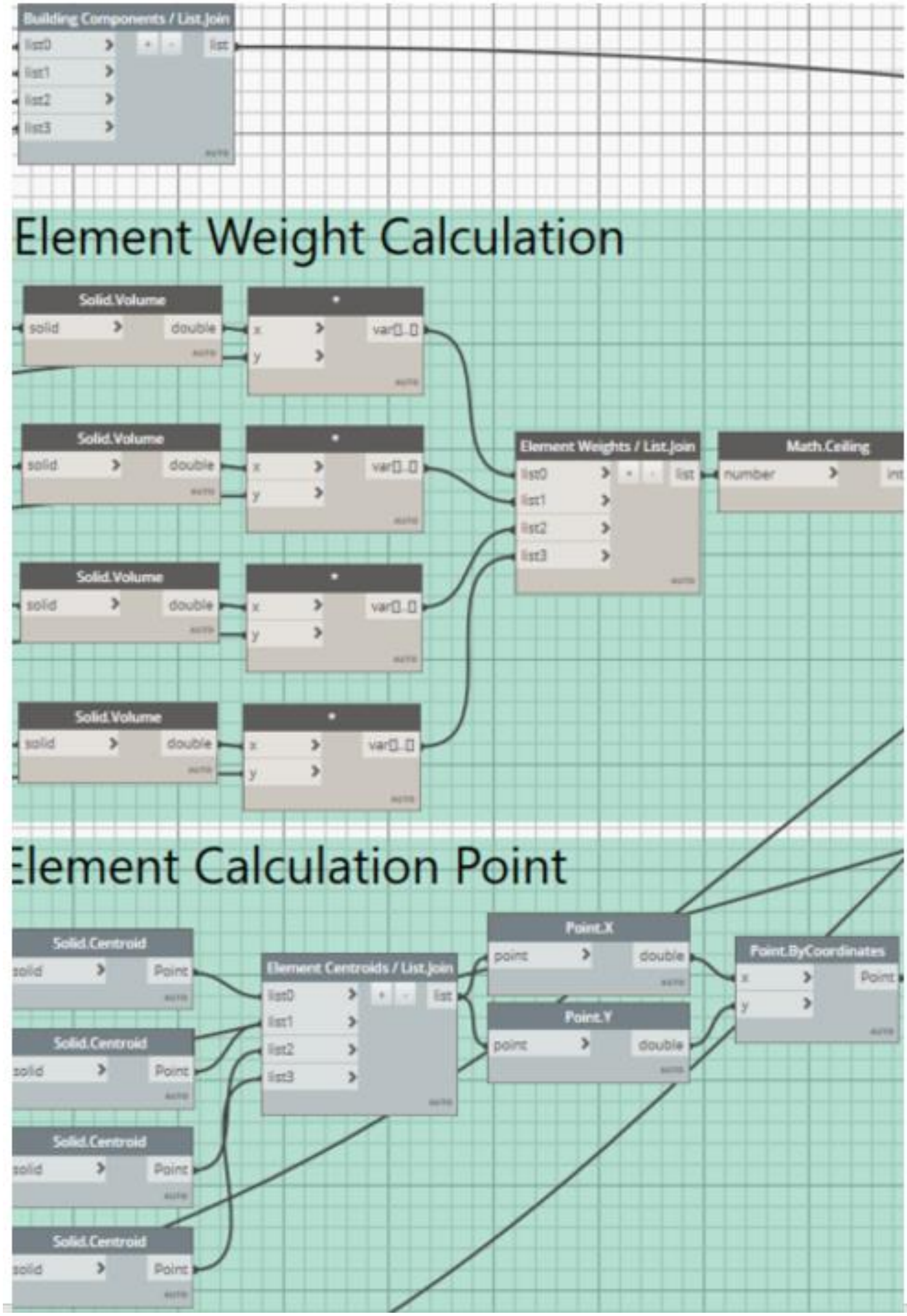


Figure 13 : Initialize Group of the Script-I

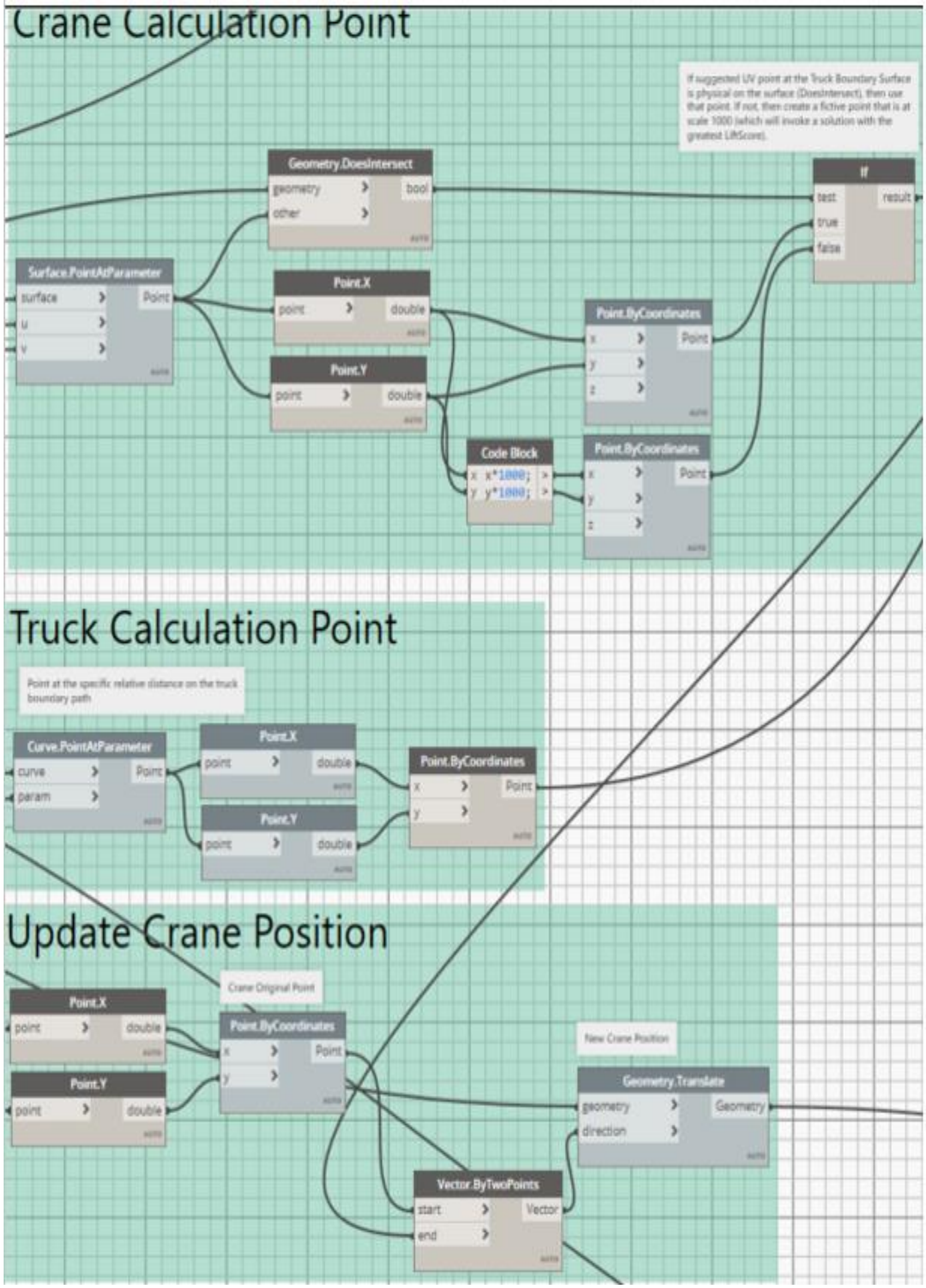


Figure 14 : Initialize Group of the Script-II

The region consists of the following node blocks:

1. Building Components: Combining the geometry of all the collected elements and arranging in the form of a list- to arrange and map data as per the indices. The elements chosen for this study include Structural Columns, Structural Framing, Floors and Walls.

2. Element Weight Calculation: The geometry is treated as solids to calculate the volume. This volume of the solid geometry is multiplied by the unit weight specified to obtain the net weight of each of the associated elements. Finally, this is consolidated and arranged in the form of a list, as well.

3. Element Calculation Point: During the Tower Crane lifting operations- one of the major concerns that surround is the shift in the centroid of the system as the lifting operations continue. This block will therefore calculate the centroid of the solids, arrange them in the form of a list, and then fetch x and y coordinates for the centroid of each of the elements.

4. Crane and Truck Calculation Point: These blocks work with the geometry of truck, crane, and the building pads across which they can move. The geometry of the surfaces is taken in the form of a coordinate system- so that various positions can be observed and visualized by navigating and changing the associated coordinates.

5. Update Truck and Crane Position: This block fetches the initial geometry of Truck and Crane and then updates the reorganized position as per the algorithm- on the Revit interface, to obtain an accurate visual representation, that maps with the input and modified parameters of the script so executed.

4.2.3 Analysis of the Initialized Data

The analysis group consists of three regions: Custom Node called Solids.SingleCraneAnalysis, Liftscore calculation block, and finally Project Fractal Output to export the design in Generative Design. Project Fractal had been updated to Beta Refinery. However, with the advent of the Generative Design plug-in in Revit 2021- Beta Refinery has now graduated. However, the workflow of creating a script in Dynamo, exporting the study via Beta Refinery to visualize the results- and finally using Generative Design to observe the possible alternatives, optimize or randomize the results and the phenomenon of ranking them- still remained applicable while the study had been performed. Figure 14 shows the analysis group of the script.

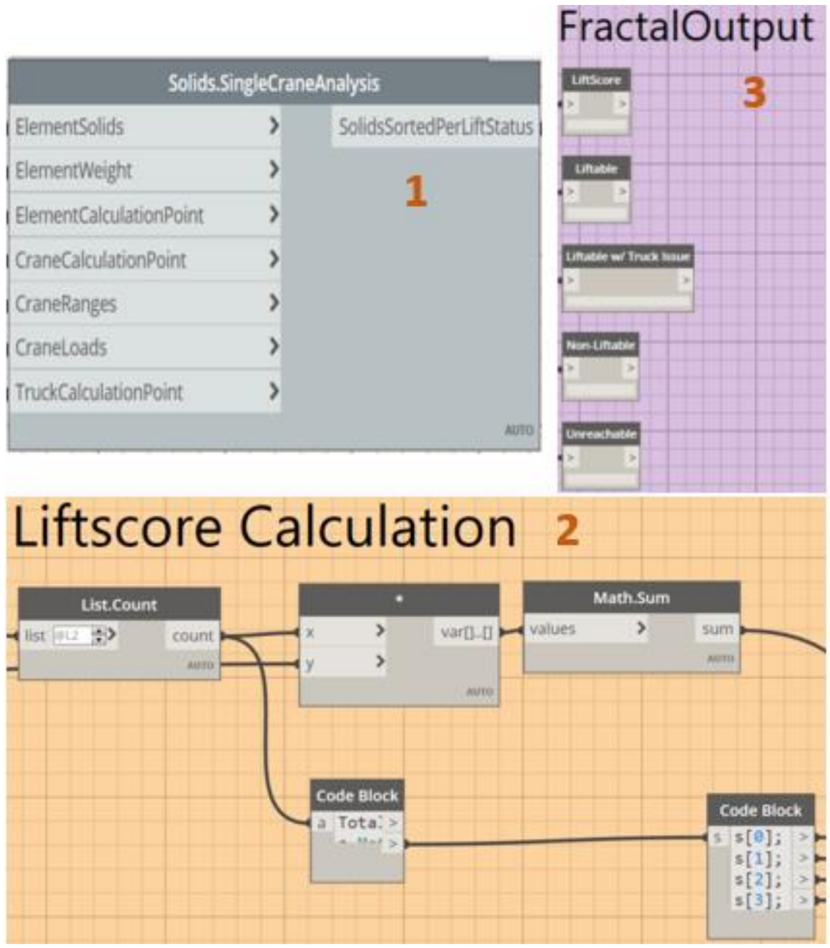


Figure 15: Analyze the Initialized Data

This group consists of the following custom nodes, nodes and groups:

1. Element Lift Analysis: This custom node takes the Geometry of elements in the form of solids, weight of the elements, their calculation points via the centroid system, the crane calculation points, the crane range and loads, and finally the truck calculation points as inputs to be algorithmically computed. This node comes from the predefined Dynamo node of BIM4Struc.CraneAnalysis, that has the following parts to it:

    a. Input Parameters: Reads the input data concerning all the eight input wires, as mentioned above.

    b. Maximum Range Capacity of the Crane: The distance between crane calculation point and centroid of each element is compared with the maximum range that the crane can reach up to. For the elements that do not satisfy the criteria, a new list called unreachable is created. All the elements get a lift score value, used henceforth for calculation- as explained in section 4.2.5.

c. Crane Capacity of each element: From the list that represents elements not excluded in (b)- the crane capacity is obtained by comparing relative distance and the associated weight with the crane's capability of handling the load at the specified range. For the elements that do not satisfy the criteria, a new list called non-liftable is created. All the elements get a lift score value, used henceforth for calculation- as explained in section 4.2.5.

d. Truck Range Capacity: From the list that represents elements not excluded in (c)- this check compares the distance between the crane and supply point to see if elements can be accessed considering the distance between specified crane position and truck. For the elements that do not satisfy the criteria, a new list called liftable but truck issue is created. The remaining elements- fall under the liftable criteria- by default. All the elements get a lift score value, used henceforth for calculation- as explained in section 4.2.5.

2. Lift Score Calculation: This block fetches the value of output obtained in the previous custom node. The total number of elements in each list is reported as a percentage of the total number of elements. Consequently, the output is a list of percentage of liftable, unreachable, liftable but truck issues and non-liftable elements expressed as a percentage to calculate the final lift score.

3. Fractal Output: This block largely consists of watch nodes to display the results obtained as output of the previous step. It consists of five watch nodes- one each to represent the percentage value of all the four criteria concerning lift status, and the final lift score value to show the value of total lift score. These nodes are marked as output- while exporting to the Generative Design script. This node is hence crucial to constrain the output, filter specific criteria, and obtain results within a specific range.

4.2.4 Evaluation of Solids

This group consists of a code block that fetches data from the previous analysis node- and assigns colors to all the elements as per their lift status. The key to allocate lift status per each color is as follows:

- Green represents the element being liftable
- Yellow indicates that the element is liftable, but has truck issue
- Orange shows that the element is non-liftable
- Red demonstrates that the element is unreachable.

However, they can be manipulated as per the users' preferences. Considering that this node largely adds colors to the already evaluated results- this step does affect the visual representation of the output. It is hence essential to provide a legend that indicates specific lift status. Figure 15 shows the image representing this portion of the code block.

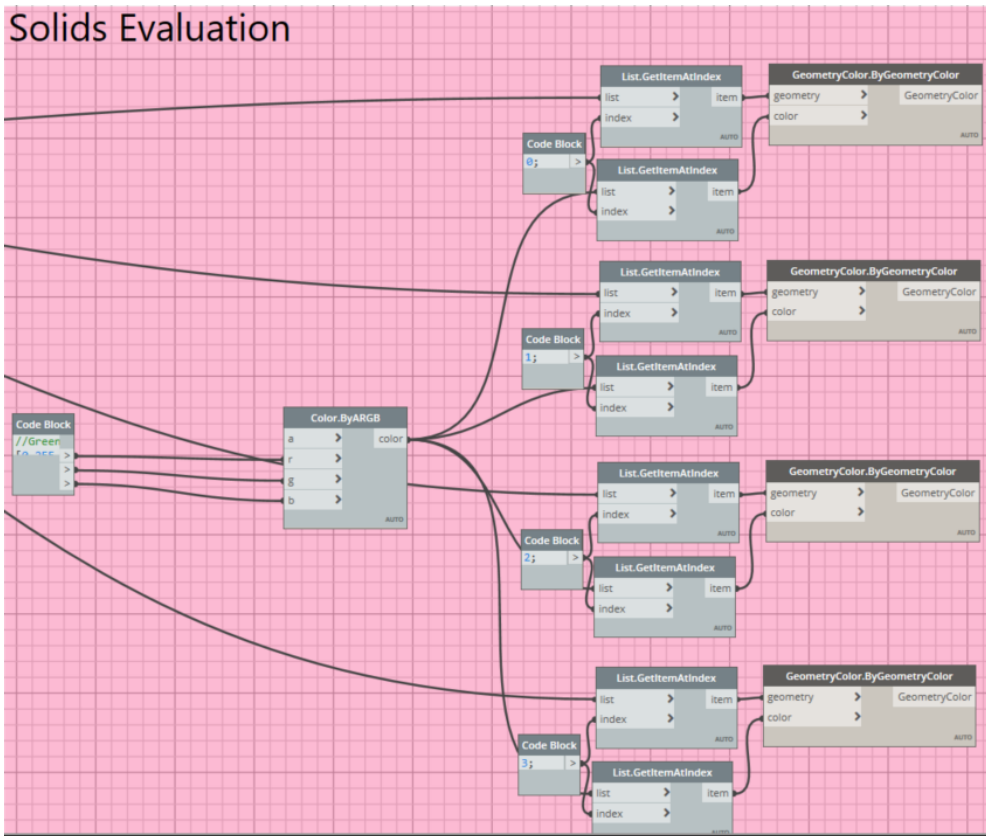


Figure 16: Evaluation of Solids

4.2.5 Calculation of Lift Score

Lift score is the key parameter of governance in the study. Section 4.2.3 explains the classification of elements in each category i.e. Unreachable, Non-Liftable, Liftable with truck issue, and Liftable. This classification, as defined by Dieter Vermeulen is again described in Figure 16.

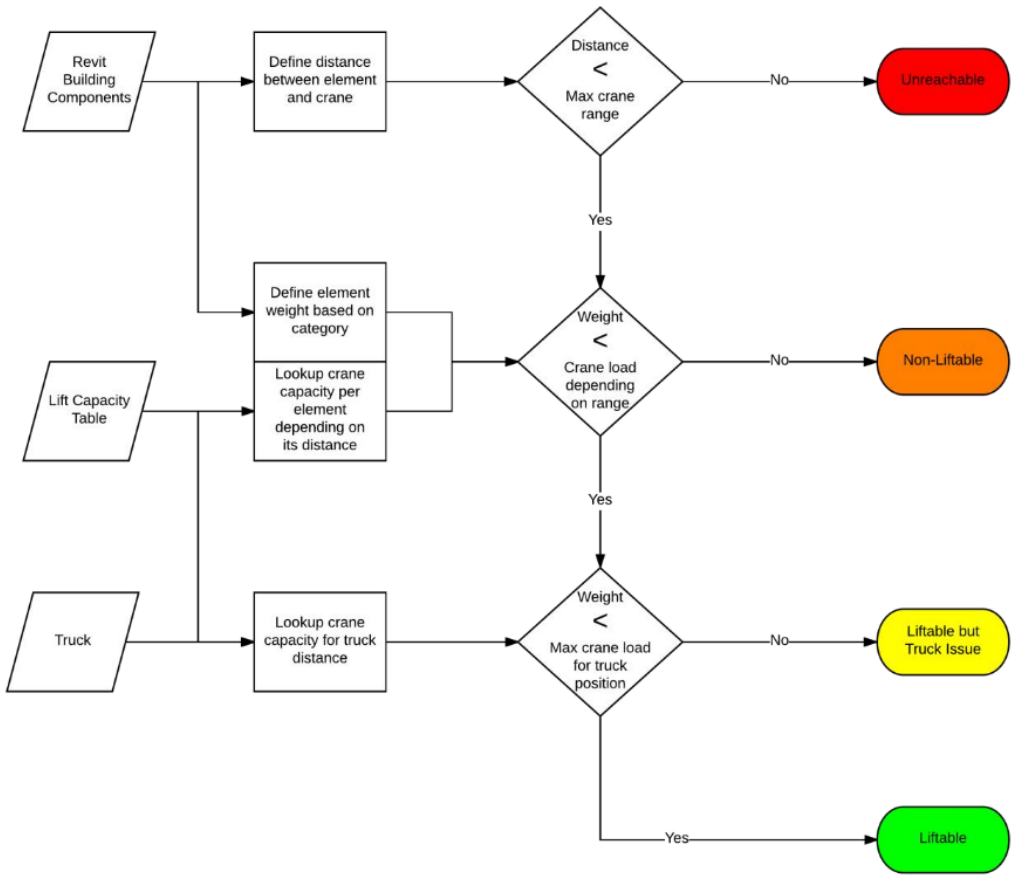


Figure 17: Flow Chart to Determine Lift Status

Based on the elements obtained, a specific lift score is assigned to each element in the model. The value of the lift score is tabulated in table 2. From the table, it can be seen that the higher the lift score, higher is the lifting effort- or in other words, higher are the potential lift issues. The aim is therefore to place the crane at such a position- that results in the lowest possible lift score—within the specified constraints. As ideal as the lift score of zero is- it is next to impossible to expect that from a given construction site--having static parameter values. Considering the scores allocated to each element- multiplied by the lift score based on its associated lift status, the absolute value of the lift score can be easily anticipated. The aim is, however, to implement the algorithm and obtain the minimum possible score.

Table 2: Allotment of Lift Score as per the Lift Status

Lift Status	Associated Lift Score
Liftable	0
Liftable but Truck Issue	5
Non Liftable	20
Unreachable	100

It is worthwhile to bring to the reader's attention that this allotment of lift scores is extremely dynamic. The user is free to change the values- and can still get a result in an equal time frame. The rationale for adopting this lift score is based on the study presented by Dieter Vermeulen at Autodesk University. Since the open-source script had the default values, and the major intention was to evaluate the workflow associated with Generative Design- the same values were adopted for this study. Any user can however tailor them as per the requirement.

4.3 Analysis for Site 1

The first construction site chosen was a commercial project in California, USA. It is a 6-story commercial project with 51 office spaces. The first floor consists of 6 offices, a designated pantry, and a reception region- which includes spaces that can be used as break hour places. For floors 2 through 6- there are 9 commercial offices on each floor along with a utility closet. The total ground construction area is 1.01 Acres- whereas the total area of property is 1.15 acres. Figure 17 shows a rendered image of the construction site, including the truck and tower crane. The BIM model depicted consists only of the target elements to be lifted by the Tower Crane- walls, floors, columns and beams. For better and relevant visuals—the cleaned-up model does not show exterior finishes, topography, and other interior details that are otherwise expected. The tower crane and truck placed are generic families- only meant for representational purposes. Actual crane data is retrieved and incorporated in the input structure of the script.

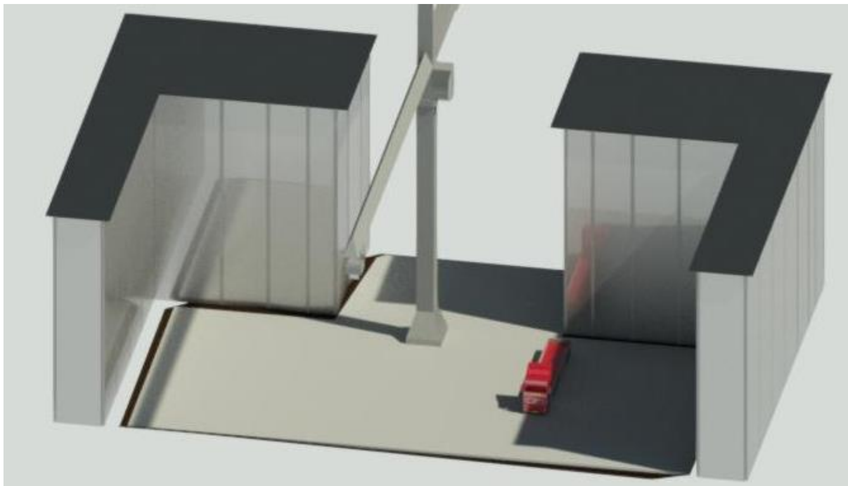


Figure 18: Rendered Image of Site 1

4.3.1 Positional Analysis

Positional analysis as construed here refers to calculating the lift score for a specific position of the tower crane on a construction site. Situational analysis was first carried out to calculate the lift score and visuals concerning liftable regions based on the existing configuration of Tower crane. After evaluating- the study was then exported to Beta Refinery to explore all the possible locations where the Tower crane could have been placed. The outcome of the created Generative Design study was a lift score pertaining to all the distinct positions of Tower crane- with an ability to filter the results as per the desired constraints. Presence of a framework that allowed implementation of constraints to filter out definite results- helped eliminate extreme yet implausible results, as well as implement any site-specific conditions which were essential in determining the optimized position. To get a holistic view of the spectrum of potential positions, and better evaluate the changes in the lift score- detailed visuals reflecting current, best and worst possible positions are highlighted, in detail.

4.3.1.1 Situational Analysis

Situational analysis reflects the lift score corresponding to the existing Tower Crane configuration. Table 3 shows the total value of lift score along with the percentage of liftable, liftable with truck issue, non-liftable and unreachable elements on the construction site.

Table 3: Situational Analysis Results for Site 1

Parameter	Output Value
Lift Score	72,360
Liftable (%)	83.6
Liftable with Truck Issue	0
Non-Liftable	4.6
Unreachable (%)	11.9

In order to better understand the above-mentioned parameters- Generative Design provides visuals of the 3D model that are color coded to understand the elements that follow in a specific range. Figure 18 shows the snapshots of the 3D model for the existing crane configuration. All elements are red are indicative of the non-liftable region, orange representing non-liftable elements and green for liftable elements.

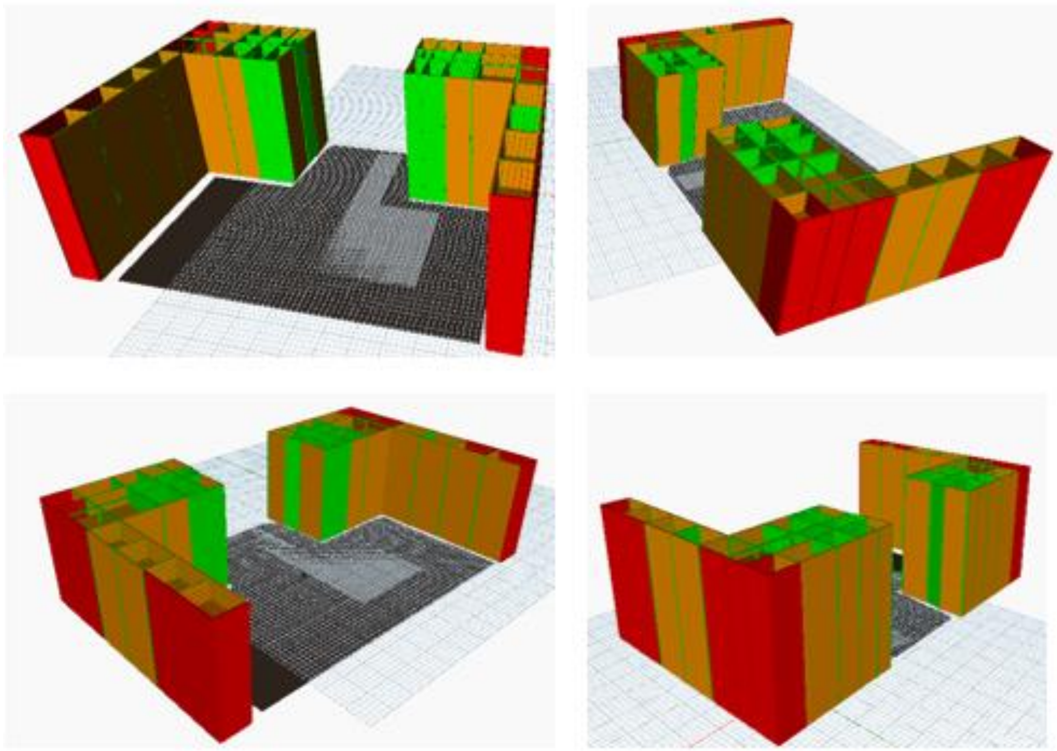


Figure 19: Visual Representation of Situational Analysis- Site 1

4.3.1.2 Creation of Study and Exploring the Outcomes

After executing the script for situational analysis of the construction site- the dynamo script was exported to Beta Refinery to optimize the position of Tower Crane and apply the relevant constraints. It is essential to ensure that crane coordinates and truck position are marked as "input", and the lift status criteria is marked as output. It is done to ensure that the Generative Design algorithm recognizes the parameters to be varied- to analyze the optimum set of values for the output. Figure 19 shows the window utilized for exporting the study.

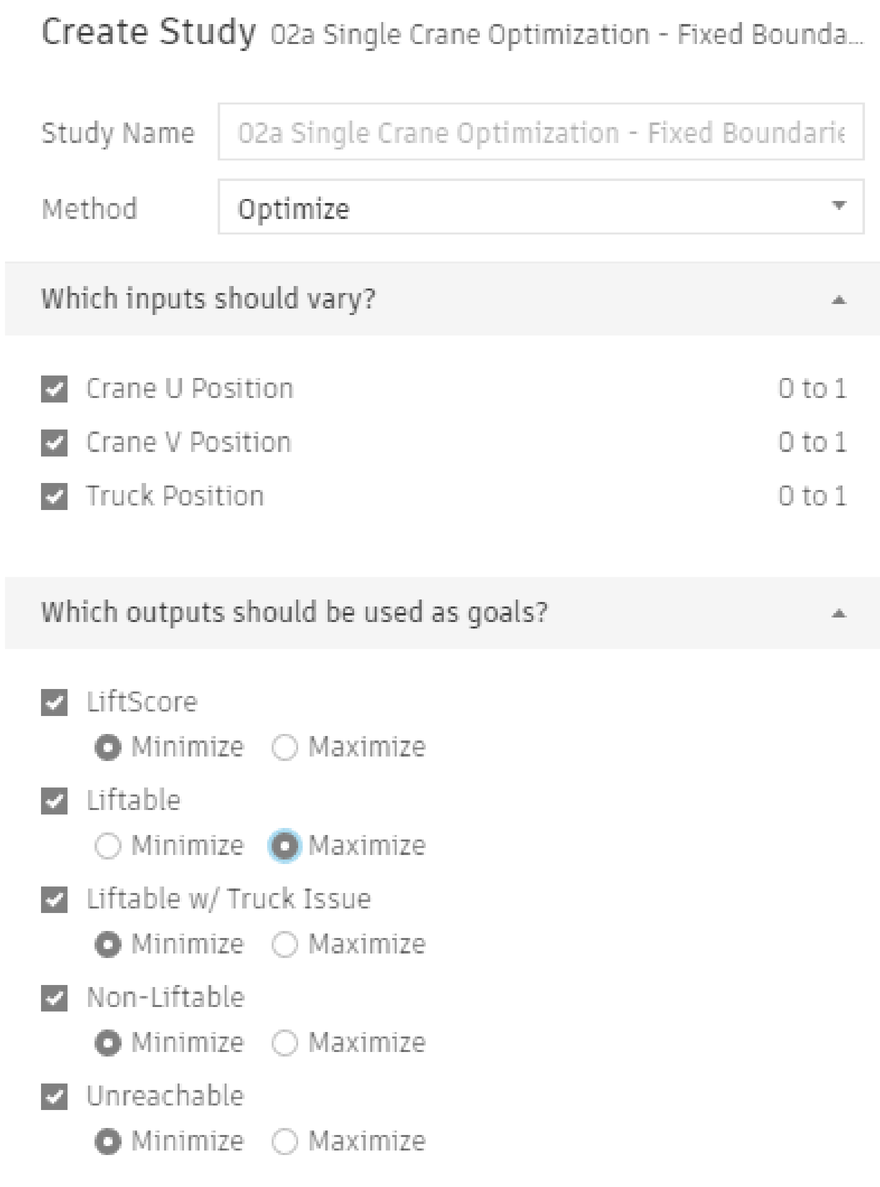


Figure 20: Creation of Study for Exploration

As evident from the image above- the crane coordinates and truck position were marked as input, whereas lift score, liftable (%), liftable with truck issue (%), non-liftable (%) and unreachable (%) were marked as outputs. The method was set to 'Optimize' owing to our end goal of optimization. Similarly, since the goal was to make maximum elements liftable by the crane range, the algorithm was trained to minimize the lift score and maximize the liftable elements. To enable the same- liftable with truck issue (%), non-liftable (%) and unreachable (%) were intended to be minimized. Finally, owing to the system requirements, handling capacity, and heaviness of the model- fifteen generations were observed, in detail. Figure 20 shows the output so obtained.

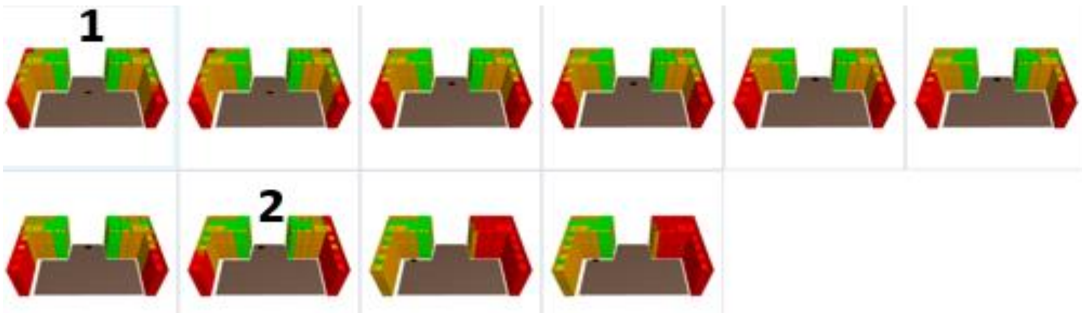


Figure 21: Generative Design outcomes for Exported Study

As reflected in the image above- all the outputs were color-coded as per the same legend. Similarly, each of the outcomes reflected the specific value of the inputs and outputs—allowing each alternative configuration to be opened in Dynamo for further exploration. In order to identify the optimized and worst possible scenario- the results were filtered as per our governing criteria of Lift score. At this stage, human intervention and past knowledge is not only an advantage but a necessity. Researcher/practitioner should identify if there are any particular flaws or shortcomings associated with the optimized position indicated by the algorithm- and overrule the best-ranked alternative if it reflects an extreme or implausible scenario. The individual then explores the second rank contender, then the third rank contender, and so on till a satisfactory configuration is obtained. Thus, the chosen alternative coupled with the algorithmic output acts as the optimum configuration for the study. For this research, a similar concept was adopted to identify the worst possible scenario. Extreme cases like placing the tower crane on a position that is evidently the most adverse one was not considered to magnify the benefits. Instead, a prospective position that was in fact likely to have been adopted was marked as the chosen scenario for the worst-case condition.

4.3.1.3 Best Case Scenario: The Optimized Configuration

After ranking the results in ascending order of the lift score- the first position in Figure 20 was identified as the best one of the pool of alternatives so generated. Table 4 shows the total value of lift score along with the percentage of liftable, liftable with truck issue, non-liftable and unreachable elements on the construction site.

Table 4: Optimized Configuration Results for Site 1

Parameter	Output Value
Lift Score	67,800
Liftable (%)	85.1
Liftable with Truck Issue	0
Non-Liftable	3.7
Unreachable (%)	11.2

Figure 21 shows the snapshots of the 3D model for the optimized crane configuration. All elements in red are indicative of the non-liftable region, orange representing non-liftable elements and green for liftable elements.

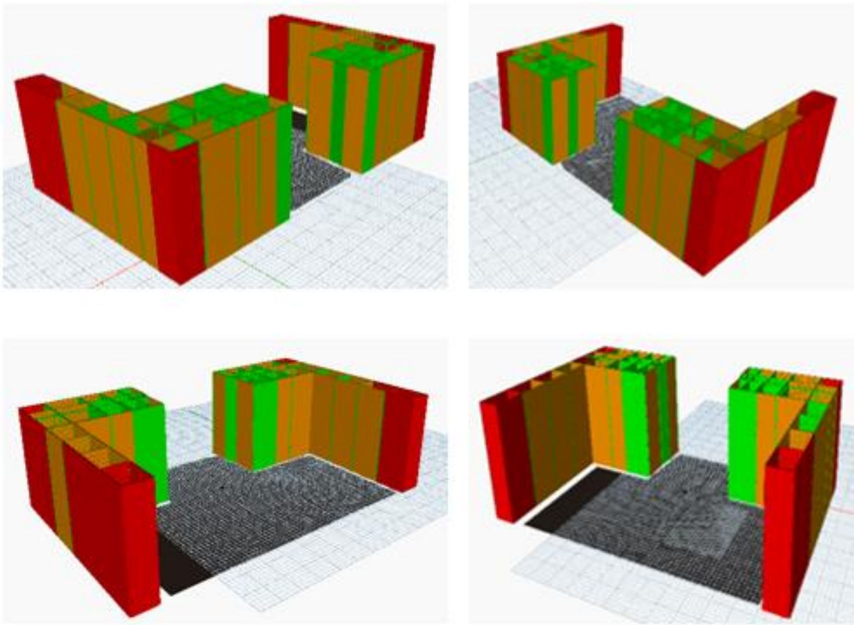


Figure 22: Visual Representation for Optimized Configuration

4.3.1.4 Worst Case Scenario

After ranking the results in ascending order of the lift score- the position highlighted as "2" in Figure 20 was identified as the least conducive position of the pool of alternatives so generated. Table 5 shows the total value of lift score along with the percentage of liftable, liftable with truck issue, non-liftable and unreachable elements on the construction site.

Table 5: Worst Case scenario analysis results for Site 1

Parameter	Output Value
Lift Score	67,800
Liftable (%)	85.1
Liftable with Truck Issue	0
Non-Liftable	3.7
Unreachable (%)	11.2

Figure 22 shows the snapshots of the 3D model for the least favorable crane configuration. All elements in red are indicative of the non-liftable region, orange representing non-liftable elements and green for liftable elements.

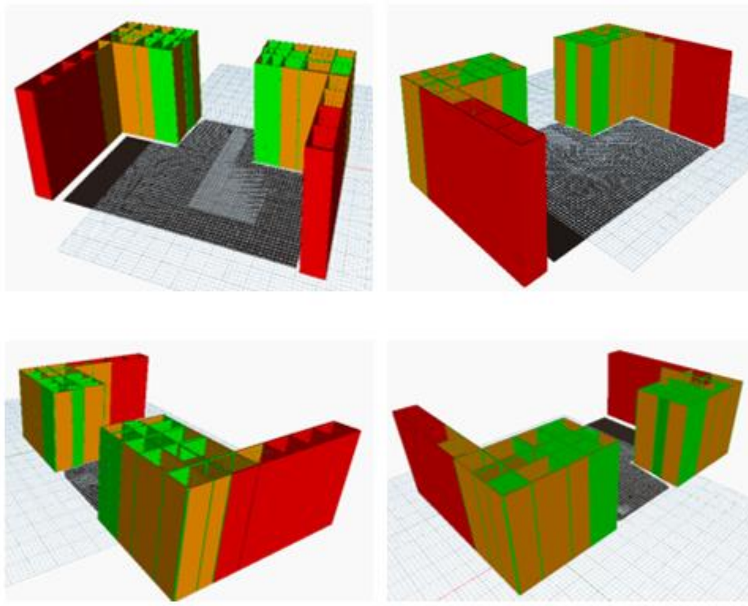


Figure 23: Visual Representation for Worst Case Scenario

4.3.2 Statistical Analysis for Site 1 Parameters

After calculating the value of lift scores and percentage of elements that follow in each category- a simple comparison was carried out to better comprehend the changes so witnessed. These statistics were crucial not only to analyze the changes and investigate the efficiency of the technique- but also to corroborate the adaptability claim when the demonstration was to be performed to the industry professionals to evaluate the usability of the proposed Generative Design algorithm. Comparison was therefore carried out between all the three scenarios for all the associated parameters. Figures 22, 23 and 24 show the consolidated raw output screenshots captured from the Dynamo interface. Table 6 shows a comparison between Optimized Configuration output and situational analysis output. Table 7 compares best and worst possibility. Similarly, Table 8 compares situational analysis and worst-case scenarios. Percentage change is reported as the ratio of change in the value of the specific output and initial output- expressed as a product of 100. Negative sign indicates a reduced value of the parameter and positive sign indicates an increase.

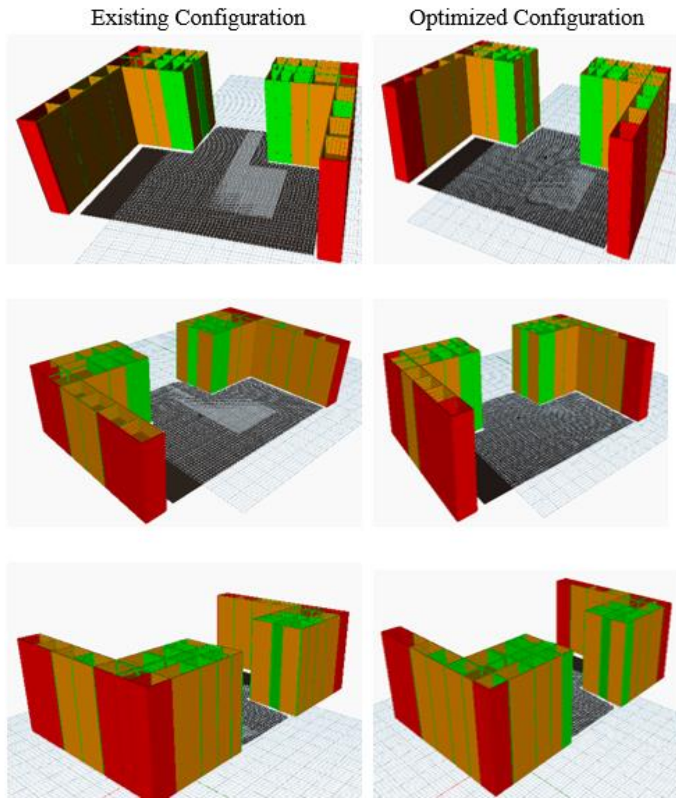


Figure 24: Output Screenshot for Existing and Optimized Configuration

Table 6: Statistical Comparison between Existing and Optimized Configuration Output

Output Parameter	Percentage Change
Lift Score	6.3 (-)
Liftable (%)	1.5 (+)
Liftable with Truck Issue	0
Non-Liftable	0.9 (-)
Unreachable (%)	0.7 (-)

From the data mentioned in the table above, it was observed that with the implementation of Generative Design algorithm- the lift score improved by a factor of 6.3%. This indicated that with the crane being positioned on the optimal configuration- the lift errors were reduced, and hence the possibility of lift issues arising reduced by 6.3%. Similarly, 1.5% of the total elements were additionally liftable- and consequently, 0.9% and 0.7% of the total elements were **not** non-liftable and unreachable, respectively.

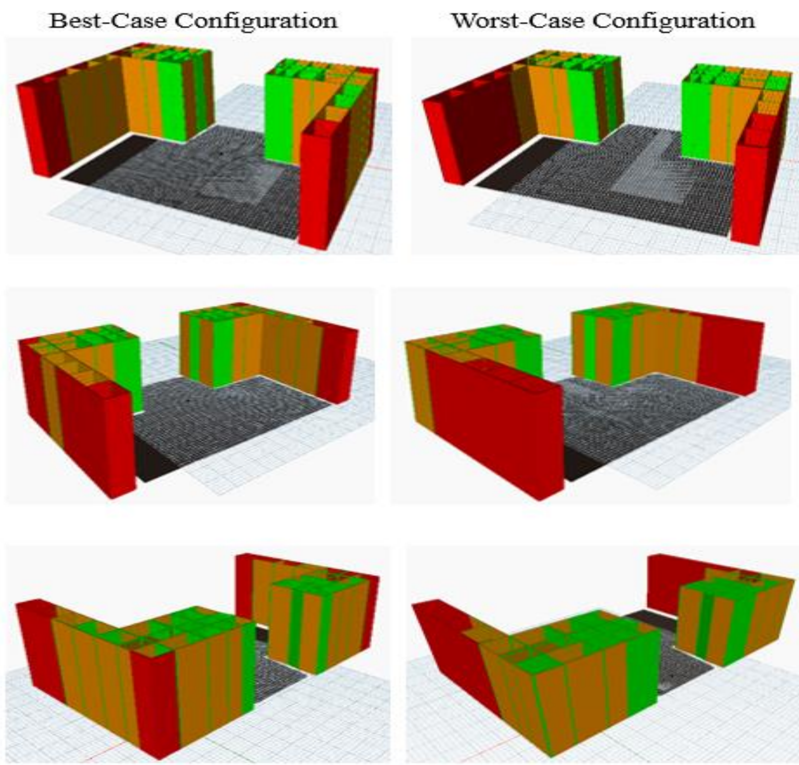


Figure 25: Output Screenshot for Best- and Worst-Case Scenario

Table 7: Statistical Comparison between Best- and Worst-Case Scenario

Output Parameter	Percentage Change
Lift Score	38.9 (-)
Liftable (%)	4.3 (+)
Liftable with Truck Issue	0
Non-Liftable	0.5 (-)

Unreachable (%)	4.8 (-)

From the data mentioned in the table above, it can be seen that with the implementation of the Generative Design algorithm to compare the best- and worst-case scenario- the lift score improved by a factor of impressive 38.9%. This indicated that with the crane being positioned on the optimal configuration- the lift errors were reduced, and hence the possibility of lift issues arising- reduced by 38.9%. Similarly, 4.3% of the total elements were additionally liftable- and consequently, 0.5% and 4.8% of the total elements not non-liftable and unreachable, respectively.

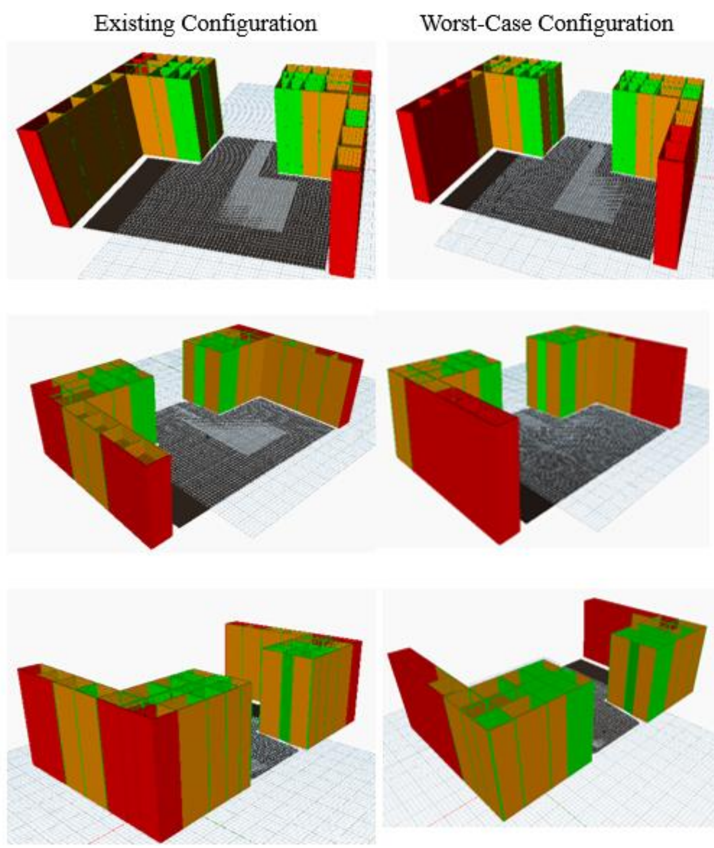


Figure 26: Output Screenshot for Current and Worst-case scenario

Table 8: Statistical Comparison between Current and Worst-case scenario

Output Parameter	Percentage Change
Lift Score	30.2 (-)
Liftable (%)	2.8 (+)
Liftable with Truck Issue	0
Non-Liftable	1.4 (-)
Unreachable (%)	4.1 (-)

From the data mentioned in the table above, it can be seen that with the implementation of Generative Design algorithm to compare the current configuration worst-case scenario- the lift score improved by a factor of an enormous 30.2%. This indicated that with the crane not being positioned on the worst possible position- the lift errors were reduced, and hence the possibility of lift issuing arising- reduced by 30.2%. Similarly, 2.8% of the total elements were additionally liftable- and consequently, 1.4% and 4.1% of the total elements were not non-liftable and unreachable, respectively.

4.3.3 Visualizing Changes and Trade-Off

One of the premier advantages of Generative Design is its ability to visualize the models in their entirety. These benefits can not only be leveraged but even augmented by observing the same view and orientation of the model, for different situations—to visualize, observe and comprehend the changes that take place. This section, therefore, pastes snips of selected portions of the model for existing situation, optimized situation and worst-case scenario, and identifies the changes that arise as a result of algorithmic implementation. Figures 25 through 28 show various views of all the three possibilities and highlight the changes in the lift-ability of Tower Crane.

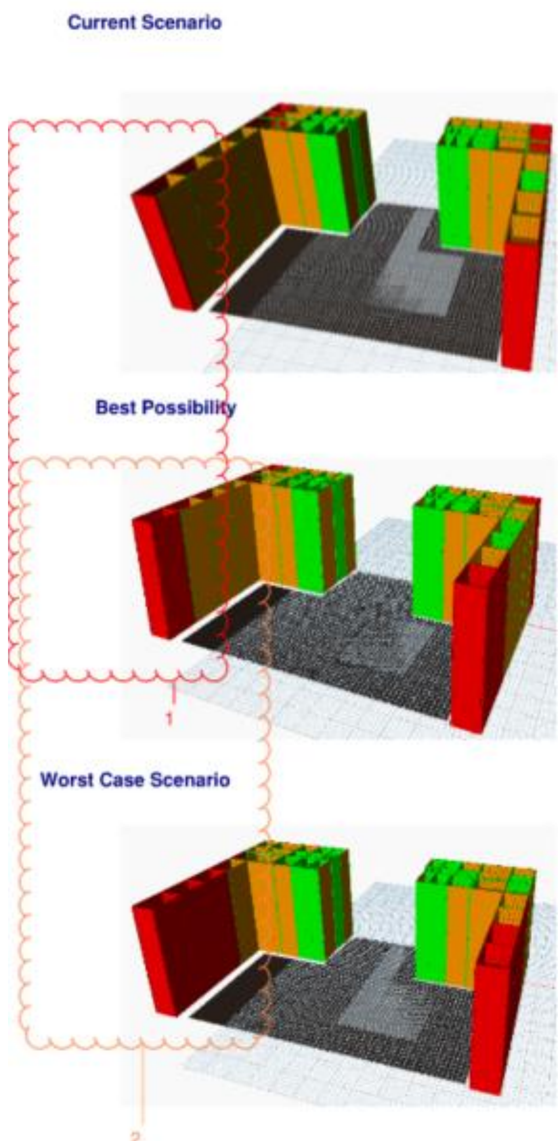


Figure 27: View I- Current, Best- and Worst-case Scenario

As shown in the figure above, two major changes were evident on the highlighted patch of the first building. The legend keys are as follows:

1- Comparing the current scenario and optimized configuration, the highlighted i.e. leftmost panel in the highlighted patch became unreachable. The panel that earlier had a weight issue now became unreachable- increasing the lift effort by five times concerning the existing configuration.

2- By moving the crane to a potential position i.e. worst-case scenario- four panels in the highlighted region became unreachable- that could have been reduced to one if it were placed at the best possible position, and zero considering the current position.

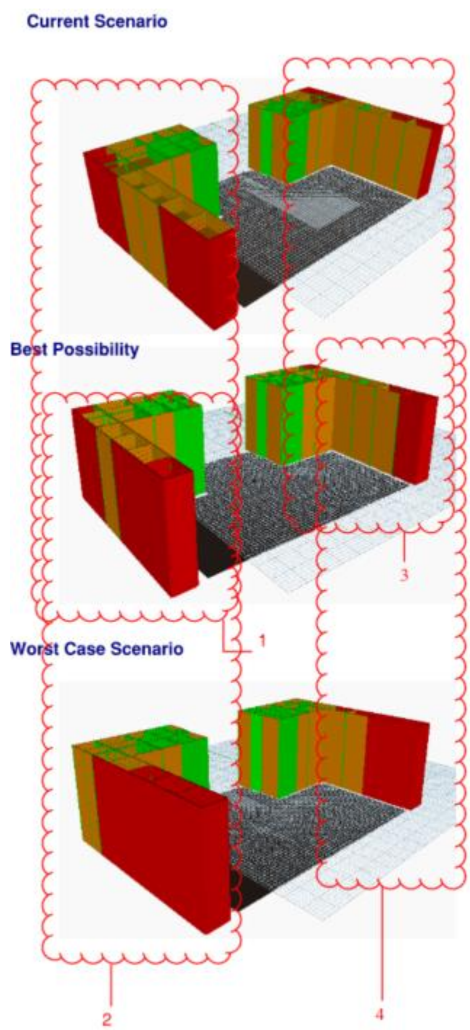


Figure 28: View II- Current, Best- and Worst-case Scenario

As shown in the figure above, four major changes were evident on the highlighted patches of the buildings. Bullets 1 and 2 reflect the same region, as depicted in Figure 26. The legend keys for the remaining are as follows:

3- One of the entire panels in the highlighted region that was non-liftable in the current scenario, became unreachable if the crane would have been placed in the optimum configuration.

4- Two panels in the highlighted region became unreachable if placed in the worst possible configuration. One of them would be non-liftable in the best-case scenario, whereas both the panels would have been non-liftable if the tower crane remained in the existing situation.

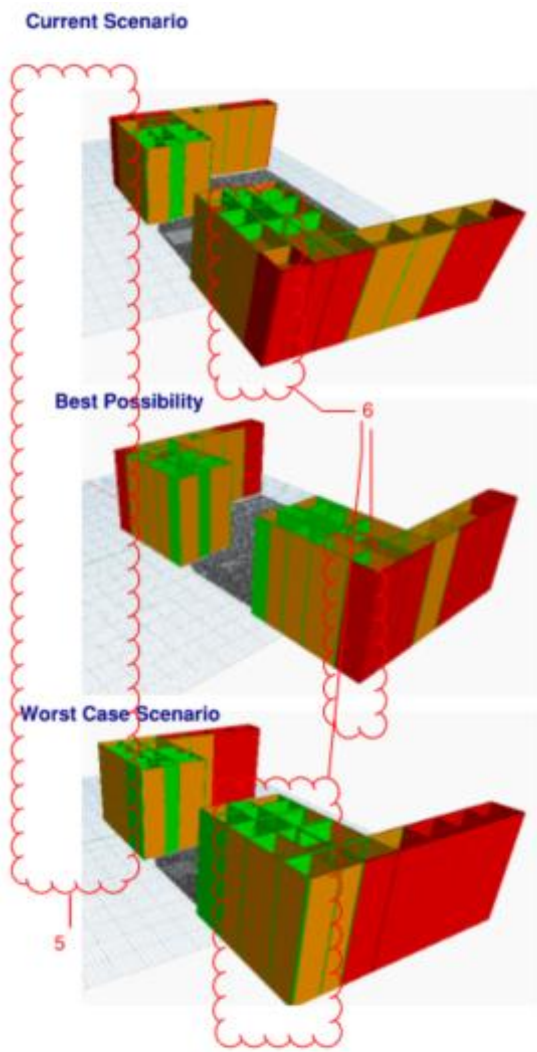


Figure 29: View III- Current, Best- and Worst-case Scenario

As shown in the figure above, two new major changes were evident on the highlighted patch of the first building. The legend keys are as follows:

5- The corner most panel in the highlighted region was non-liftable only in the worst-case scenario. It, however, became unreachable when observed for the current and best possible scenario.

6- The highlighted corner-most panel was completely unreachable in the current scenario and even in the best possible scenario. It was, however, non-liftable only in the worst-case scenario.

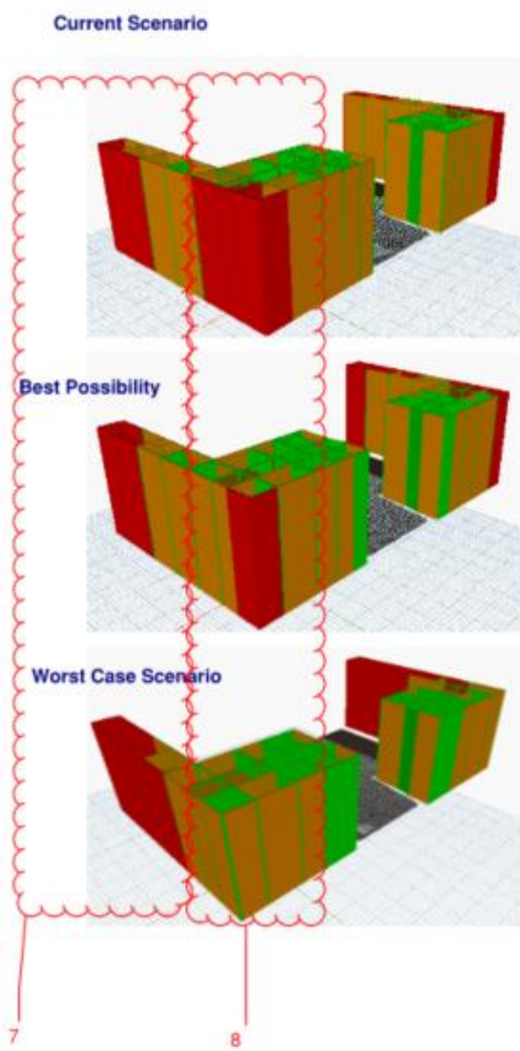


Figure 30: View IV- Current, Best- and Worst-case Scenario

As shown in the figure above, two new major changes were evident on the highlighted patch of the first building. The legend keys are as follows:

7- In the corner most panel of the highlighted region- four panels were unreachable in the worst-case scenario, as compared to two in the current and best-case scenario of the tower crane configuration.

8- As highlighted in the right cloud- four panels in the current scenario were currently unreachable. This number, however, reduced to two in the best-case scenario. Interestingly, the number reduced to zero in the worst-case scenario.

4.4 Analysis for Site 2

The second construction site was a residential project based in Western India. The project has five eleven-story buildings. Each floor has two apartments and an elevator as well as a staircase as means of communication. The total construction region is 3.94 acres and the total area of property is 4.63 acres. Figure 29 shows a rendered image of the construction site- with the initial position of Tower Crane and truck marked on it. Tower Crane and truck used here are only for representational purposes. Actual load data, range details, and specifications were fetched from the actual site plans.

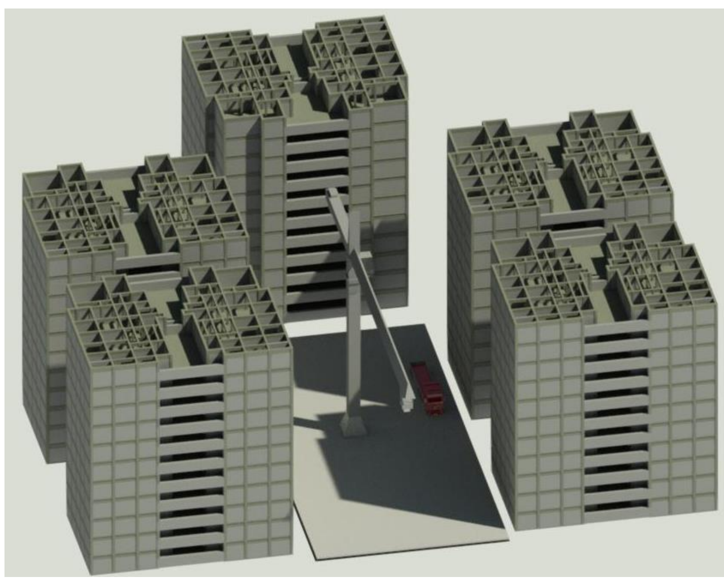


Figure 31: Rendered Image for Site 2

4.4.1 Positional Analysis

Positional analysis as construed here refers to calculating the lift score for a specific position of the tower crane on a construction site. Situational analysis was first carried out to calculate the lift score and visuals concerning liftable regions based on the existing configuration of the Tower crane. After evaluating- the study was then exported to Beta Refinery to explore all the possible locations where the Tower crane could have been placed. The final outcome of the created

Generative Design study was a lift score for all the distinct positions of Tower crane- with an ability to filter the results as per the desired constraints.

4.4.1.1 Situational Analysis

Situational analysis reflects the lift score corresponding to the existing Tower Crane configuration. Table 9 shows the total value of lift score along with the percentage of liftable, liftable with truck issue, non-liftable and unreachable elements on the construction site.

Table 9: Situational Analysis Results for Site 2

Parameter	Output Value
Lift Score	275,500
Liftable (%)	84.6
Liftable with Truck Issue	0
Non-Liftable	4.6
Unreachable (%)	10.8

In order to better understand the above-mentioned parameters- Generative Design provides visuals of the 3D model that are color coded to understand the elements that follow in a specific range. Figure 30 shows the snapshots of the 3D model for the existing crane configuration. All elements in red are indicative of the non-liftable region, orange representing non-liftable elements and green for liftable elements.

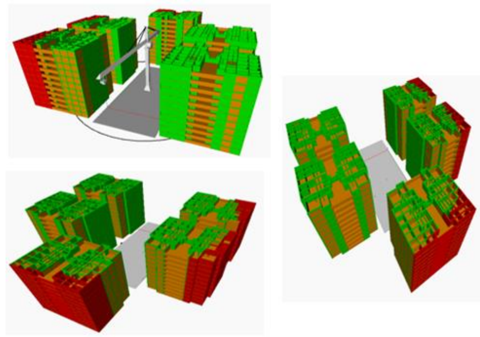


Figure 32: Visual Representation of Situational Analysis – Site 2

4.4.1.2 Best Case Scenario: The Optimized Configuration

After ranking the results in ascending order of the lift score- an optimal position was identified as the best one of the pool of alternatives so generated. Table 10 shows the total value of lift score along with the percentage of liftable, liftable with truck issue, non-liftable and unreachable elements on the construction site.

Table 10: Optimized Configuration Results for Site 2

Parameter	Output Value
Lift Score	208,180
Liftable (%)	87.3
Liftable with Truck Issue	0
Non-Liftable	4.7
Unreachable (%)	7.9

Figure 31 shows the snapshots of the 3D model for the optimized crane configuration. All elements in red are indicative of the non-liftable region, orange representing non-liftable elements and green for liftable elements.

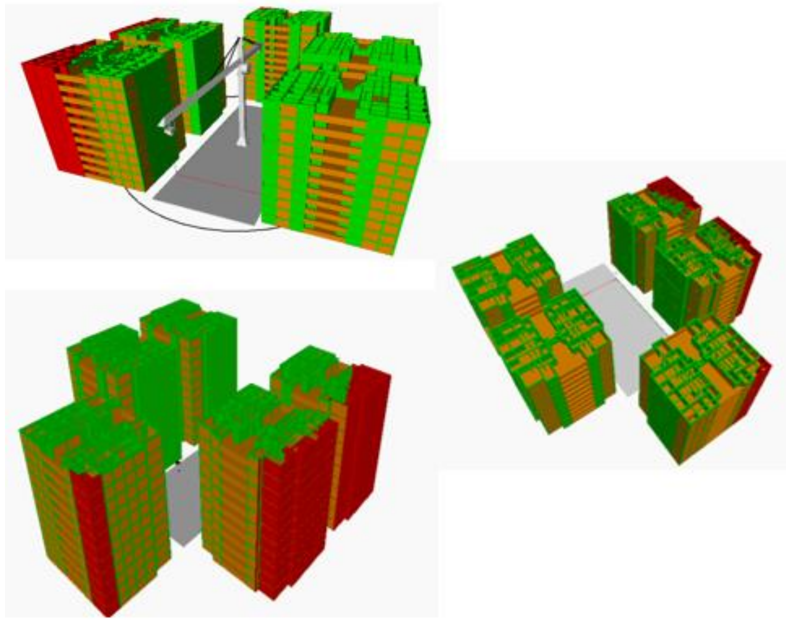


Figure 33: Visual Representation for Optimized Configuration – Site 2

4.4.1.3 Worst Case Scenario

After ranking the results in ascending order of the lift score- the least conducive position of the pool of alternatives so generated was identified. Table 11 shows the total value of lift score along with the percentage of liftable, liftable with truck issue, non-liftable and unreachable elements on the construction site.

Table 11: Worst Case scenario analysis results for Site 2

Parameter	Output Value
Lift Score	288,920
Liftable (%)	84
Liftable with Truck Issue	0
Non-Liftable	4.6
Unreachable (%)	11.4

Figure 32 shows the snapshots of the 3D model for the least favorable crane configuration. All elements in red are indicative of the non-liftable region, orange representing non-liftable elements and green for liftable elements.

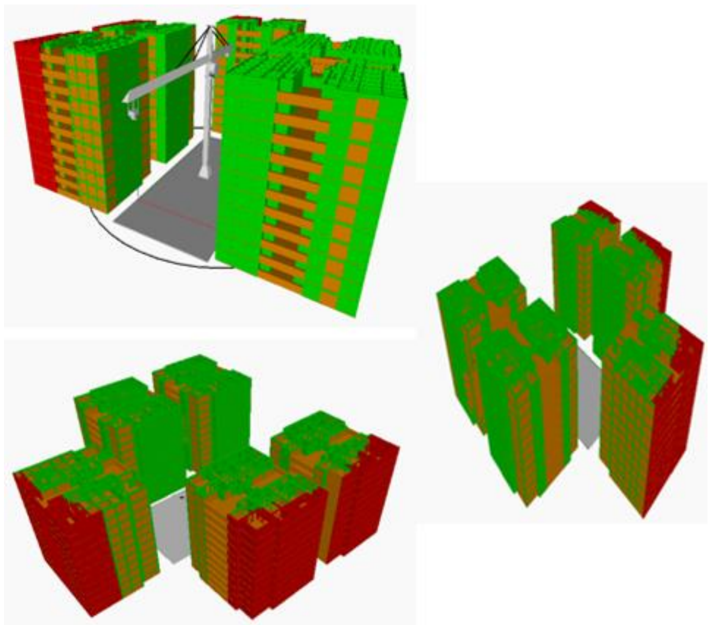


Figure 34: Visual Representation for Worst Case Scenario – Site 2

4.4.2 Statistical Analysis for Site 2 Parameters

After calculating the value of lift scores and percentage of elements that follow in each category- a simple comparison was carried out to better comprehend the changes so witnessed. Figures 33, 34, and 35 show the raw output screenshot captured from the Dynamo interface. Table 12 shows a comparison between Optimized Configuration output and situational analysis output. Table 13 compares the best and worst possibility. Similarly, Table 14 compares situational analysis and worst-case scenarios. Percentage change is reported as the ratio of change in the value of the specific output and initial output- expressed as a product of 100. The negative sign indicates a reduced value of the parameter and a positive sign indicates an increase.

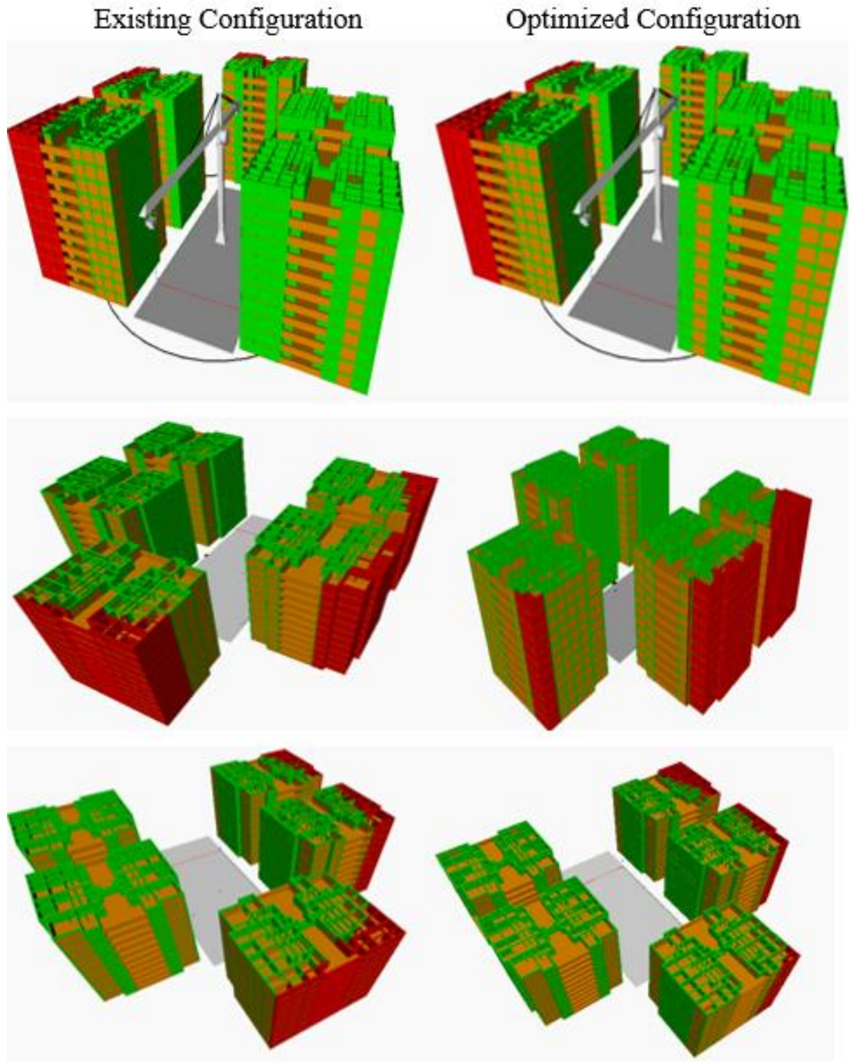


Figure 35: Output Screenshot for Existing and Optimized Configuration

Table 12: Statistical Comparison between Existing and Optimized Configuration Output

Output Parameter	Percentage Change
Lift Score	25 (-)
Liftable (%)	2.7 (+)
Liftable with Truck Issue	0
Non-Liftable	0.1 (-)
Unreachable (%)	2.9 (-)

From the data mentioned in the table above, it can be seen that with the implementation of Generative Design algorithm- the lift score improved by a factor of 25%. This indicated that with the crane being positioned on the optimal configuration- the lift errors were reduced, and hence the possibility of lift issues arising- reduced by 25%. Similarly, 2.7% of the total elements were additionally liftable- and consequently, 0.1% and 2.9% of the total elements were not non-liftable and unreachable, respectively.

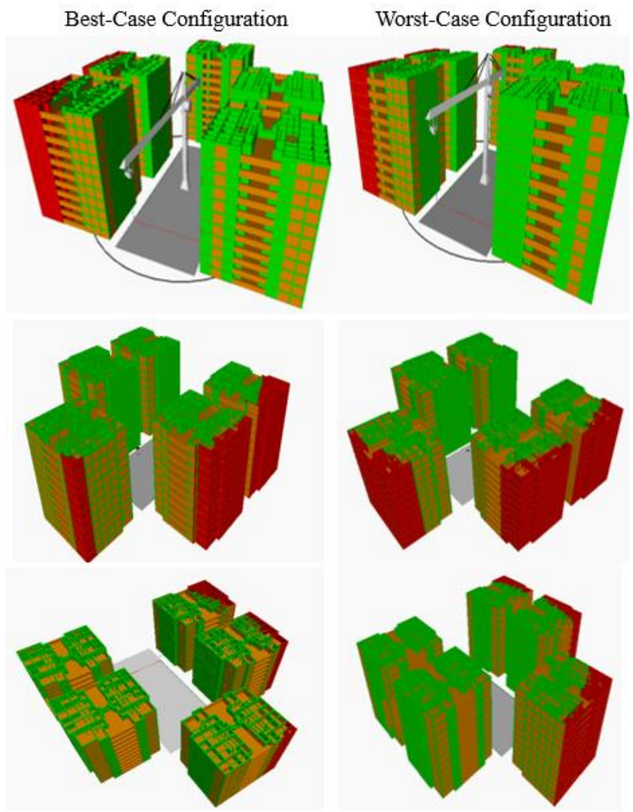


Figure 36: Output Screenshot for Best- and Worst-Case Scenario

Table 13: Statistical Comparison between Best- and Worst-Case Scenario

Output Parameter	Percentage Change
Lift Score	39 (+)
Liftable (%)	3.3 (-)
Liftable with Truck Issue	0
Non-Liftable	0.1 (-)
Unreachable (%)	3.5 (+)

From the data mentioned in the table above, it can be seen that with the implementation of Generative Design algorithm to compare the best- and worst-case scenario- the lift score improved by a factor of whopping 39%. This indicated that with the crane being positioned on the optimal configuration- the lift errors were reduced, and hence the possibility of lift issues arising- reduced by 39%. Similarly, 3.3% of the total elements were additionally liftable- and consequently, 0.1% and 3.5% of the total elements were not non-liftable and unreachable, respectively.

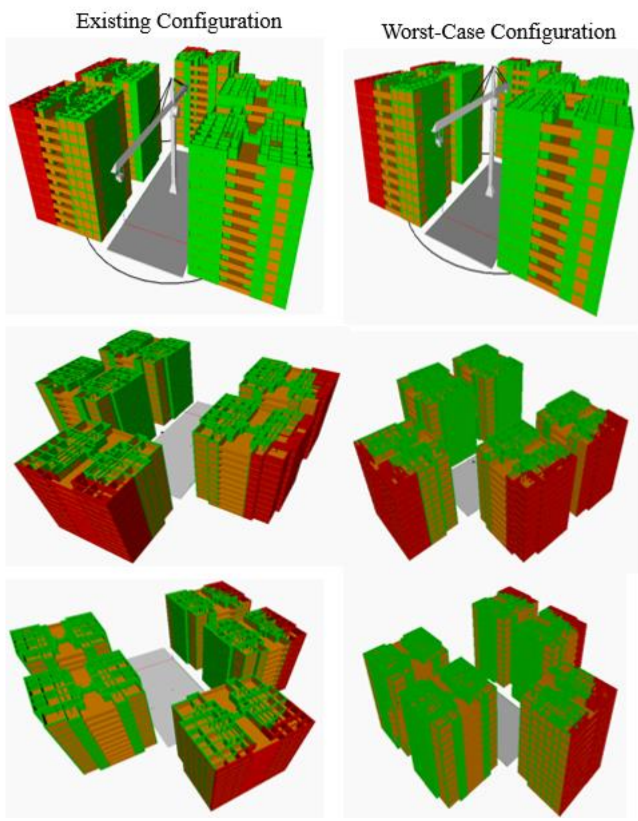


Figure 37: Output Screenshot for Current and Worst-case scenario

Table 14: Statistical Comparison between Current and Worst-case scenario

Output Parameter	Percentage Change
Lift Score	4.9 (-)
Liftable (%)	0.6 (+)
Liftable with Truck Issue	0
Non-Liftable	0 (-)
Unreachable (%)	0.6 (-)

From the data mentioned in the table above, it can be seen that with the implementation of Generative Design algorithm to compare the current configuration worst-case scenario- the lift score improved by a factor of 4.9%. This indicated that with the crane not being positioned in the worst possible position- the lift errors were reduced, and hence the possibility of lift issues arising- reduced by 4.9%. Similarly, 0.6% of the total elements were additionally liftable- and consequently, 0.6% of the total elements were not unreachable.

4.4.3 Visualizing Changes and Trade-Off

One of the premier advantages of Generative Design is its ability to visualize the models in their entirety. These benefits can not only be leveraged but even augmented by observing the same view and orientation of the model, for different situations—to visualize, observe and comprehend the changes that take place. This section, therefore, pastes snips of selected portions of model for existing situation, optimized situation, and worst-case scenario, and identifies the changes that arise as a result of algorithmic implementation. Figures 36 through 37 show various views of all the three possibilities and highlight the changes in the lift-ability of Tower Crane.

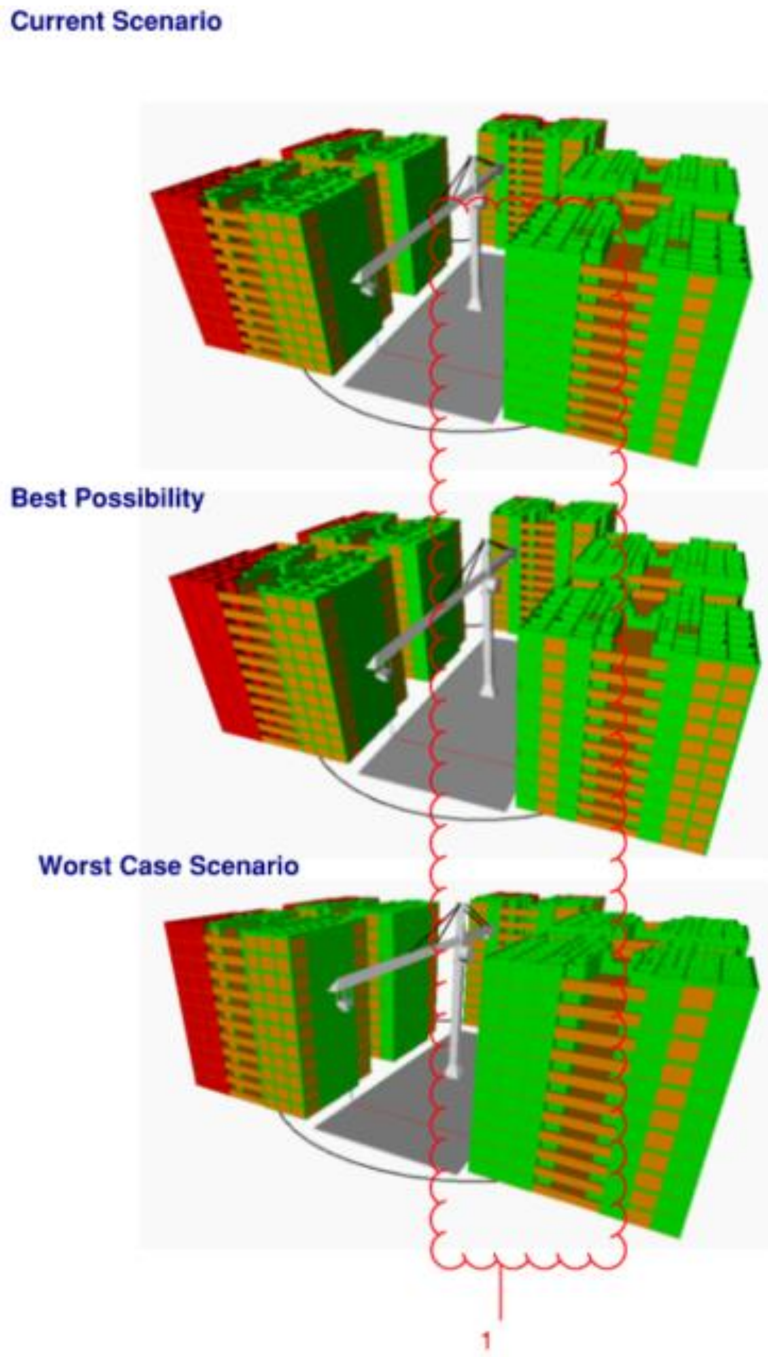


Figure 38: View I- Current, Best- and Worst-case Scenario

As shown in the figure above, there was one major change evident in the highlighted patch of the first building. The legend key is as follows:

1- The highlighted patch that was liftable in the current and worst-case scenario faced a weight issue when placed on the algorithmically determined optimum position.

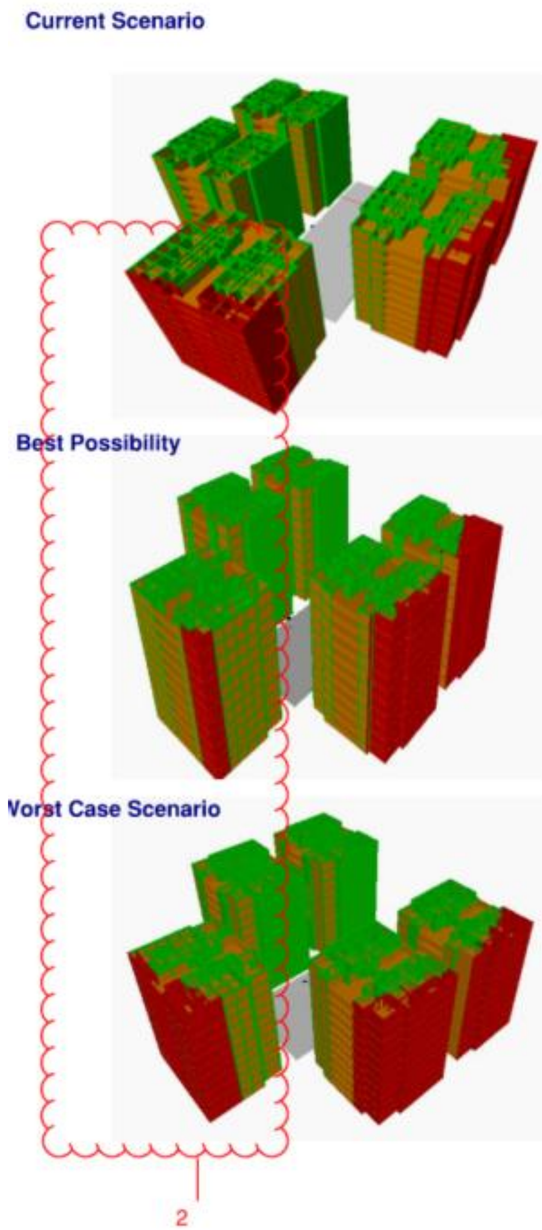


Figure 39: View II- Current, Best- and Worst-case Scenario

As shown in the figure above, there was one major change that is evident in the highlighted patch of the buildings. The legend key is as follows:

2- The entire exterior façade on the rear end of the property (south elevation) was not unreachable only in the best case i.e. optimum configuration. The unreachable region transformed into one having weight issues while transitioning from the current or worst-case scenario to the best case one.

4.5 Rationale for Trade-Off

One of the premier benefits of using Generative Design driven by Beta Refinery- that allows the exploration of multiple design outcomes lies in visualizing the complete model for the prospective alternative. It is very essential, therefore, to observe the model in its entirety before arriving at a sound decision. The visuals combined with the statistical lift data is what makes this process reliable. As seen in all the scenarios above- it is very difficult to decide the final position of tower crane by just cursorily analyzing the generated visuals. It is, hence impossible to arrive at the best position by just counting the number of panels or counting the associated elements for each lift status. The entire procedure of performing the trade-off is substantiated by the incorporation of the following two points:

1. Prioritization: Visualization helps in observing the models. On a construction site- some regions and elements have a higher preference for being lifted by the tower crane. These visuals ensure that even if the lift score is not the lowest- the target region is still liftable. Prioritization through visuals aid in ensuring that essential areas are lifted- and not compromised by directly adopting the algorithmic data output, in the form of net lift-score. Lift status of individual elements, as a sub-part of the net lift score for the construction site, helps in catering to the designated lift requirements of every element/group while still optimizing the ultimate position of tower crane on construction site.

2. Holistic Decision Making: Initial rash choices or forming uninformed decisions can lead to missing out on focusing on the bigger picture. Rather than generating visuals for a part of the model- the output interface allows the decision-maker to explore all nuances. By not observing a part of the model- the user eliminates chances of making a less informed decision. Premier example for this is judging based on scenarios discussed in 4.3.3. In neither of the four views- is there a unanimous forerunner. Hence, if the decisions are formed by exploring just one of the associated views- decision-makers are more likely to arrive at a solution that is not the most conducive or optimal throughout the course of the project.

Prioritization and Holistic decision-making are one of the key outcomes of the study undertaken. They not only highlight the importance of visuals in their entirety but also authenticate the need for corroborating via statistics. Generative Design is construed as an amalgamation of Visual Based and Mathematical based optimization models-- and trade-offs for decision making validate the proposed claim to a large extent!

4.6 Participants' Demographics for Usability Study

The usability study selected 12 participants having relevant experience in tower crane. Group 1 consisted of interns, entry-level engineers and contractual associates who had firsthand witnessed tower crane operations on the construction site. For the chosen participants in this group- the experience ranged from managing job site during crane lifts and assisting project managers determine the tower crane position- to supporting field engineers to ensure productive operational cycles of the equipment. This group has been named Group A- from hereon.

Group 2 largely consisted of Project Engineers and Project Managers, and an executive-level director. This group encompassed experience pertaining to direct decision making for tower crane selection, placement and operations- and also scheduling and sequencing events in a manner that the existing activities didn't interfere with the crane operations. This group has been called Group B, hereafter.

4.6.1 Participant Demographics

The Pre-Demonstration Demographic Questionnaire, attached in Appendix-A was sent out to industry professionals to record their willingness to be a part of the study. In total twelve participants were shortlisted and bifurcated into two groups.

Group A:

Participant 1: (A1) – Participant A1 has two years of experience in specialized and industrialized construction. The participant has been witnessing tower crane's functioning ever since the first day on the construction site. In fact, owing to the nature of the work- mini mobile cranes (not tower crane) have also been witnessed by the volunteer for element handling operations in extremely high and low-temperature zones. The individual has not worked firsthand on the BIM models and was never exposed to Generative Design, ever before.

Participant 2: (A2) – Participant A2 has three years of experience in the architectural and construction industry. The participant started working as an architect but later transferred to the construction side of the business. The individual has majorly assisted project managers on the office site in determining and managing the tower crane schedule- and was therefore exposed to the factors that are considered in the tower crane pre-planning phase. The volunteer has, in-total, worked with Tower crane for a little less than a year and has been working with BIM technologies for over four years. Participant did know about the concept of Generative Design- and had sporadically worked on the underlying concepts as a part of the academic curriculum.

Participant 3: (A3) – Participant A3 has three and a half years of experience on the civil engineering side of the projects. Similar to A2, the participant has largely assisted the Construction Management team throughout the project lifecycle. The participant highlighted the absence of a designated Point of contact for crane operations- which made the definition of their roles extremely complex. With over three years of watching and observing tower crane operations on the construction site- the participant mentioned never having used anything related to technology on the job site- specifically for Tower Crane or site logistics.

Participant 4: (A4) – The trajectory of the participant is similar to A2. The individual transformed from being an Architect to Junior Field Engineer to a Field Engineer now. With two years of experience as an architect and two years as a field engineer- the individual was extremely keen on observing the integration of the two specialized realms. Having spent a majority of the time on the field- the participant has been witnessing the on-site management of activities and crane operations for a little over eighteen months. In one of the projects, moreover, the participant was associated with the management of tower crane operations on a mountainous region- with a plethora of accessibility issues. Participant had extensively worked with BIM before the transition but had not witnessed Generative Design, in action.

Participant 5: (A5)- The participant has a net work experience of one year via internships on the construction site. Despite of the duties largely revolving around the entirety of the construction site- individual has been actively associated with tower crane, on the academic and theoretical side. The participant currently guides over a hundred students in the domain of site logistics and crane operations- and has read and been exposed to a multitude of industrial studies based on selection and utilization of on-site equipment. The individual had been exposed to BIM technologies, as well as Generative Design technologies- only via academic coursework.

Participant 6: (A6)- Participant A6 works as a Junior Project Engineer at a commercial construction firm. The individual has eighteen months of experience that includes specialized assistance to crane operators in ensuring safe and clash-free operations. The participant knows and is aware of BIM technologies owing to a BIM department in the firm. However, no direct exposure or hands-on experience had been distinctly recorded.

Group B:

Participant 1: (B1) – Participant B1 works as an Assistant General Manager for Projects and Construction at a general contracting firm. The individual has been working in the construction industry for more than eight years and has handled several portfolios that range from working as a Site Superintendent to Senior Project manager. Despite having several projects under supervision, the participant still monitors and is accountable for every decision pertinent to on-site operations and planning. Additionally, the participant has taken up responsibilities that also belong to efficient site execution in the construction of roads and highways. The individual, however, was never exposed to any of the BIM technologies or Generative Design concepts- neither in the academic curriculum nor in the construction industry.

Participant 2: (B2) – Participant B2 works as a Senior Project Manager for Residential and Commercial construction undertaken by the organization that the individual is associated with. The participant has worked on the preconstruction and project management side of construction and has been associated with the execution side of construction since 2014. The individual has, on many occasions, been answerable to several authorities regarding failed crane operations, clashes resulting as a product of malfunctioning crane, and even safety issues arising due to improper placement of Tower crane. The participant has been an advocate of technology and takes pride in digitizing the conventional process by introducing technology at the associated firm.

Participant 3: (B3) – Participant B3 switched to the heavy civil construction industry from intensive commercial construction after being associated with the latter for more than eight years. Individual describes themselves as a field-lover and says that the ultimate aim is to always be glued on-site. Participant accepts being a bit resistant to technology because the individual has always been skeptical about it affecting the larger field operations. Participant, despite documenting around 15,000 workhours around crane mentions being an ever-curious soul who marks this piece of equipment as being unpredictable yet beautifully complex.

Participant 4: (B4) – Participant B4 works as a Project Engineer at an organization that specializes in Datacenter and Institutional construction. Owing to the locations that the individual has largely worked at, the volunteer's involvement in this study helped specifically concentrate on the care that needs to be taken while a Tower crane operates on congested sites with numerous constraints on the work region. Participant had been exposed to BIM technologies not only at an academic level- but also at the user-ended part of leveraging VDC benefits. Participant accepts that the organization is extremely open to new ideas and does everything possible with BIM.

Participant 5: (B5) – Participant works as a Project Manager at a General Contractor firm. Being someone who works at the junction of On-Site field execution and Office driven project management- the individual has witnessed the operations and functioning of crane across four different countries. The individual's diverse experience over a period of five years did include utilization of primitive technology in the form of CAD drawings and digitized documentation.

Participant 6: (B6) – Participant B6 is one of the youngest executive-level individuals in the region that the organization largely operates in. The individual is now a Managing Director and acting Vice President for a firm that has over 75 permanent employees and specializes in Residential construction. The participant had largely worked as a Site Superintendent before taking over the family business. Participant admits to having zero experience with the construction technologies- but says that it stands as the imminent milestone that the company is trying to achieve.

The researcher acknowledges the existence of a diverse set of participants whose contribution in the sampling pool helped represent diverse experiences that differed in types of construction projects and industries, size of the construction site, country of operation, and even level of detail of technology adoption and exposure.

4.7 Likert Scale Analysis using Qualtrics

For the twelve shortlisted participants, details of which have been described above- questions listed in Appendix B were used as a measure of obtaining statistics for each of the usability aspects. All the participants were first given an overview of the study highlighting the problem and purpose statement of the study and describing the underlying objective and intended methodology. After the briefing session- the participant witnessed a live demonstration of how Generative Design has been used for this study. After visualizing the prospective positions of Tower crane on the construction site with lift status of crucial elements, and getting a brief of the statistics required – the participant filled out a Likert Scale survey using Qualtrics as the platform. Figure 38 shows a screenshot of the raw data captured for Group A and Figure 39 for Group B. As seen, the questions have been codified as well- making it easier to map a specific response by a participant for a specific question. The researcher's interpretation of the data obtained for this specific aspect is discussed subsequently.

Question Code		Group A					
		A1	A2	A3	A4	A5	A6
	Aspect 1: Ease of Learning						
1A	Learning Generative Design for Tower Crane Planning would be an easy task	5	3	4	2	3	4
1B	Generative Design can be easily linked/associated with Tower Crane Planning activities	5	4	4	2	4	5
1C	The developed model can be easily implemented after preliminary learning/training	4	3	5	2	2	3
		4.67	3.33	4.33	2.00	3.00	4.00
	Aspect 2: Efficiency of Usage						
2A	The developed model helps visualize the potential tower crane positions	4	5	5	4	4	5
2B	The developed model reasonably encapsulates the essential features of Tower Crane Positioning	4	5	4	3	4	4
2C	Generative Design helps effectively determine the optimum position of a Tower Crane	4	5	5	3	4	5
		4.00	5.00	4.67	3.33	4.00	4.67
	Aspect 3: Ease of Remembrance						
3A	The optimization algorithm used for Tower Crane Planning is simple and lucid	4	4	4	3	4	3
3B	The concepts of Generative Design can be easily applied from one site to another site without requiring a refreshing tutorial	3	2	5	2	3	2
		3.50	3.00	4.50	2.50	3.50	2.50
	Aspect 4: Prevention of Errors						
4A	Generative Design is useful to reduce or mitigate the errors otherwise associated with TCP	5	4	4	5	4	4
4B	The developed GD model does not have inherent errors that might further complicate the TCP process	4	4	3	3	3	5
		4.5	4	3.5	4	3.5	4.5
	Aspect 5: Subjective Pleasing						
5A	GD is a promising technique to deal with issues pertaining to TCP	5	4	4	5	4	5
5B	GD posits benefits to several stakeholders associated with the construction process	5	5	4	4	4	4
5C	GD is useful than conventional ways of determining the Tower Crane Position	5	4	5	4	4	5
5D	GD appropriately addresses the lift-ability issue of Tower Crane Positioning	4	4	4	3	4	5
5E	I would be willing to use GD for next tasks revolving around TCP	5	4	4	4	4	4
5F	I would recommend my team and fellow tskaeholders to use Generative Design for Tower Crane Planning in future	5	4	5	4	4	5
		4.83	4.17	4.33	4.00	4.00	4.67

Figure 40: Likert Scale Raw Data for Group A

Question Code		Group B					
		B1	B2	B3	B4	B5	B6
	Aspect 1: Ease of Learning						
1A	Learning Generative Design for Tower Crane Planning would be an easy task	5	4	2	4	4	3
1B	Generative Design can be easily linked/associated with Tower Crane Planning activities	5	5	5	4	5	4
1C	The developed model can be easily implemented after preliminary learning/training	2	4	2	3	4	3
		4.00	4.33	3.00	3.67	4.33	3.33
	Aspect 2: Efficiency of Usage						
2A	The developed model helps visualize the potential tower crane positions	5	5	5	5	5	4
2B	The developed model reasonably encapsulates the essential features of Tower Crane Positioning	4	5	4	5	4	5
2C	Generative Design helps effectively determine the optimum position of a Tower Crane	4	4	5	5	5	4
		4.33	4.67	4.67	5.00	4.67	4.33
	Aspect 3: Ease of Remembrance						
3A	The optimization algorithm used for Tower Crane Planning is simple and lucid	5	5	2	4	3	2
3B	The concepts of Generative Design can be easily applied from one site to another site without requiring a refreshing tutorial	4	5	1	4	5	4
		4.50	5.00	1.50	4.00	4.00	3.00
	Aspect 4: Prevention of Errors						
4A	Generative Design is useful to reduce or mitigate the errors otherwise associated with TCP	4	4	5	4	4	4
4B	The developed GD model does not have inherent errors that might further complicate the TCP process	4	4	4	4	3	4
		4	4	4.5	4	3.5	4
	Aspect 5: Subjective Pleasing						
5A	GD is a promising technique to deal with issues pertaining to TCP	5	4	5	5	5	5
5B	GD posits benefits to several stakeholders associated with the construction process	4	4	5	5	4	5
5C	GD is useful than conventional ways of determining the Tower Crane Position	4	4	4	4	4	5
5D	GD appropriately addresses the lift-ability issue of Tower Crane Positioning	4	4	2	5	5	4
5E	I would be willing to use GD for next tasks revolving around TCP	4	4	4	4	5	4
5F	I would recommend my team and fellow tskaeholders to use Generative Design for Tower Crane Planning in future	4	4	4	4	5	4
		4.17	4.00	4.00	4.50	4.67	4.50

Figure 41: Likert Scale Raw Data for Group B

4.7.1 Ease of Learning

Ease of Learning for this study was meant to determine the participant's interpretation of how difficult is it for them to absorb the software essentials. It was essentially tested by seeking answers to the statements on whether 1) Learning Generative Design would be an easy task or not, 2) If Generative Design can be linked to the Tower Crane Planning activities, and 3) If the developed model can be incorporated in the daily construction site practices after getting an initial drive. The researcher's interpretation of the data obtained for this specific aspect is discussed subsequently.

4.7.1.1 Group A

Overall, Ease of Learning was identified as one of the most noteworthy barriers that might restrict industry professionals from adopting this technique. In fact, for participants A4 and A5- ease of learning was the least satisfied usability criteria. Moreover, for participants A2, A3 and A6; ease of learning was second-lowest when it came to learning the Generative Design technique for on-site implementation. Participants A2 and A5 both mentioned that for someone having no previous exposure to technology implementation, it can be a huge jump from being completely unaware of the technology specifics to handling a Visual Programming based specialized algorithm. Participant A1, however, mentioned that learning is a function of the training provided. One of the key routes to a beneficial implementation will hence begin with resourceful and specialized training. Ease of Learning has been construed as hands-on utilization of this technique, and for Group A- the average score for this aspect was overall the second-lowest- when compared to all the other criteria. With the exception of Participant A1, learning the algorithm is, therefore, clearly interpreted as an arduous task for practical implementation by all the participants of Group A.

4.7.1.1 Group B

Similar to Group A- ease of learning was ranked at the lowest spot by Group B while comparing it with the rest of the usability aspects. Participant B1 was the only individual who thought that Ease of Learning was the largest impediment in successfully leveraging the benefits of this technology. Participant B3 highlighted the need to analyze the current state of BIM and technology maturity in the target organization before intending to straightaway adopt a specific technology plug-in. Participant B6, however, acknowledged that if someone has previous knowledge of BIM functioning- the process becomes logically coherent and easy to follow. For Group B- the usability score for this aspect was the second-lowest- making it one of the potential grounds that might impede the incorporation of this technique.

4.7.1.2 Comparison

A pictorial comparison of the scores presented by Group A and Group B is depicted in Figure 40.

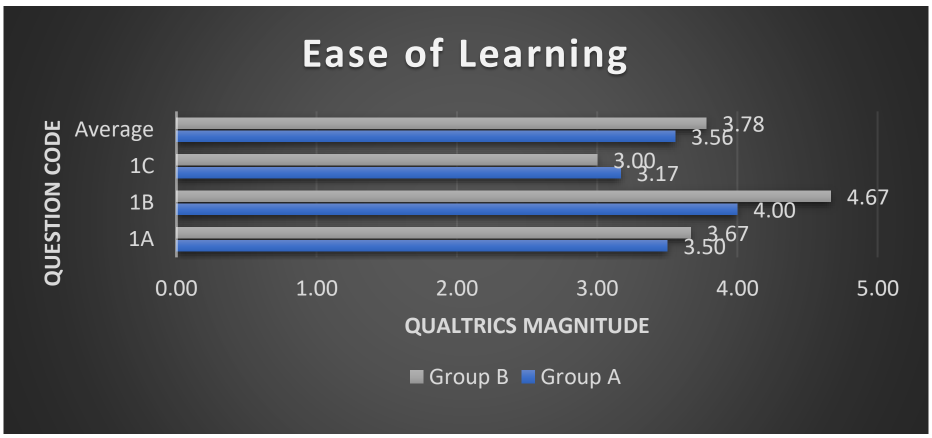


Figure 42: Ease of Learning Comparison Chart

As seen from the image above, Group B had relatively marked the technique as being easier for learning than Group A. One explanation for this is the repeated exposure to technology by the members of Group B. Spending more time at various positions- this group had more exposure to various VDC technologies in action than Group A. Another explanation to this is the ease of learning- ‘in general’ by the members of Group B. Participant B5 mentioned adopting to several changes happening in the way construction sites have been operating, especially since the past couple of years. Participant B2 mentioned that “having spent so many years in the construction industry, it just becomes easier to correlate things”. Overall Ease of Learning is still one of the largest potential barriers- however, owing to correlational and relatability aspects between technology and site practices- Group B viewed this aspect at a diminished stage from being a barrier. Instead, they anticipated a gentle learning curve, ultimately making it usable in the long run.

4.7.2 Efficiency of Usage

This aspect essentially aimed to test if the developed model 1) helped visualize the prospective positions of tower crane, 2) incorporated the essential features of Tower Crane positioning and 3) effectively determined the optimum Position of tower crane. Both the groups gave an extremely positive response as discussed below.

4.7.2.1 Group A

Considering the overall response to technology, Group A gave an extremely positive response to the Efficiency of Usage aspect. Participants A2, A3 and A6 rated efficiency of usage as the best parameter to cater to the usability needs- with Participant A2 giving an exact score of Strongly Agree to all the associated statements intended to test the criteria. Participant A1 stated that with the conditions stated to emphasize a specific criterion to maximize the lift-ability-the algorithm successfully takes into consideration the density and crane specifications which are crucial in determining the lift status of the element and overall lift score of the construction site. Overall, efficiency of usage was the second most effective usability aspect- based on the responses casted by participants of Group A.

4.7.2.2 Group B

Similar to Group A – participants of Group B gave an appreciable response to the usage efficiency aspect of Generative Design's usability. Participants B3, B4 and B5 gave their highest endorsement for this aspect of the study, while B1, B2 and B6 rated this as the second most effective usability parameter. Participant B4 while strongly agreeing to all the statements highlighted the need and effectiveness of color-coded visuals in this process. The individual mentioned that "construction site professionals are visually driven and like to see things exactly as they happen on the site. Visuals beyond simple appeal is what makes the conception process more reliable and relatable". Completely, Group B gave the best possible response to the Efficiency of Usage parameter of usability, absolutely and relatively.

4.7.2.3 Comparison

A pictorial comparison of the scores presented by Group A and Group B is depicted in Figure 41.

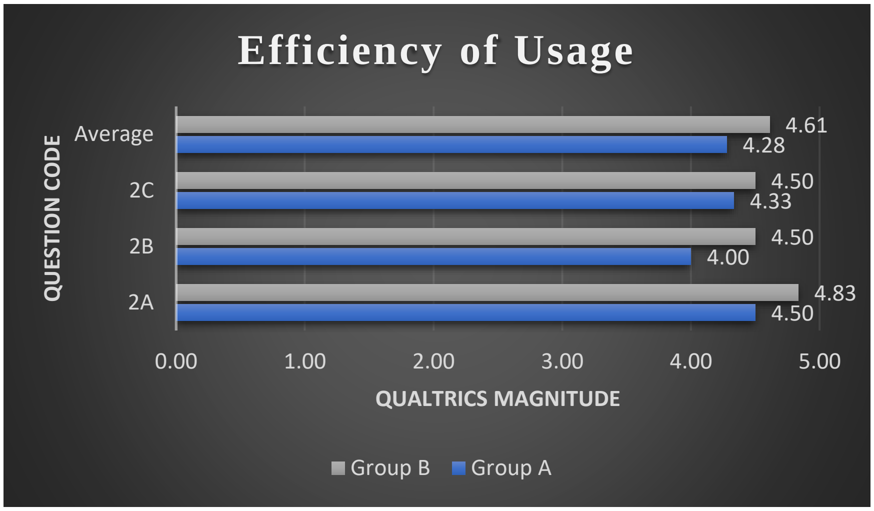


Figure 43: Efficiency of Usage Comparison Chart

As evident from the chart above, both Group A and Group B both gave almost perfect responses to the efficiency of usage criteria. With two perfect scores of five – A2 and B4, the aspect was the highest-ranked usability criterion by Group B and second-highest by Group A. Efficiency of Usage is one of the important measures that solely evaluates the potential of Generative Design. Participant A6 explicitly stated that "the efficiency (of usage) aspect is of utmost importance because if there is an inherent level of incompetence in the proposed technique- the importance of the rest of parameters becomes questionable, by default". Participant B1 stated that the algorithm is a logical extension of the claim that Generative Design amalgamates the visualization and mathematical capabilities to finally optimize the position of tower crane. Some of the recurring reasons as to why the technique was demonstrated to be highly efficient included: accurate visual representation of site conditions, appealing visuals with substantial information, and appropriate lift-ability constraints to optimize the final position of Tower crane.

4.7.3 Ease of Remembrance

The ease of remembrance essentially tested the usability of generative design to understand if 1) the algorithm followed a simple and clear logic, and 2) there is a need for refreshing tutorial while the same concept is applied on a different construction site. This aspect thus tests the understanding/learning portion, as well as the retention component of the script to be utilized for optimization.

4.7.3.1 Group A

Ease of Remembrance was one of the most encumbering experiences- as visible from the responses cast by Group A participants. With an absolute magnitude of just 3.25- this aspect was identified as the strongest aspect that restricted a wide adaptability of Generative Design. As mentioned by participant A4- “if I use Generative Design on one of my projects today, and then after a couple of years- I don’t think I have the technology retention aptitude to utilize it as effectively as I would otherwise”. As an extension to this- Participant A5 said “It is always easy to learn something, use it and get done with it. The problem comes when one is expected to remember the minutiae and then use it with equal skillfulness”. This aspect received the lowest score relative to the rest of the aspects- by participants A2, A4, and A6. Ease of remembrance was, therefore, ranked lowest when evaluating the usability aspect of Generative Design.

4.7.3.2 Group B

Just like Group A- group B did not deliver a very high score while evaluating ease of remembrance as a usability metric. Participants B3 and B6 rated this aspect as the lowest one on the Likert scale while comparing with other criteria. Participant B3 highlighted a prospective reason for that “After spending so many years on the construction site, our minds are programmed in a certain manner. Introducing a new piece of technology that replaces the conventional style might take much longer and need something more impactful than an initial force”. Participant B6 also emphasized that repeated exposure and widespread adoption is essential to use as well as remember this technology. Overall, Group B rated the aspect: Ease of Remembrance as the least favorable aspect of usability while testing the adoption criteria for Generative Design.

4.7.3.3 Comparison

A pictorial comparison of the scores presented by Group A and Group B is depicted in Figure 42.

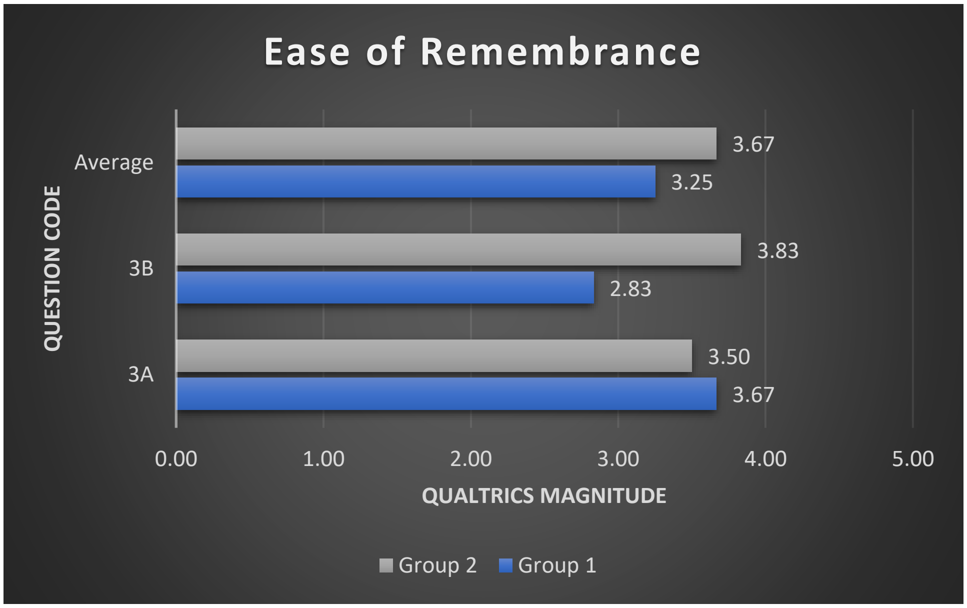


Figure 44: Ease of Remembrance Comparison Chart

As seen in the raw Likert scale data as well as the image appended above- Ease of Remembrance is the most adverse usability aspect that needs to be judiciously addressed if Generative Design is intended to be incorporated on a large scale. Both Group A and Group B marked their lowest level of satisfaction on this criterion. Participant B6 made a statement that deserves an extreme level of thought process: "Ease of Learning and Remembrance go hand-in-hand. If front-end users are not well equipped to perform optimization they fail to learn the concept in its entirety. Inept learning leads to deficient learning that makes its subsequent application confusing as well as challenging". Therefore, in order to address the ease of remembrance obstacle effectually- it is paramount to ensure that a proper learning route is undertaken at first- and is emphasized enough to motivate the users to spend time making it worthwhile in the long run.

4.7.4 Prevention of Errors

The usability aspect titled Prevention of Errors-aimed to ensure that logical or inherent errors in the proposed algorithm is not a factor that negatively affects the usability of Generative Design for tower crane planning. This criterion was essentially used to test if the algorithm 1) Held the capability to eliminate existent errors in the Tower crane planning process and 2) Had inherent errors that rendered the technology utilization portion as a fallacy.

4.7.4.1 Group A

Group A had overall given a positive verdict- which implied that Generative Design can in fact aid in delivering error-free results and aid in resourceful decision making. Participant A4 gave the highest possible score for this aspect- stating that it is the distinguishing feature of this algorithm. Participant A1 added, “Keeping the model limited to lift-score is a wise decision. Because larger the number of the factors you include, more complex the process shapes up to be”. Participant A5 mentioned that “We are taught to rely on conventional rules, assuming that it never goes wrong. Such models are effective in the sense that- they anticipate these errors and return decisions that are based off of mitigating measures”. Prevention of Error ranked third on the usability ranking criteria- based on the final opinion of Group A members.

4.7.4.2 Group B

Overall, on the Prevention of Errors aspect- Group B gave a good evaluation of this usability metric. However, participants B1 and B5 gave the lowest score to this parameter. The common grounds on which the scores were stated was to make the model more comprehensive that incorporates more features than just the lift-score of the crane. Participant B1 said “Positioning of a crane depends on innumerable (literally) factors. If the model has a framework that can initialize more sets of dynamic data sets that represent site-specific data- it would be more comprehensive”. Participant B4, on similar lines, extended the thought by saying “Understanding that lift-score has been deliberately sought after- is the key to knowing the intentions of this study. For the model to be more encompassing- it needs to first go out on the construction site. And this framework is a good set of appetizers to lay the foundation for what comes next”. Overall, this aspect was ranked third, based on the complete evaluation of all the aspects.

4.7.4.3 Comparison

A pictorial comparison of the scores presented by Group A and Group B is depicted in Figure 43.

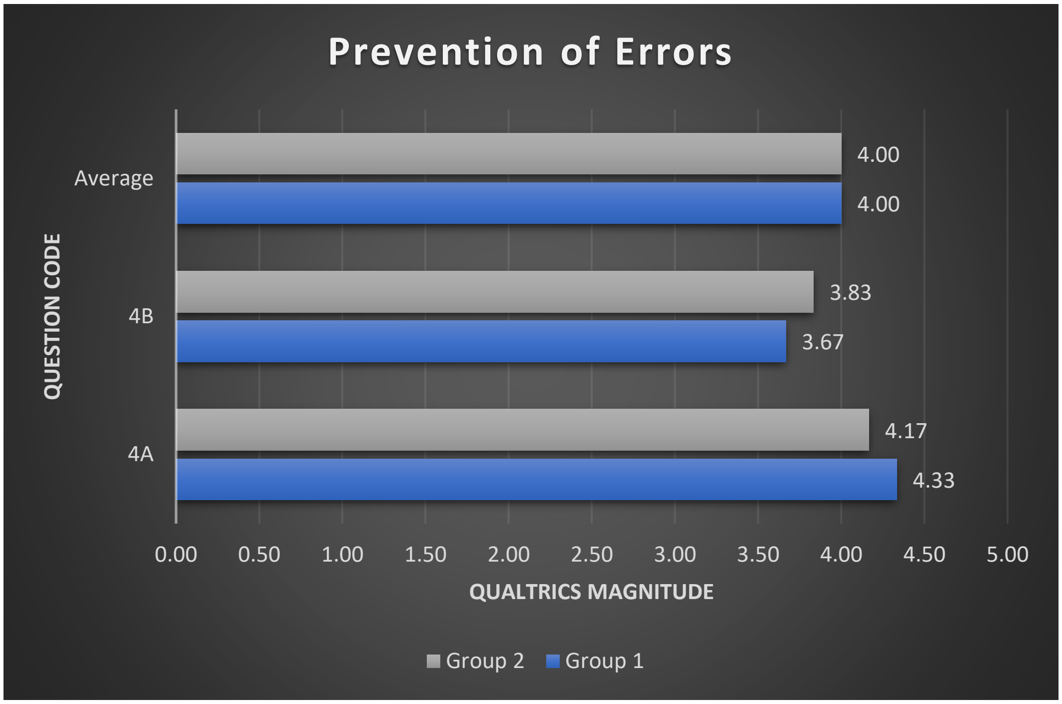


Figure 45: Prevention of Errors Comparison Chart

Combining the raw data obtained via Qualtrics with the pictorial comparison, it was observed that for both the groups- the prevention of errors ranked third in the list. Additionally, both the groups gave an exact same net score of 4.0 as a definite metric on the grounds of Prevention of Errors in the usability portion. Participant B3 said, “A visual framework with appropriate reasoning is need of the hour- not only for tower crane or site logistics but for every operation that needs exhaustive thinking and decision making”. As seen from the Qualtrics- the response to this aspect was mixed and broad, but participant A1’s statement accurately summed up all the notions that accompanied evaluation of this aspect- “Restricting the study to just Lift score should not be treated as an error or fallacy”. As with every proof-of-concept study, this research aimed to analyze one portion of the large picture and carry out an objective feedback analysis to evaluate the efficacy of the technique.

4.7.5 Subjective Pleasing

In the researcher’s opinion- subjective pleasing is necessary to ensure that the technique is not just promising theoretically or statistically, but holds the potential to make its way in the organization’s functional hierarchy. Therefore, this aspect had the most number of statements that tested if

Generative Design 1) Is promising to deal with existing issues, 2) Demonstrates benefits to several stakeholders associated in the process, 3) Is better than conventional processes, 4) Adequately addresses the lift-ability criteria, 5) Causes willingness of usage in subsequent tasks, and 6) Creates recommendations for future work.

4.7.5.1 Group A

Subjective pleasing was the best-received usability aspect concerning Generative Design implementation, especially for Group A. Participants A1, A4, A5, and A6 gave their maximum absolute and relative scores while responding to this section of the study. Participant A5 mentioned that "Implementation, Usage, and Benefits of Generative Design are all widespread and applicable to literally everyone associated with the logistical operations". Participant A1 added that "I have seen miracles happening with technology. With a proper plan in my mind, I would definitely recommend this to my team members". Group A gave their maximum value of response to this technique making it the most favorable usability aspect of all.

4.7.5.2 Group B

Group B also gave an extremely positive response to the usability of this technique. Participant B5 said that "I have always been fascinated by moving visuals of construction site on the screen. What pleases me the most is the value it holds beyond immature captivation and just marketing propagandas". Participant B6 expanded upon the thought of introducing the technology component on their projects. Participant added "This one hour of interview has only motivated me more to invest in the domain of technology. I want to believe that this is just the beginning and with a designated framework- the returns are much more than just productive processes". Group B gave the second-highest evaluation to this aspect of usability- approving the model on intra-personal factors, as well as on realistically plausible grounds.

4.7.5.3 Comparison

A pictorial comparison of the scores presented by Group A and Group B is depicted in Figure 44.

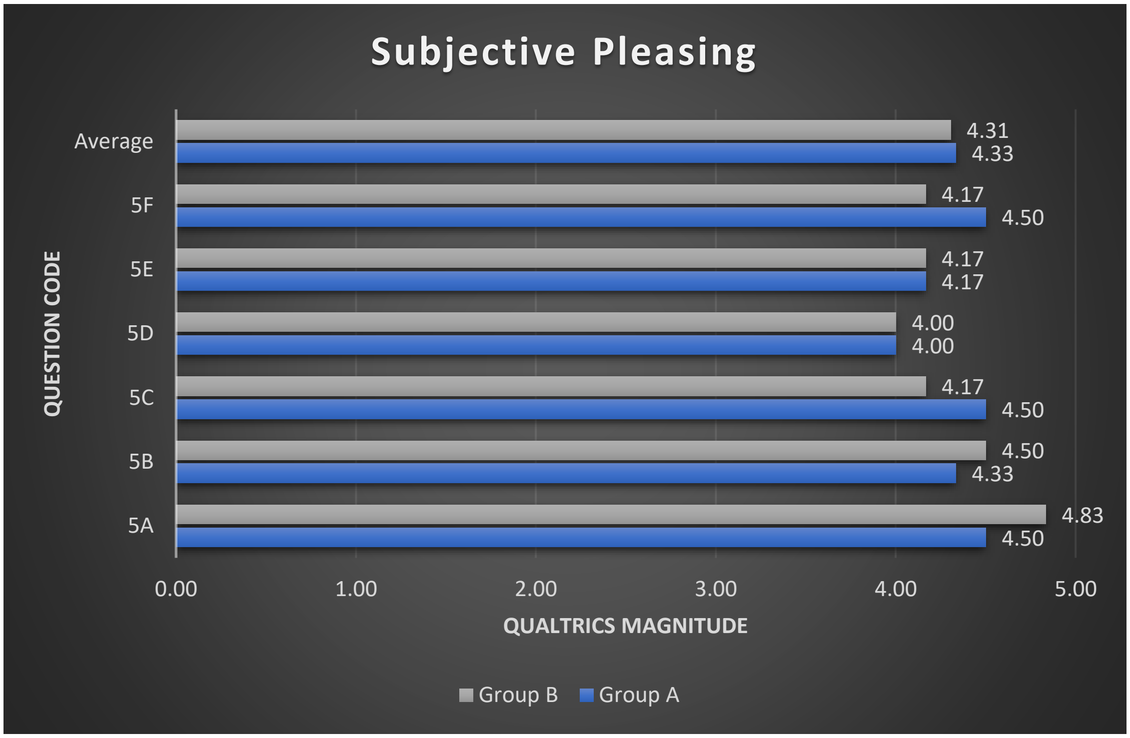


Figure 46: Subjective Pleasing Comparison Chart

The researcher believes that subjective pleasing is an extremely important criterion that needs to be evaluated while proposing any technology at the forefront. There are instances wherein the model works flawlessly and mitigates almost all the pertinent issues but fails to be implemented- because the stakeholders don't "believe" in the technology. Subjective pleasing thus becomes crucial to get objective feedback beyond the predefined evaluation grounds set via the questionnaire. Similar to Efficiency of Usage, the Subjective Pleasing criteria qualified on all the governing factors- making it successful without any reservations. This aspect was ranked number one by Group A and two by Group B. Participant A6's comment on the technique perfectly sums up- not only this aspect of usability but the core of Generative Design "BIM facilitates double quality control. I came across this quote that says BIM facilitates the construction process two times- once digitally and once on the field. Generative Design magnifies this process by 'n' number of times. You are practically building the model 10 times- once via each iteration".

4.8 Open Ended Questionnaire

The open-ended questionnaire was intended to provide a platform for the participants to deliberate more on the technology and express their opinion beyond the Likert scale aspects. These interviews not only provided a medium for participants to ask questions and express concerns but also helped obtain justification to their responses cast on the Qualtrics platform.

4.8.1 Test for Adaptability and Governing Aspects

The question asked to the participant was:

> "Do you feel that the developed model can be implemented on the construction site for Tower Crane Planning? What aspects of the model make it adaptable?"

4.8.1.1 Group A

With the inclusion of conditions that surround the successful implementation, all the six participants of Group A said that the Generative Design model is usable on the construction site for Tower crane positioning.

- Participant A1 said that "this algorithm helps eliminate planning redundancies that are present in the preconstruction phase. The concept of Trade-Off is what helps carry out an in-depth analysis of lift-ability criteria".
- Participant A3 mentioned that "this model can be used for several lifting operations. In some of the construction sites, it can be used to test the lift-ability of the reinforcement as well- making this model more comprehensive on grounds of lift-ability".
- Overall, the group's response was positive in adopting the technology, and factors like color coding along with a well-defined calculation methodology made the model adaptable as well as user-ended.

4.8.1.2 Group B

Group B, just like Group A gave an extremely positive response to the adaptability factor for usability.

- Participant B3 highlighted the input structure as one of the pivotal factors that make the Generative Design model adaptable.

- Participant B1 added to the same thought highlighting input structure as a motivating factor. Individual said “The data is readily available for everything that the input structure requires. It’s more like rerouting the available data to generate results that are statistically backed”.

- Participant B2 emphasized a very crucial aspect of any construction activity- “Transparency”. Participant added, “This technique acts as an insurance to the decision made. Couple months down the line- if someone asks me reasons for my choice- I have visual and logical conclusion to support my standpoint”.

- Finally, apart from prioritization and visual representation- participant B5 said that based on the regions not lifted- one can identify the need and type for additional crawlers or equipment needed,

4.8.1.3 Summary

It can unambiguously be said that the developed model has been marked as adaptable and usable on the construction site. While some participants believed that the model fit without necessitating any change- some recommended additional factors as discussed in 4.7.2. In a nutshell, following aspects make the model adaptable and well-receivable by the construction site professionals.

i) Visuals for prioritization with color coding for lift status
ii) Statistics backed with understanding and correlation with visuals
iii) Input Structure: Dynamic and intuitive framework
iv) Data availability and rerouting
v) Insurance technique for validation

4.8.2 Working with model capabilities

This facet was essentially introduced to test two factors of the algorithm: i) Changing the existing structure, and ii) Augmenting the existing structure. While the first part is essential to ensure that everything proposed via the model capabilities is accurate to function- the second portion is crucial to diversify and make the model widely acceptable. The question asked to test this aspect was:

> “Is there anything in the developed model or paradigm that you would like to add or change to make the optimization process more efficient and the technique widely adaptable?”

4.8.2.1 Group A

On a general note, Group A mentioned points to make the model more adaptable and inclusive. While everything already included in the model did make sense and required no change, recommendations were given to magnify the usability- once it is incorporated.

- Participant A1 and A6 both mentioned including wind load in the input structure. Participant A6 said "Especially in hilly and mountainous regions- wind load changes exponentially with the rise in altitude. It is therefore imperative to include code-referenced provisions to account for the accurate range v/s load chart dropdowns".

- Participant A4 and A6 elaborated on the foundation needed for the crane- to be deliberated upon, beforehand, as this largely restricts the positions where a crane can be placed or not.

- Participant A4 furthermore mentioned the possibility of varying densities of the same element in an extremely complex model. A region-wise density node in the input structure can thus help account for the variations in the loads to be lifted.

- Participant A3 investigated the option of accounting for crane dismantling structure at the end of its useful life. With a dynamic BIM model this can be feasible. The crane location can be mapped on the site structure at project completion to mark the required boundaries and analyze the spatial availability.

- Participant A6 recommended project sequencing factors to be considered. A 4D schedule with regular simulation runs can help evaluate the lift-ability at more frequent intervals.

- Finally, participant A2 recommended exploring the possibility of using a normalized graph pattern for site patches to see if a more reliable result can be generated.

4.8.2.2 Group B

Group B also had constructive suggestions to broaden the scope of the model.

- Just like Group A participants- B1, B3, B5 and B6 suggested the inclusion of wind load in the algorithm- to account for varying lifting capabilities.

- Both B1 and B6 also mentioned and emphasized the Crane's foundation and dismantling criteria to be considered- owing to the impact they possess in the decision-making process.

- Participant B3 suggested the inclusion of material storage regions and heaps and temporary structures to be considered for the initial phases of the project. Individual said "I would recommend integrating it with the overall Site Logistical plans because the existence of scaffolding and other smaller temporary structures on the construction site can hinder the free flow of crane operations and create sudden shutdowns".

- Similar to participant A6- B4 proposed a 4D schedule as that can also aid in better arriving at decisions involving time factors for elements having distinct lift status values.

- Extending B3's suggestion of including a logistics plan- B5 mentioned that "the imposed plans are needed to analyze the need for double or even triple crane on sites. Then with the same algorithm- we can set up an anti-collision and monitoring system". A double crane optimization framework does actually exist on the Autodesk University portal. It is an extension of the current study.

- One of the most eccentric suggestions was however provided by participant B2. B2 said that we also need to acknowledge the constraints and limitations the truck has. If the truck has heavy modular structures- it can neither be frequently moved nor is the existing weight structure a singular one. Participant says "The slab on which truck rests may not be able to withstand the load of the truck and it cannot, hence, be positioned at a place, otherwise not accounted for the rest of the project". The individual does clarify that this a rare situation and might not necessarily fall under the purview of crane positioning.

4.8.2.3 Summary

The essence of this aspect lies in understanding the fact that all the participants recommended the proposed measures- after vouching for initially incorporating the model on construction site. A suggestion was to test the Generative Design model on a construction site with low risk and perform a test run on less-critical activities. The underlying assumption still enforces the point that the model is worth implementing on the construction site for starters, because only then can multiple factors be added to make it more promising and vaster. Redirecting the attention towards the two most repeated factors that require consideration- Wind Load and Crane's foundation. They play an important role in optimizing the position of the Tower crane and for an all-inclusive model, their incorporation is next to inevitable. Third on the priority list would be the sequencing of construction activities for the model to dynamically incorporate the phase-wise construction fundamentals. The researcher believes that for the rest of the suggestions to be given appropriate consideration, the applicability of the existing model needs to be tested first.

4.8.3 Logical correlation of the model

This nuance of the usability aspect was important to be put in the questionnaire- to warrant a logical and coherent flow of information to the participant. To investigate the portion: the question asked was:

> "During any part of the demonstration, did you feel lost while comprehending the logic associated with Generative Design and incorporation of Tower Crane Planning parameters? If so, what and why?"

4.8.3.1 Group A

Understanding visual programming can be daunting, at first, for someone who has never had experience with coding or BIM technologies before.

- Participants A2 and A5 mentioned that the algorithmic and automation portions were difficult to follow along.
- Participant A1 said that "comprehending logical coding concepts may not be the easiest but knowing that it is not a core requisite or requirement does motivate, a bit".
- Participant A6 said that input structure does include human intervention and if that portion is not dealt with utmost consideration- the entire output hierarchy can be ruined. Individual said "input structure can be simplified to some extent. Not because it is complicated - but because of an explicit need for the user to manually connect and wire the initial nodes- you need an additional layer of security—enforced via a complete understanding of visual flows".
- Overall, the participants did not report any logical concerns while visualizing the flow- with participants A3 and A4 mentioning the algorithmic structure to be "crystal clear despite of not having extreme BIM background or exposure".

4.8.3.2 Group B

Collectively, just like Group A, Group B gave a validation to the logical portions of the proposed algorithm.

- While participant B1 believed that it is because of the software affinity that the individual possessed, B3 confirmed that a distinct association with computational tools did not engender logical shortcomings.
- Participants B2 and B6 both vouched for knowing more about the "how" segment of the technology. They mentioned that an entire flow through all the code segments and associated nodes would have made the understanding more lucid.
- Finally, participant B4 mentioned that "I know that numbers are necessary and still had their involvement for a specific part of the study- but they can be made more intuitive for someone totally paranoid about the mathematics portions".

4.8.3.3 Summary

Overall, none of the participants expressed a severe concern about understanding the underlying logic. However, to make the logic clearer- two differing opinions were surprisingly garnered. While a portion of participants believed that even with minimal coding and input requirements- numbers and algorithmic coding can be overwhelming, a certain number of participants hoped to get more information on the way coding had been carried out and things had been programmed. The researcher believes that there is no generalization, in terms of the depth of visual programming logic that should be presented to an individual or an organization. While some might appreciate terse portions of Dynamo and some might require deeper explanation, some might require lesser mathematics involved.

4.8.4 Willingness to Learning and Adaptability

This aspect of the study aims to analyze the participant's personal willingness to spend time learning the technology and inclination towards adopting the technique on their future projects. To test the same: two questions were asked:

- Would you be willing to spend a couple of hours learning the functioning of this technique—to make it usable in the long run? If no, why not?
- On your next project or construction task- would you be willing to use this or similar Generative Design-based model for Tower Crane position optimization? Why or why not?

4.8.4.1 Group A

Group A participants expressed interest in learning more about the Generative Design algorithm.

- While participants A1, A3 and A6 said that it would add value to their personal knowledge and technology acumen, participant A4 viewed this opportunity as a "Delta addition to the existing BIM knowledge".
- Participant A5 said that "disconnect of technology on construction site is a real practice- which makes the extremely useful BIM models under-utilized. I would love to use these techniques to reduce manual errors and repetitive calculation, by considering training and efficiency as a parameter".
- Finally, participant A2 quantified return on investment and believed that in the long-run- it is all worth the efforts. In all, all the participants of Group A firmly believed that the

technique had immense value for the intended use and would be a great source of breakthrough learning in their professional trajectories.

4.8.4.2 Group B

Participants of Group B also gave a constructive response to learning this technology.

- B3, B4 and B5 said that learning technology is the need of the hour, and there is no reason for one to not use or learn it. They mentioned that it is crucial to prepare beforehand and implement the applicable algorithm successfully when the time comes.

- Participant B1 said that "Learning is the only way to stay updated. I would in fact be willing to spend a couple days, not just months to learn more about this- because I see my efforts getting paid off in the long run".

- Participant B2 said that with urbanization and vertical construction booming the market statistics- the importance of crane is ever-increasing. Participant expanded saying "with more cranes- it is necessary to ensure more productive cycles. I see this technology doing that for me".

- At an organizational scale- participant B6 mentioned "In the previous projects- I have had to hire three consultants just to solve the tower crane planning issues. With this approach- I can have my own inputs in the process- rather than blindly following them".

- All the participants of Group B agreed that learning the software and its implementation in future projects is definitely worth looking into- without a doubt.

4.8.4.3 Summary

All the twelve participants of the study expressed maximum level of willingness in learning the technology, and henceforth implanting it in their future projects. While a large portion of Group A participants viewed this as an opportunity to build upon their existing knowledge-base, Group B participants gave a higher-level perspective and envisioned the benefits in the long run. Return on Investment, eagerness to learn and stay technologically updated, and need for an optimization framework owing to Tower crane's increasing importance- have all served as guiding factors in this study.

4.8.5 Organizational Perspective and Barriers to Implementation

This aspect of the study aims to test the organizational acceptance of the technology and identify the barriers that one might face while proposing the technology to an organization's stakeholders. The question that the participants answered was:

> "Do you feel that the stakeholders of your organization would be willing to adopt this model for Tower Crane Planning? What are the barriers that might prevent them from the utilization of this technique?"

4.8.5.1 Group A

The majority of Group A participants mentioned the same set of reasons as to why the technology might not be as effective as it deemed to be: BIM Maturity of the organization and inertia to adopt technological advancements. Participants said that if there is a BIM team already established in the organization- it is just two steps more for them. It makes more sense for them to easily adapt to this procedure- because ultimately, they are routing the available data in the right direction- to obtain more value from the existing pieces of information. Similarly, if an organization does not have a BIM team at all, it's a technological revolution for them. They first need to establish a team and standards, start developing reliable models- and then implement this procedure. Therefore, for organizations lacking BIM developments- the procedure can be a bit overwhelming. Participant B3 however mentions as an outsourcing route- but that is something extremely specific and subjective. Another factor that might hinder the implementation- as mentioned by B5 is "Knowledge and Level of Development of BIM. Even if there exists a BIM team- they need to be accurately convinced of the change to be brought in and supplement the proposal with training cost data and time value of money".

4.8.5.2 Group B

Largely, the opinions of Group B participants were not principally different than those in Group A.

- Participant B1 and B6 said that if there exists a BIM team- it's a win-win for them considering the data handling outcomes.
- Participant B2 considered the psychological mindset of the decision-makers and said that "People might not have an open-minded attitude about the new techniques. They need to

appreciate the need and significance associated. Only then can they be open to adopting this technique".

- Participant B3 mentioned a minor remedy to making the technology more promotable- by corroborating the claims with reference case studies undertaken on similar projects/industries.
- Participant B6 also mentioned that "Residential and commercial construction contractors and companies will see a larger usage than Heavy civil and Industrial construction stakeholders".
- Extending on the mathematical concepts- participant B4 says "Not having an affinity towards numbers being incorporated in the field practices- might lead to the decision-makers not believe in this technology- thereby acting as a barrier".
- Participant B6 extended on the cost issues by saying that an organization might need a cost-time-benefit ratio to decide. "If the initial cost of implementation is more than benefits associated, an owner or general contractor can recruit an additional superintendent to get a fresh perspective and validate the developed plans".

4.8.5.3 Summary

Based on the interviews conducted for twelve participants, major barriers identified to the implementation of technology included: Decision makers' reluctance to utilizing new technologies, the organization's openness to bringing a change, and finally the state of maturity of the BIM Team. One thing worth noticing in all the responses is that- no individual identified a flaw in the Generative Design algorithm or its appropriate account of Tower crane planning features. Participants agree that barriers would be more on the intra- and inter-personal level, and organizational factors' side—rather than on the core technology or the algorithmic side.

4.8.6 Stakeholder Benefits

In order to ensure an effective implementation of the proposed technique- it is crucial to investigate the stakeholders associated with the process, and also who would be the most benefitted out of it. To get an answer to this, the following question was asked to the participants:

> "Who do you think would be most benefitted if this technique is incorporated? Why?"

4.8.6.1 Group A

The majority of the Group A participants said that all the stakeholders associated with the construction process would be benefited out of it.

- Participant A4 and A6 mentioned that since this a process that involves everyone who one would find along the construction line of action- every stakeholder would benefit out of it.
- Participant A5 mentions that "This technique can be directly correlated to safety and optimization. I believe these two are essential traits that should concern everyone in the project. Hence- all the stakeholders should ideally benefit out of it."
- Participants A1 and A3 mention that a crane operator is someone who should be able to leverage the benefits, as well. A3 said "When a crane is positioned correctly- the crane operator believes in the system and can direct more attention towards other critical tasks. Crane operators hold a value that cannot be quantified- and if they can see an advantage out of it- the technology is actually making a difference".
- Participant A2 added to the benefit section saying: "All the contractors and specialty contracts now have a definite route and an ability deliver results on time". On a lighter note, the participant said "If there is a specialty crane vendor who prescribes fees based on the number of crane workhours, they might not gain a lot from this process- as a productive crane cycle would mean lesser hours of downtime, and hence no additional fees that would otherwise have leveraged".

4.8.6.2 Group B

Just like Group A- all of Group B participants also agreed upon the fact that all the stakeholders associated with the project would have the ability to leverage benefits associated with this process.

- Participants B3, B5 and B6 mentioned that the benefits of this process extend beyond those directly associated with tower crane- and extend to the site logistics team, vendors and trade contractors.
- Participant B2 added that "This can actually shape up a lot of the policies, and enforcing restrictions based on safety. Especially in the initial process of these runs- extra care must be taken to incorporate the factor of safety".
- Participant B4 added that the steel erection team would be able to enter and exit the site quickly and efficiently- when the tower crane is in action.

4.8.6.3 Summary

Identifying the stakeholders who would be most benefitted in the process- was one of the few aspects in this process that generated almost the same answer from all the participants. It is, therefore, evident that all the members and contributors that take part in the construction lifecycle would be able to appreciate the technique and leverage the advantages that accompany the successful implementation of the paradigm.

4.8.7 Applications of Generative Design in AEC

This section aims to go test the potential of Generative Design beyond Tower Crane Planning, in the AEC Industry. This question was not only intended to ensure that the participants' understanding of the underlying concept is well-understood but also to add a new dimension to the study- by providing a platform to the participants to present their out-of-the-box thinking applications. The researcher, personally believes, that this section is one of the key takeaways of this study, and holds immense potential to direct future research in a specific direction. The question posed to the participants was:

> "Do you foresee applications of Generative Design in any other domain of the AEC Industry? Can you please elaborate?"

This section does not intend to test the differences in the technology adoption by the two groups, nor the core usability aspect- and hence the results are clubbed together, and presented as follows:

- Participant A1 suggested that this algorithm can be used extensively in Remodeling and renovation. Especially when existing construction is dealt with- the number of constraints multiply exponentially. A generative Design platform would be a single platform to add those constraints and better visualize the results.

- Participant A2 emphasized more on the Architectural side of the industry. Participant said that an architect's imagination gets a new medium to focus on minute issues. Architects can use this on facades and brick masonry designs to make eccentric and wavy patterns. The platform can help determine feasibility as well as identify the most lucrative option.

- Participant A3 elaborated on the site logistics end and mentions that this technique can incorporate material storage and stacking efforts- synchronized with the labor efforts. By incorporating manual efforts- there would finally be a statistic attached to it. It can ultimately help in labor allocation.

- Participant A4 mentioned the possibility of automating parametric modeling concepts via this algorithm. While creating MEP families- several nodes need to be connected- while some need to be tested, some are variable. Based on the target output of the fixture, the variable nodes can be programmed.

- Participant A5 discussed the energy aspect of Generative Design. The individual references one of the most effective Generative Design studies of energy analysis that deals with the orientation of parts of a building to maximize the daylight for the design of HVAC systems.

- Participant A6 hinted at the possibility of integrating the Generative Design algorithm with the Virtual Reality platform. Participant says “If there’s a way to see every exported outcome in VR- visualization can attain an entirely new perspective”.

- Participant B1 expanded the applications of Generative Design to the road and highway industry. The individual mentions that in a highway project that B1 worked with- there were seven to eight thousand girders that had to be positioned on an interstate highway. Participant said that an optimal placement could better determine accurate Reduced Levels of road- and accordingly determine excavation plans.

- Participant B2 said that Generative Design can help obtain levels of parking system—impact of which increases when parking is underground and demands extensive excavation. Individual said that sometimes you don’t need two levels and can go for something like one and a half. Generative Design can help determine the orientation and suggest a specific route to attain the desired goal. Even if the software says that one quarter would suffice- the cost of not excavating even six feet below, can save a fortune. An ability to view the intermediate design milestones is really a reliable test for feasibility.

- Participant B3 recommended the development of a framework with coded provisions embedded in it. This can help generate life safety plans for a specific incident. Rather than having a general life safety plan, incident-specific plans for fire, gas leak, and directional tornado can be developed. The framework can also incorporate specific ADA guidelines.

- Participant B4 narrowed down the applications to the sequencing of specific constraints. The individual said that the Generative Design algorithm can help in scheduling the placement of gypsum boards based on a specific concrete placement timeline.

- Participant B5 envisioned these applications in Pipeline works. While working on utility lines and civil works- the optimal route of pipe and diameter is extremely variable. Various factors like existing service lines, the pressure of the flow, configuration of the building, and specific cut-out zones affect the design and placement of pipe. All these constraints can be implemented to arrive at the two specific outputs—that can later be filtered out based on cost and feasibility.

- Participant B6 viewed the algorithm being used in Prefabrication. Participant mentions that modular components might not have the capacity of being extensively re-handled. A well-defined plan with optimal placement can specify minimum changes based on the handling capacity.

4.9 Outspreading Generative Design for Tower Crane Planning

Via the feedback obtained through interviews with the industry professionals- an attempt was made by the researcher to identify some crucial points surrounding Tower Crane positioning can be addressed or not. While some of the concerns are readily catered to via the existing model, some can be accomplished by minutely expanding the scope of the model. Finally, some issues might need more attention rather than just altering software capabilities. In this section, the researcher addresses some of the concerns expressed and a possible route that might act as a solution for future researchers in this field. These are lines of actions developed by the researcher while working along the course of the study.

1. Participant A4 mentioned the need for considering electric power lines while positioning the Tower crane. Under no circumstances can any part of the crane or the element lifted interfere with the existing overhead lines.

   Solution: The location of the existing lines can be obtained and modeled via a family-in-place. By embedding this model-in-place in Revit, it can be marked as a constraint to limit the options that might lead to a crane movement that collides with these lines. In fact, these constraints can be programmed to specify a minimum distance of ten feet, and for the power of 750 kV or higher- a distance of sixteen feet can be mentioned.

2. Participant B5 mentioned the possibility of overturning and a clear demarcation of the fall region. Clear highlighting of work-regions is an inherent advantage of BIM. Instead, with the added possibility of Generative Design, factors like crane alignment and skewing possibilities can be tested via Generative Design. Several mathematical and visual factors can also be incorporated in this technology like accident region, failure areas, derailment, expected downtime and productivity, and designated spaces for repairment and replacement.

3. Participant B1 mentioned that “Geometry and load capacity of cranes deserve more attention than a rough estimation or anticipation. The proposed algorithm has an intuitive framework that can consider the load limiting factors, swing radius (and hence the issues of unguarded swing radius), side lifting, boom stop illustration, and collision monitoring for coordinated swing path and work operations. They can all be integrated into the lift study drawing- which can be used as a document on the construction site.

4. Participant B3 enquired about the provisions of the critical lift plan in the study. One of the most effective expansions of this study base would be to incorporate a critical lift plan in the Generative Design algorithm. When crane reaches the 90% capacity- the model can identify the associated work regions during the lift to allow image-enabled safety marking and better prioritize the operations. When this range is reached- the algorithm can be instructed to export the crane position and configuration along with lift height to better highlight the position. This would help obtain boom length and angle as a function of load lifted.

5. Participant A6's idea of VR might extend beyond just tertiary visualization. The exported optimal study can help crane operators to get an idea of the possible blind-lifts and come up with a plan to tackle the same- beforehand.

6. Participant B4 mentioned OSHA standards for cranes and their impact in deciding the final position of Tower crane.

   a. For 125% of personnel hoisting and proof testing components- a multiplying factor can be included in the code block to work around with the range and load criteria.

   b. Extending on Proof Testing, a filter can be applied to Tower crane positions that do not meet the proof testing requirements- and then not consider them at all!

   c. Following the same concept, as that mentioned in 6(a)- a load weight of 50% can be easily taken under consideration.

7. While mentioning spatial constraints for pipeline that B5 mentioned as an application of Generative Design- it is worthwhile to highlight that it can also be applied to the Tower crane space considerations and availability. In fact, participant B5 added that the existing model can be used to account for extending outriggers, tail swing- movement of rear counterweights, and marking of steep drop-offs.

8. As an extension of B4's thought to include incident specific life safety plans- the current model development can account for the Project lift safety plan. The storage and portable tanks for the handling of flammable and combustible liquids- can be accounted for by modeling of access roads, and defining lines for hauling, marking setup, and staging area for classified load, suspended load, and Derrick inclusions.

4.10 Summary

The chapter began by introducing the objective of the study and revisiting the research questions. It provided a detailed explanation of the script adopted for the study- and later implemented the same on two construction sites. For both the sites- positional analysis was carried out that first garnered lift score and associated statistics for the existing crane configuration- and later for the best- and worst-case scenario. A visual and statistical comparison helped gauge the efficacy of the Generative Design algorithm for tower crane positioning. The concept of trade-off was coined to better present the observed benefits post-implementation. The second part of the chapter dealt with the usability aspect. All the five usability aspects were discussed based on the responses presented by twelve participants on the Likert scale. These aspects were ranked in order of precedence for both the groups- for the comparison between the groups to be finally carried out. Later in the usability section, each question asked during the open-ended interview was discussed first as a group, and later summarized to get a designated feedback for each aspect. The chapter concluded by first exploring the potential of Generative Design in AEC industry- followed by the researcher's recommendations to tackle the existing concerns and augment the existing framework for Tower Crane planning.

5 CONCLUSION

The final chapter of this study begins by re-introducing the objective, research questions, methodology, and anticipated outcomes of the study. Later, based on the outcomes described in Chapter 4, it presents a summary of the results obtained- and describes the significance and potential outcomes that this study tags along. The final component of this study identifies potential limitations and recommends future research to combat any shortcomings observed via this study. It concludes by bolstering trustworthiness and takes a reflection on the study's goals.

5.1 Overview of the Study

During the planning phase of a construction project- there are a number of issues that stem because of ad-hoc plan determination, subjective interpretations by the decision-makers, and reliance on the conventional thumb rules. Owing to the significance that a Tower Crane holds on a construction site- the problem statement of this study was narrowed down to focus on this substantial yet significant piece of equipment. The problem addressed by the study was thus the improper planning associated with the construction crane conformations while developing a Construction Site layout plan.

Post a deeper analysis of the problem statement and an exhaustive literature review to identify the loopholes associated, the study began by defining an absolute intent. The objective of this study was to implement a BIM-driven Generative Design algorithmic framework to optimize the position of Tower crane on a given construction site. The developed model was intended to be easily usable on the construction site, comprehensible by the industry professionals, and required minimal mathematical and computational complexities. In order to achieve that- a Generative Design model was developed using open source scripts that required minimum alterations, and negligible modifications when used on different construction sites. Construction site professionals were involved in this study to garner objective feedback and test the applicability of the model.

The purpose of this study was thus to optimize the position of the tower crane in a construction site layout plan. To better encapsulate the proof-of-concept as well as the usability aspect- two research questions were framed to route the direction of this study.

1. How significant is Generative Design in optimizing the Tower Crane position?
2. What criteria affect the utilization of Generative Design for Tower Crane planning?

To answer the first research question- exploratory research using case-study design was utilized. A BIM model of one construction site, each, from the US and India were obtained. Based on the existing position of the Tower crane and the optimized configuration- a comparison between lift-ability of elements was carried out. The outcome was reported in the form of a percentage change in the lift score.

To investigate the usability aspect- Descriptive Qualitative research was carried out. Twelve participants were identified and classified into two groups based on their organizational designation and years of experience with Tower crane. Participants witnessed a demonstration of Generative Design, answered a set of Questions via Likert scale, and interviewed with the researcher to provide feedback on the usability of this technique. The value of mean was computed for all the five usability aspects- Ease of Learning, Efficiency of Usage, Ease of Remembrance, Prevention of Errors, and Subjective Pleasing, and compared for both the groups. For the latter part- narrative analysis was carried out to get a holistic evaluation of the proposed technique for the intended purpose.

5.2 Summary of Results

This section summarizes all the outcomes of the study undertaken, concisely and conclusively. It has been broken down into points to map each outcome with the anticipated result.

1. On implementing the algorithm for site 1- it was discovered that the lift-ability and lift efforts of the Tower crane improve by 6.3%, with more than 1.5% more elements being liftable. Similarly, there is a difference of about 38.9% in the lift score between the best- and worst-case scenarios, with about 4.3% more of the total elements being liftable.

2. By using the Generative Design framework for Site 2- the lift-ability and lift efforts of the tower crane improves by 25% when it is placed on the optimized configuration, as compared to the existing one with 2.7% more of the total elements being directly liftable. This difference increases to 39%, in terms of lift efforts, when best- and worst- case scenarios are compared- with a change of about 3.3% more elements being directly liftable.

3. For both the sites mentioned above, I believe that these results are extremely substantial when it comes to showcasing the ability of Generative Design. This is because the sites are extremely congested, and the initial position of tower crane was itself one of the best

possible configurations. Based on my understanding of statistics- the percentage improvement is still noteworthy and demonstrates an evident application witnessed on the application of the technique.

4. Generative Design was intended to be utilized as a platform that had both computational capabilities as well as a visual framework that makes the optimization process more intuitive. The benefits of this amalgamated platform were distinctly observable when the study was carried out. My interviews were one of the crucial ways to corroborate the point. I understood the practical importance of coupling visuals with statistics to arrive at informed decisions. The practitioners don't necessarily understand mathematical nuances- but their need is inevitable. I view this combination as a platter- with visuals being the end product, arriving due to the appropriate utilization of algorithmic optimization as the driving ingredient.

5. One of the key features that made the Generative Design framework stand-out was via coining the concept of Trade-off. This context facilitated the implementation of Prioritization in terms of elements being lifted, and a holistic decision-making framework to form an informed conclusion. If I were asked to provide one takeaway from the proof-of-concept study- it must be the trade-off. This deliverable accurately helps incorporate human judgement to make a decision and prioritize the specifics. Based on the knowledge I have garnered during this phase- I am certain that based on the availability of expertise in this field- even the magnitude and extent of the human involvement and judgement can be varied- to arrive at the final conclusion.

6. The order of precedence for all the usability aspects was as follows:

    a. For Group A:

       Subjective Pleasing > Efficiency of Usage > Prevention of Errors> Ease of Learning> Ease of Remembrance

    b. For Group B:

       Efficiency of Usage> Subjective Pleasing> Prevention of Errors> Ease of Learning> Ease of Remembrance

7. Based on the above-mentioned precedence, obtained via the Likert scale- it was observed that both the groups have similar responses to the usability of Generative Design. It can be said that while the front end-users see the impact that this technique possesses and are more than willing to use it- the major factor that might hinder a unanimous acceptance would be the initial learning curve and the retention capacity. Thus- one of the certain and definite ways to promulgate the idea of Generative Design is by educating and spreading the information about the technology. The response to other factors is a clear indication that once the users get a hold of the technique- they have enough awareness and motivation to extract value from the optimization framework. What pleasantly astounded me the most was the similar response to this technique by both the associated groups. I think this is a victory in the sense that- a singular framework will help cater to the concerns of both the groups, and in-turn aid them to leverage complete benefits of the system.

8. Based on the open-ended interviews conducted, it was observed that statistically backed visuals, intuitive and effective handling of data, and extreme level of validation for insurance make the model adaptable and convenient to use in the construction industry. Owing to repeated emphasis, however, it is necessary to ensure that a larger version of the model takes into account the wind load associated with the site location, soil and structural capabilities of the topographical pad, and a schedule synchronized with the model. Based on the current state of the model- all the participants certified the logical flow of control to be existent in the optimization framework. I was really content to know that the interviewees understood that foundation of laying focus on one parameter for the test of the study and garnering appropriate feedback for comprehension before putting forward a gigantic model. My thought of beginning with a small-piece, identifying the necessary changes, to finally deliver a master-piece seemed to well received by the participants, as well.

9. Participants expressed interest in learning the technique and using it in the long run considering the expansion of knowledgebase at their personal end, evident return on investments, and envisaging the power it holds in the current state of technology transformation. It is believed that for the organizations that already have a BIM team established – the usability of this technique would be much more conducive. On the other hand, the process can be daunting for firms that need to establish a technology department – owing to the initial resistance, inertia, and a technological transformation. However, once this technology embarks on the route of effective implementation- all the stakeholders are envisioned to leverage the benefits that it possesses. I think ‘change’ is the driving force that needs to be considered while promoting any technology. The extent of change directly determines the rate of adoption. Same is the feedback on Generative design from an organizational perspective. Existence and maturity of the BIM team needs to be adequately accounted for before introducing a widespread technological revolution.

10. Based on the outcomes of the proof-of-concept studies, Likert scale evaluation, and narrative analysis- the researcher identifies a number of possible improvements that can be carried out in the model, with minimal alterations to the existing structure. The study wraps up by viewing on a large scale- the possible applications of Generative Design in multiple sectors of AEC. I would like to reiterate here, that the potential of Generative Design is immense when it comes to construction site planning and logistics. My knowledge of site management warrants the fact that effective decision-making is a challenge when numerous alternatives need to be explored. I would say that Generative Design is the decision maker’s best ally to advance this process.

5.3 Contributions and Recommendations

5.3.1 Contributions of the Study

I carried out this study with the intent of bridging the gap between academic research and industry implementation. With my aim of helping the construction site professionals effectively plan the construction site layout and optimize the position of Tower crane on a given construction site, this study would be a definite guide for professionals who give due consideration to the lift-ability of elements on construction site.

The problem statement I came up with is pivotal to overcome the issues that are caused due to decisions solely based on previous experience, rules of thumb, extreme reliance on conventional techniques, and rash decisions taken without appropriate substance. My purpose through this study intends to motivate professionals to explore the sector of design exploration. For any study that involves numerous possible outcomes, has parameters that can be varied, and constraints that can be regulated- the proposed route to attain the purpose should guide future researchers to lay the foundation for their research topic.

The methodology I crafted for this study is a combination of statistical exploratory study followed by Likert scale and narrative analysis to get feedback and identify barriers to implementation of a novel technique. I see the construction industry as ever-changing, and so view the methodology tailored in this study to be helpful to all the professionals who wish to explore the technology, as well as the usability side of the study. Exploring both sides of this coin- should bolster a comprehensive usage, implementation, and response to adoption.

The outcomes obtained from the study are crucial to all the researchers and site professionals who are associated with construction site logistics. I understand that this study is centered around tower cranes, but it is expected that the outcomes from the Exploratory research would help extrapolate the ideas to several important modules associated with construction site planning. Similarly, the feedback on usability aspects should help researchers and developers working in the pilot project domains understand the aspects needed to be taken under consideration- that can better promote technology adoption. On one hand, I see this framework to be specific enough to holistically understand the implementation of the technique on tower crane positioning, but on the other hand- I view the methodology and conceptual framework to be generalizable and replicable to be incorporated for studies with similar intent or route.

5.3.2 Recommendations for Future Studies

Based on the study that spanned across a year and a half, the researcher suggests the following modifications that can be carried out to enlarge the scope of the study:

1. The study is one of the first set of research studies specifically focused on the integration of Generative Design and Construction Site Layout Planning. It, therefore, resorted to using open-source scripts, to get an initial assessment of the technique's potential. Future researchers can and should include more nodes and programmed logics to the visual programming tool by incorporating the recommendations presented formerly.

    a. In addition to that, the decision-making tool can allow the selection of cranes and the number of cranes to make the process more applicable across the project lifecycle.

    b. The study can include more elements, instead of just walls, beams, columns and slabs to better arrive at holistic results.

2. The statistical parameters for the significance component consisted of mean comparison between various site configurations. The study can be performed across various types and more construction sites to obtain an average curve- that would be more generalizable.

3. The usability aspect of this study included twelve participants with a qualitative study. The study can include more usability aspects with a larger number of participants. In fact, a quantitative study can be performed- to compare the results obtained by both the research designs.

4. Finally, the researcher encourages the readers to explore the potential of Generative Design in various sectors of AEC- to better understand the anticipated applications in decision making.

5.4 Potential Limitations

Some of the potential limitations of this study include:

1. The study uses Dynamo as a Revit add-in, and uses visual programming as a medium to achieve Generative Design outcomes. Several other tools beyond Visual Programming- in the domain of manufacturing and production, should also be explored.

2. Owing to the software's response and ability to handle large models- limited number of seeds and generations were explored. Certain positions and configurations can be eliminated by this algorithm- which can provide better insights to the decision-maker.

3. The study assumes idealistic conditions when a Tower crane is in operation. Completed site layout and intricate details may interfere with the unencumbered execution of the anticipated timeline.

4. The usability aspects addressed in this study are not all-inclusive. There is a huge possibility that the adaptability of the technique can extend beyond the five pre-defined parameters.

5. A sample size of twelve participants, although is twice compared to the studies referenced- may not be sufficient to arrive at concrete results that are statistically driven. If the motive is to obtain objective statistics rather than open-ended feedback- a quantitative study should be sought after.

6. Participants' responses are assumed to be unbiased and informative. It is assumed that the participant has accurately recalled upon the previous experience without any preconceived notions- based on previous experiences.

7. Finally, for a detailed analysis- additional statistical measures like ANOVA analysis and chi-square test can be used.

5.5 Trustworthiness

To organize the research as being trustworthy: it emphasizes three major elements- elimination of bias, reliability, and validity. Subsequent sections reiterate how the governing measures are inherited in each of these elements- and provide a rationale as to how they were achieved.

5.5.1 Elimination of Biases

Elimination of bias is necessary to facilitate the avoidance of a partial question that can be stem across numerous phases of research conduct, analysis, and even publication (Pannucci & Wilkins, 2005). The following measures were taken to eliminate the accompanying biases:

1. Sampling Frame Bias: Per approval by IRB, the Pre-Demonstration demographic questionnaire was distributed across various professional websites to include a wide range of professionals having diverse backgrounds. The sample also included invited participants; whose years of qualified experience were crucial to get a new perspective to the study.

2. Non-response Bias: All the shortlisted volunteers and invited participants were extremely responsive. Not only did this obviate the need to send recurring emails and reminders, but also eliminated the existence of a skewed sample.

3. Intentional Bias: The problem, purpose, and methodology of the study has been backed by references from literature to avoid the possibility of subjective intervention. Furthermore, the results are achieved by observing zero deviation from the proposed methodology- that validates the absence of intentional bias.

4. Opinion of Uninformed: When arriving at the final sample- only the participants having relevant experience in the domain, and could be put in one of the groups- were chosen for demonstration and interviews. A combination of purposeful and simple random sampling techniques ensured trustworthy feedback and elimination of sampling bias respectively.

5. Complexity: Participants were given brief and to-the-point demonstrations, and later posed questions that were easy to follow and limited in number. This ensured that even if there were multiple steps to the process- the methodology was straightforward and did not lead to complexity.

5.5.2 Reliability

Specifically for Qualitative Research- the measures identified to ensure reliability include credibility, transferability, dependability and confirmation of findings (Lincoln & Guba, 1985). Based on the framework adopted by Cory (2019), this study ensures reliability through following means:

1. This study achieves credibility by using well-defined and known research methods, that follow specific sampling techniques and analysis methods. Following a Working Hypothesis- conceptual framework, tailed by a mixture of simple random sampling and purposive techniques aided in the successful employment of Mean Comparison and Narrative Analysis.

2. To ensure transferability- verbatims of applicable portions of participants' interviews followed by the associated context are presented, so that with a study having a similar number of participants- findings specific to the study's setting can be replicated to similar populations and backgrounds.

3. Dependability is highlighted by describing the entire study in an extremely high level of detail. Future professionals working to utilize the study can therefore replicate this study- and develop their own set of findings.

4. Confirmation of findings is bolstered by emphasizing the fact that all the outcomes, results and conclusions generated as a part of this study arrive via definite analysis of the algorithmic implementation and participants' responses.

5.5.3 Validity

Validity can be defined as "the correctness or credibility of a description, conclusion, explanation, interpretation or other sort of account" (Maxwell, 1996, p.87). Ashok (2020) identified seven such parameters to ensure Validity, specifically for Qualitative Research. The factors and the accompanying measures implemented are as follows:

1. 'Comparison' was incorporated in the form of comparing the study across various groups having diverse previous experience.

2. Quasi-Statistics were implemented by utilizing Semi-Quantitative analysis by converting the Likert scale opinions to a numerical value. Similarly, Narrative analysis was used to transcribe subjective opinion and feedback and categorical usability aspects.

3. Data-triangulation was achieved by taking construction site samples from two different countries and including diverse participants to bring an assorted experience to the table.

4. No specific negative evidence exists in the literature that contradicts the problem, purpose, or objective of the study. Thus, there is no discrepant evidence as a threat to the validity.

5. Respondent Validation was applicable only in the narrative analysis portion. After the participant answers a specific question, the researcher cross-checked and confirmed if the opinion is interpreted in an accurate sense.

6. Rich Data was ensured by acquiring appropriate construction site models having required construction site features for the course of the study.

7. Intensive Involvement was ensured via regular conversation and communication with the participants.

Construct validity was utilized to additionally confirm the outcomes of the first research question. This was ensured by reviewing previous studies revolving around tower crane's lift-ability, and safeguarding the absence of any eccentric or contradicting outcomes. Face validity was utilized for testing the usability aspect of Generative Design for tower crane positioning. Respondents' facial expressions, communication of thoughts, and interpretation of underlying logical reasonings endorsed their opinions provided.

5.6 Reflection

I wish I had a definite timeline and thought process as to accurately justify the outline of this study. But one specific thing that I was, am and will always be steadfast about- is the desire to do something new. A desire to do something that I have not done before- and the desire to do something that has not been done before. This master's thesis for me was all about exploring, experimenting, reading, learning, and then of course writing. What started as an idea that spanned across three different spheres, shaped up into a coherent piece of logical research- all thanks to my advisor and committee members. My reflection upon my thesis would be to first classify the study into three different paradigms, attempting to bring them together- and join the jigsaw puzzle, not to deliberately arrive at something disordered, but to route the study to synthesize the available information.

I stumbled across Visual Programming when I first saw Bill Allen's lecture on Dynamo at the Autodesk University. I discussed the idea with my immensely knowledgeable advisor, who supported me saying- I should and can go ahead if I believed that I had the necessary programming acumen. He mentioned one of the previous studies using Dynamo that he was the principal investigator of, and then there was no going back! Even if there was no direct programming or coding associated- without my previous exposure to codified languages- C++ and C#, justifying and explaining the logic to industry professionals would have been a daunting task in itself.

The next part of the study included identifying the paradigms that can be achieved via Visual Programming and Dynamo. By reviewing a little less than infinite papers- I came across the discipline of Generative Design applied to AEC Industry. A paper on Generative Design that explored how visual programming outputs can be used to leverage the benefits of the former, helped me add a level of detail to the existing plan- Using Visual Programming to explore the benefits of "XYZ in the AEC Industry". It was only a bit later that I realized that XYZ will be the guiding force of my research. That's when I paused this component and explored problem statements in construction- that could be later attempted to correlate with Generative Design. Coincidentally, the author whose paper I initially referred to- happened to one of my committee members, a couple of months later.

By getting in touch with several AEC professionals and Computational Design experts- my attention was caught by the domain of Construction Site Logistics. Owing to my previous experience, I always believed that construction site management is one of the most crucial yet creative tasks that can be undertaken in the field. As it is said "It is more about art and skill, rather than just knowledge". Now is when several different things integrated. I came across Doctoral thesis that focused on tower crane, at the same time I stumbled across a book specifically meant for construction site management. I was fortunate enough, to then have one of the editors of that book on my committee. The decisive moment was discovering the lecture presented by Dieter Vermeulen at Autodesk University. This lecture integrated all the aspects that I initially discussed- and that's all I literally wanted to get started with the research. This lecture and the associated handouts helped me achieve my objectives- and also gave an initial push to using the scripts and adding a research dimension to something beyond unreal – that already exists.

All studies that I referred to while framing my research question- focused on using one construction site, as a test for the proof-of-concept. I wanted to do more instead of taking just one construction site. And so- I went for two (not four) – even if that meant twice the efforts for the same study. I wanted to explore, self-validate and give an assurance to myself of the paradigm I proposed. Getting two BIM models of construction site, that too with a position of tower crane marked on it- was the initial challenge. But after I got them- all I had to do was clean-up the models. Models had everything right from foundation to landscaping, and in-place families to energy details- but cleaning up the model was not as difficult as it seemed. Despite using open-source scripts, the efforts that go in tailoring them, understanding them, and utilizing them to meet the research objectives is the decisive point. For an introductory study- the visual programming scripts might not be their best friends, however, with clear objectives and purpose- the study attained a well-defined route. Undertaking a study that lacked enough literature evidence but had ample motivation- was the driving force and beauty of my first component of the research question.

Purdue has always ingrained in me- the thought to work at the junction of VDC technology and Industry implementation. With the notion that- if I propose a technology, which can indeed be a breakthrough for some organizations, it is paramount to first test it and have it validated- rather than going leaps and bounds in elaborating the scope. This paved way for my second research question. Based on my previous quantitative study experiences, I would say that it might give direct results with reportable statistics. There is not much human inference associated- and it gives you a direct output. That was not what I wanted! Instead of having 100 people answer the questions without knowing the justification for their standpoint- I wanted to interact with a handful of qualified professionals to understand the thinking component that surrounds the “why” component. This was again the junction when I decided to take an extra step. Interviewing 12 people not just by having them fill out Qualtrics, but by taking an open-ended interview, was an experience of a lifetime! The abundance of knowledge that professionals provide, along with their phenomenal insights- makes all the efforts worth the time. Qualitative study is a blessing- and for all those who believe in quality rather than numbers, there should be no second thoughts.

This study has made me more courageous than ever! All thanks to everyone I mentioned in the acknowledgments section, I take immense pride in the study I have undertaken- and value the outcomes that this opportunity has provided me with. All I would like to say is- until next time!

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APPENDIX A: PRE-DEMONSTRATION DEMOGRAPHIC QUESTIONNAIRE

A generalized questionnaire developed by the researcher would be provided to all the volunteers before they are demonstrated the Generative Design technique. This is meant to gather information pertaining to their previous experience with Tower Crane Planning, direct exposure to various technologies, and their relevant knowledge of the construction industry.

1. What is your current position in the organization you are associated with?
    a. Intern/Contractual Position/Entry Level Associate (<3 Years of Work Experience)
    b. Project Engineer/Project Manager
    c. Executive Level Position (Managing Director/Vice President/President)
    d. Other: Please Specify- _______________

2. What does your educational background majorly revolve around?
    a. Civil Engineering
    b. Construction Management
    c. Architecture
    d. Other: Please Specify- _______________

3. How much cumulative work experience do you have in the construction industry?

    Your Answer: _____________

4. What type of construction projects do you most closely associate with?
    a. Residential/Commercial
    b. Infrastructure Projects
    c. Industrial Construction
    d. Specialized Construction (Healthcare/Datacenter construction etc.)
    e. Other: Please specify- ___________

5. Have you had any direct experience or decision-making authority with any of the Tower Crane operations? (Material Handling/ Choosing type of tower crane/Number of tower cranes/Streamlining Tower Crane Operations etc.)? If so, please list them:

    ____

6. Have you personally witnessed a compromise in construction safety/cost management/schedule because of inefficient Tower Crane Planning?
    Yes/No/Not Sure: _________

7. Have you had any previous experience with BIM/VDC Technologies?
    Yes/No/Not Sure: ______________

8. Please list all the software/VDC tools you have utilized or witnessed.
    ____
    ____

9. Overall, how would you rate your subjective experience with such technological tools in construction? (Per Q8)
    On a Scale of 1-5: ____________

10. Personally, do you believe that effective incorporation of advanced VDC technologies could help resolve Tower Crane Planning issues?
    Yes/No/Not Sure: _____________

11. Are you aware or have you witnessed/used any of the Generative Design paradigms in any industry?
    Yes/No/Not Sure: ___________

12. If so, do you believe it has the power to resolve issues related to Tower Crane's lift-ability?
    Yes/No/Not Sure: ________

APPENDIX B: POST-DEMONSTRATION EVALUATION: RESPONSE TO STATEMENTS USING LIKERT SCALE

Aspect 1: Ease of Learning

	Strongly Disagree (1)	Disagree (2)	Neither Agree/Disagree (3)	Agree (4)	Strongly Agree (5)
Learning Generative Design for Tower Crane Planning would be an easy task					
Generative Design can be easily linked/associated with existent Tower Crane Planning activities					
After preliminary learning-Generative Design can be implemented without supporting aids or external help					

Aspect 2: Efficiency of Usage

	Strongly Disagree (1)	Disagree (2)	Neither Agree/Disagree (3)	Agree (4)	Strongly Agree (5)
Visualization Efficiency: Using Generative Design will help better visualize tower crane positions than the traditional methods					
Efficiency of Understanding Features: The essential features of Tower Crane Positioning can be better understood and encapsulated with Generative Design than traditional methods					
Generative Design helps makes decisions of arriving					

at an optimum Tower Crane position more quickly than traditional processes

Aspect 3: Ease of Remembrance

	Strongly Disagree (1)	Disagree (2)	Neither Agree/Disagree (3)	Agree (4)	Strongly Agree (5)
Given the developed workflows, the steps on using Generative Design for Tower Crane Planning can be easily revisited					
After applying Generative Design algorithm on one site- it can be applied to other sites with minimal training or without extensive refreshing tutorials					

Aspect 4: Prevention of Errors

	Strongly Disagree (1)	Disagree (2)	Neither Agree/Disagree (3)	Agree (4)	Strongly Agree (5)
Generative Design is useful to reduce or mitigate the errors otherwise associated with traditional Tower Crane Planning procedures					
The developed Generative Design model does not have inherent errors that might further complicate the Tower Crane Planning process					

Aspect 5: Subjective Pleasing

	Strongly Disagree (1)	Disagree (2)	Neither Agree/Disagree (3)	Agree (4)	Strongly Agree (5)
Generative Design is a promising technique to deal with issues pertaining to Tower Crane Planning					
Generative Design posits benefits to several stakeholders associated with the construction process					
Generative Design is useful than conventional ways of determining the Tower Crane Position					
Generative Design appropriately addresses the lift-ability issue of Tower Crane Positioning					
I would be willing to use Generative Design for next tasks revolving around Tower Crane Planning					
I would recommend my team and fellow stakeholders to use Generative Design for Tower Crane Planning in future					

APPENDIX C: OPEN ENDED QUESTIONNAIRE

Interview takes around 30-45 minutes.

Date and Time of Interview _______________

Person Interviewed _______________

Mode of Interview: Virtual (Online)

Researches announces to inform the interviewee that the participation is voluntary and that he/she is free to stop the interview at any point in time. Researches also ensures that the participant has no reservations on the interview being recorded.

1. Do you feel that the developed model can be implemented on the construction site for Tower Crane Planning? What aspects of the model make it adaptable?
2. Is there anything in the developed model or paradigm that you would like to add or change to make the optimization process more efficient and the technique widely adaptable?
3. During any part of the demonstration, did you feel lost while comprehending the logic associated with Generative Design and incorporation of Tower Crane Planning parameters? If so, what and why?
4. Would you be willing to spend a couple of hours learning the functioning of this technique—to make it usable in the long run? If no, why not?
5. Do you feel that the stakeholders of your organization would be willing to adopt this model for Tower Crane Planning? What are the barriers that might prevent them from the utilization of this technique?
6. Who do you think would be most benefitted if this technique is incorporated? Why?
7. On your next project or construction task- would you be willing to use this or similar Generative Design-based model for Tower Crane position optimization? Why or why not?
8. Do you foresee applications of Generative Design in any other domain of the AEC Industry? Can you please elaborate?
9. Anything else you would like to add about your overall experience?

APPENDIX D: INSTITUITIONAL REVIEW BOARD APPROVAL – I

Birewar, Raj Pradip

From: irb@purdue.edu
Sent: Wednesday, November 18, 2020 9:26 AM
To: Cory, Clark A; Birewar, Raj Pradip
Subject: IRB-2020-1665 - Initial: Not Human Subjects Research (NHSR)

PURDUE
UNIVERSITY

This Memo is Generated From the Purdue University Human Research Protection Program System, Cayuse IRB.

Date: November 18, 2020
PI: CLARK CORY
Re: Initial - IRB-2020-1665
Generative Design for Construction Site Layout Planning - Proof of Concept

Through the answers you provided in response to questions in the Cayuse IRB system, Purdue's HRPP has determined that the research does not qualify as Human Subjects Research under federal human subjects research regulations (e.g., 45 CFR 46).

Decision: No Human Subjects Research
Findings:
Research Notes:

The answers provided in your Cayuse IRB application indicate:

- You will not collect data from human subjects for the purpose of research intended to create generalizable knowledge. Reasons that are not considered research include purposes such as internal programmatic evaluation, quality improvement, or business analysis.
- You will not involve human subjects by collecting data from a living individual through intervention of interaction with the individual and/or identifiable private information.

What are your responsibilities now, as you move forward?

- If you have further questions about this determination, you must contact the Purdue HRPP/IRB.
- You and the members of your research team acknowledge that this study is subject to review at any time by Purdue's HRPP staff, Institutional Review Board, and/or Research Quality Assurance unit. At any time, this project may be subject to monitoring by these Purdue entities to confirm the applicability of this determination. The Purdue IRB has final authority in determining if an activity is Human Subjects Research requiring IRB review.
- This determination is the Purdue HRPP assessment of regulations related only to human subjects research protections. This determination does not constitute approval from any other Purdue campus department or outside agency. The Principal Investigator and all researchers are required to affirm that the research meets all applicable local/state/federal laws and university policies that may apply.

- Finally, if any changes occur with respect to this project, recognize that such changes could change the need for review by HRPP/IRB. Should you change the intent of the activity to involve publication, presentation, or any different application of this work, it is likely that IRB review will be required. Therefore, it is important that you again complete Cayuse IRB to ensure that the IRB review requirements remain the same.

If you need assistance with the submission revisions, please contact irb@purdue.edu for assistance or an appointment. We are here to help!

Sincerely,

Purdue University Human Research Protection Program/ Institutional Review Board
Login to Cayuse IRB

APPENDIX E: INSTITUITIONAL REVIEW BOARD APPROVAL – II

Birewar, Raj Pradip

From:	irb@purdue.edu
Sent:	Monday, December 7, 2020 6:23 PM
To:	Cory, Clark A; Birewar, Raj Pradip
Subject:	IRB-2020-1654 - Initial: 1. COVID-19 EXEMPTION MEMO

PURDUE
UNIVERSITY

This Memo is Generated From the Purdue University Human Research Protection Program System, Cayuse IRB.

*****THIS LETTER IS BEING ISSUED DURING THE FACE TO FACE RESTRICTION ON HUMAN SUBJECTS RESEARCH STUDIES RELATED TO COVID-19. THIS DOCUMENT SERVES AS PROTOCOL APPROVAL FROM THE HRPP/IRB, BUT DOES NOT PERMIT FACE TO FACE RESEARCH UNTIL AN APPROVED UNIVERSITY COVID-19 RESEARCH SPACE SOP PERMITS RESEARCH OPERATIONS. ******

Date: December 7, 2020
PI: CLARK CORY
Re: Initial - IRB-2020-1654
Generative Design for Construction Site Layout Planning - Usability Aspect

The Purdue University Human Research Protection Program (HRPP) has determined that the research project identified above qualifies as exempt from IRB review, under federal human subjects research regulations 45 CFR 46.104. The Category for this Exemption is listed below . Protocols exempted by the Purdue HRPP do not require regular renewal. However, the administrative check-in date is December 7, 2023. The IRB must be notified when this study is closed. If a study closure request has not been initiated by this date, the HRPP will request study status update for the record.

Specific notes related to your study are found below.
Decision: Exempt
Category: Category 2.(i). Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording).
The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects.

Any modifications to the approved study must be submitted for review through Cayuse IRB. All approval letters and study documents are located within the Study Details in Cayuse IRB.

What are your responsibilities now, as you move forward with your research?

Document Retention: The PI is responsible for keeping all regulated documents, including IRB correspondence such as this letter, approved study documents, and signed consent forms for at least three (3) years following protocol closure for audit purposes. Documents regulated by HIPAA, such as Release Authorizations, must be maintained for six (6) years.

1

Site Permission: If your research is conducted at locations outside of Purdue University (such as schools, hospitals, or businesses), you must obtain written permission from all sites to recruit, consent, study, or observe participants. Generally, such permission comes in the form of a letter from the school superintendent, director, or manager. You must maintain a copy of this permission with study records.

Training: All researchers collecting or analyzing data from this study must renew training in human subjects research via the CITI Program (www.citiprogram.org) every 4 years. New personnel must complete training and be added to the protocol before beginning research with human participants or their data.

Modifications: Change to any aspect of this protocol or research personnel must be approved by the IRB before implementation, except when necessary to eliminate apparent immediate hazards to subjects or others. In such situations, the IRB should still be notified immediately.

Unanticipated Problems/Adverse Events: Unanticipated problems involving risks to subjects or others, serious adverse events, and
noncompliance with the approved protocol must be reported to the IRB immediately through an incident report. When in doubt, consult with the HRPP/IRB.

Monitoring: The HRPP reminds researchers that this study is subject to monitoring at any time by Purdue's HRPP staff, Institutional Review Board, Research Quality Assurance unit, or authorized external entities. Timely cooperation with monitoring procedures is an expectation of IRB approval.

Change of Institutions: If the PI leaves Purdue, the study must be closed or the PI must be replaced on the study or transferred to a new IRB. Studies without a Purdue University PI will be closed.

Other Approvals: This Purdue IRB approval covers only regulations related to human subjects research protections (e.g. 45 CFR 46). This determination does not constitute approval from any other Purdue campus departments, research sites, or outside agencies. The Principal Investigator and all researchers are required to affirm that the research meets all applicable local/state/ federal laws and university policies that may apply.

If you have questions about this determination or your responsibilities when conducting human subjects research on this project or any other, please do not hesitate to contact Purdue's HRPP at irb@purdue.edu or 765-494-5942. We are here to help!

Sincerely,

Purdue University Human Research Protection Program/ Institutional Review Board
Login to Cayuse IRB

See Purdue HRPP/IRB Measures in Response to COVID-19 https://www.irb.purdue.edu/docs/IRB%20Covid-19%20Recommendations.pdf