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Computational design for construction site optimization

Progettazione computazionale per l'ottimizzazione del cantiere

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STATEMENT OF INTEGRITY

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I further declare that I have fully acknowledged the Code of ethics and conduct of Politecnico di Milano.

SOMMARIO

L'utilizzo di metodi computazionali all'interno del processo BIM nel settore dell'Ingegneria dell'Architettura e delle Costruzioni ha mostrato grandi possibilità per ottenere soluzioni progettuali ottimizzate. Attualmente, la progettazione architettonica e degli edifici fa leva in gran parte sui metodi di progettazione computazionale. In confronto, c'è poca attenzione sull'utilizzo dell'approccio di progettazione computazionale per pianificare i cantieri, un'attività che ha un impatto significativo su aspetti importanti di un progetto di costruzione, come la produttività, la sicurezza dei lavoratori, i costi e il tempo del progetto. Vi è quindi la necessità di ulteriori sforzi per implementare metodi di calcolo che ottimizzino la progettazione e la pianificazione dei cantieri.

L'evoluzione degli strumenti di progettazione, la necessità di produttività e il collegamento con la stampa tridimensionale e le tecniche di prefabbricazione stanno spingendo il settore AEC a sviluppare approcci computazionali alla costruzione. Nei nuovi cantieri, le strutture, i sistemi, il personale, il flusso di materiali e attrezzature devono essere concepiti e gestiti prima dell'inizio dei lavori per colmare il divario tra progettazione e installazione. La progettazione computazionale ottiene questi obiettivi attraverso procedure iterative che si basano su regole di programmazione e algoritmi di Intelligenza Artificiale, integrabili con metodologie BIM nella digitalizzazione del processo di costruzione.

Lo scopo di questo studio era di utilizzare la potenza della progettazione computazionale nella pianificazione di un cantiere. Lo scopo era sviluppare soluzioni basate su BIM ad alcuni dei problemi riscontrati nei cantieri utilizzando uno strumento di progettazione computazionale, ad esempio il software Dynamo selezionato per questo studio. Gli esperimenti di progettazione computazionale sono stati eseguiti su un modello BIM di sito astratto e, successivamente, le soluzioni sviluppate sono state applicate e valutate su un caso di studio che prevedeva la costruzione di un edificio ospedaliero. I risultati dello studio mostrano coerenza nell'applicazione delle soluzioni Dynamo proposte, indicando così un'elevata fattibilità nell'adozione dell'approccio di progettazione computazionale per la pianificazione del cantiere. Le soluzioni generate includono planimetria spaziale ottimizzata, posizioni ottimizzate di più gru a torre, sicurezza ottimizzata, manovrabilità migliorata dei veicoli del sito sulle strade del sito e flussi ridotti al minimo. Tuttavia, esistono ancora aree di miglioramenti futuri, ad esempio, l'uso di metodi di scripting più potenti come la codifica Python per migliorare l'automazione del cantiere e l'efficienza degli script della soluzione.

Le soluzioni proposte devono essere applicate durante la fase di progettazione iniziale di un progetto di costruzione. Ciò non solo ridurrebbe il divario tra progettazione e installazione, ma gestirà anche meglio le complessità del sito prima dell'inizio della costruzione vera e propria. Inoltre, le soluzioni dinamiche fornite dagli script Dynamo potrebbero aiutare a gestire i cambiamenti in loco man mano che la costruzione procede. Le soluzioni proposte potrebbero essere implementate durante la gara o su progetti di costruzione in corso. Il team di progetto può utilizzare gli script generativi per generare diversi scenari del sito e trovare le migliori soluzioni in base alle regole e ai vincoli prevalenti del sito. Il potenziale impatto delle soluzioni sviluppate sul settore edile è una pianificazione logistica e costi più informata, maggiore produttività, maggiore sicurezza in loco e migliore coordinamento tra le parti interessate del progetto.

Parole chiave: Algoritmi, BIM, Ottimizzazione del cantiere, Pianificazione del cantiere, Progettazione computazionale

ABSTRACT

The use of computational methods within the BIM process in the Architecture Engineering and Construction (AEC) sector has shown great possibilities in obtaining optimized design solutions. Currently, the architectural and building design largely leverage the computational design methods. In comparison, there is little focus on using the computational design approach to plan construction sites – an activity that has significant impact on important aspects of a construction project, such as productivity, safety of workers, project costs and time. There is therefore a need for additional efforts towards implementing computation methods that optimize the design and planning of construction sites.

The evolution of design tools, the need for productivity, and the connection with 3-dimensional printing and prefabrication techniques are pushing the AEC sector to develop computational approaches to construction. At new construction sites, structures, systems, personnel, material and equipment flow need to be conceived and managed before the start of work in order to bridge the gap between design and installation. Computational design obtains these goals through iterative procedures that are based on programming rules and Artificial Intelligence algorithms, which can be integrated with BIM methodologies in the digitalization of the construction process.

The aim of this study was to utilize the power of computational design in planning a construction site. The purpose was to develop BIM-based solutions to some of the problems experienced at construction sites using a computational design tool i.e. Dynamo software as selected for this study. Computational design experiments were performed on an abstract site BIM model, and thereafter the developed solutions were applied and evaluated on a case study that involved the construction of a hospital building. The study results show consistency in the application of the proposed Dynamo solutions, thus indicating a high feasibility in adopting the computational design approach for construction site planning. The generated solutions include optimized spatial layout plan, optimized positions of multiple tower cranes, maximized safety, improved manoeuvrability of site vehicles on site roads, and minimized flows. However, there still exists areas of future improvements, for example, the use of more powerful scripting methods such as Python coding to improve construction site automation and efficiency of the solution scripts.

The proposed solutions are to be applied during the initial design phase of a construction project. This would not only reduce the gap between design and installation, but also better manage site complexities before the actual construction begins. Moreover, the dynamic solutions provided by the Dynamo scripts could assist to manage changes on site as construction progresses. The proposed solutions could be implemented during tendering or on ongoing construction projects. The project team may use the generative scripts to generate different site scenarios and find the best solutions based on the prevailing site rules and constraints. The potential impact of the developed solutions on the construction industry is a better-informed cost and logistical planning, increased productivity, improved safety on site and better coordination among the project stakeholders.

Keywords: Algorithms, BIM, Computational design, Construction site planning, Site optimization

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CHAPTER 1. INTRODUCTION

1.1. Background

The evolution of design and construction technologies within the Architecture, Engineering and Construction (AEC) sector has promoted increased collaboration among professionals in the industry. The use of Building Information Modelling (BIM), for example, has improved communication between stakeholders, and enhanced workflows. Many benefits have been attributed to the use of BIM in the AEC industry (Bryde *et al.*, 2013; Dowsett and Harty, 2013; Doumbouya *et al.*, 2016; Mesároš and Mandiák, 2017), most of which are realized during the construction and facility maintenance phases. However, the AEC sector is yet to fully explore the capabilities of BIM use in the planning and optimization of construction sites. Including a construction site planner for the role of site planning and optimization, particularly during the initial design phase of a construction project as illustrated in Figure 1.1 can be of significant benefit to the construction project. Some of the benefits to project productivity, cost and safety are mentioned in the literature (Khatib *et al.*, 2007).

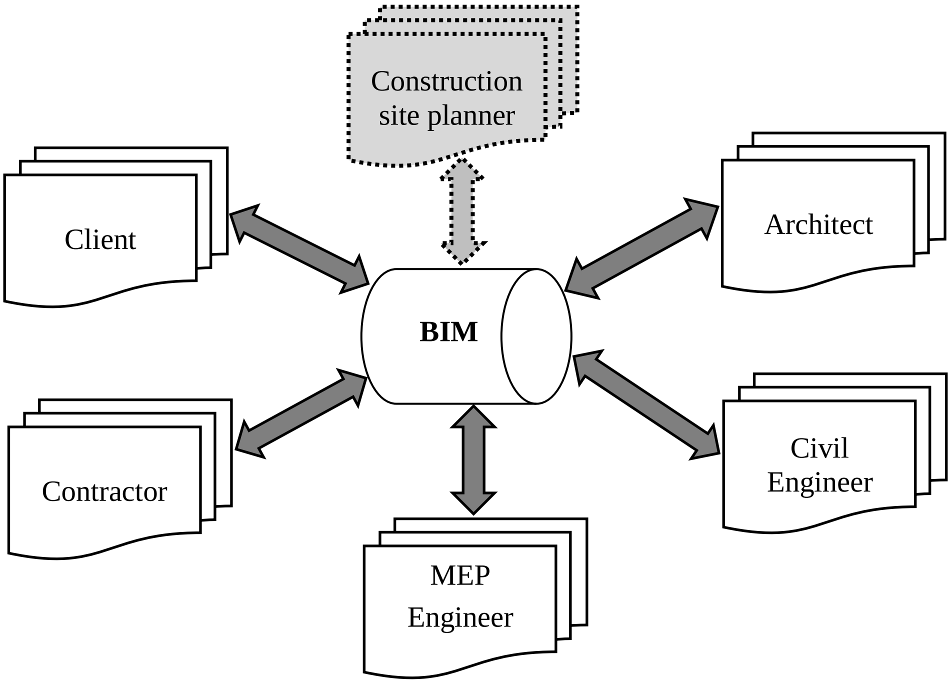

Figure 1.1: Construction site planner as a stakeholder in a construction project

Large-scale AEC projects involving the construction of complex buildings, industrial plants or infrastructure, often face challenges regarding planning and management of construction site. These challenges include, the safety of workers on site, streamlining of the construction processes and material flows, and enhancement of productivity. Several methods that leverage on the current technological and scientific advancements attempt to solve these challenges, for example, the use of genetic algorithms and simulation-based site planning. However, a BIM standard framework for construction site planning and optimization to enhance safety and productivity does not exist yet.

Although several authorities have developed safety regulations and standards to mitigate risks and increase performance on construction sites (International Labour Office, 1992, 1995; Reese and Eidson, 2006; The Council of the European Communities, 2007) implementing these regulations on sites remains a challenge to most construction professionals. The challenge arises when translating these regulations – often in document formats – into workable safety and performance plans that are usually 2-dimensional drawings (Khatib *et al.*, 2007; Feng and Lu, 2017). The use of BIM through construction site information modelling and visualization can offer a solution to this challenge. Through visualization, safety checkpoints can be noted on the 3-D model. By comparing the model with the actual construction site, the checkpoints and hazards can be identified and a solution found.

For higher productivity, the planning of a construction site layout should optimize several factors such as, (i) the flow of materials by establishing short and fast transportation routes, (ii) clarity and efficient use of equipment such as tower cranes, excavators and trucks on site, and (iii) ensure a safe working environment for workers e.g. by establishing safety distances (Feng and Lu, 2017; Oral *et al.*, 2018). The local site conditions and constraints, technical feasibility, cost and time should also be considered (Francis, 2019). Other factors such as labour force, equipment to be used, location and sizes of storage zones should also be considered during the planning stage (Astour and Franz, 2014). The computational design approach can be explored by construction site planners to generate optimized solutions while considering the correlating site factors mentioned above.

1.2. Motivation and significance of study

The use of computational methods and scientific approach within a BIM process in the construction industry has shown great possibilities in obtaining controlled and optimized design solutions. Currently, the architectural and building design largely leverage the computational and generative design methods. In comparison, there is little application of computational methods to the planning of construction site layout and workflows – a phase that has significant influence on the key factors of a construction project such as productivity, health and safety of workers, and project costs (Kaveh *et al.*, 2018). Operational matters of a construction site continue to receive little attention during the design phase in the AEC industry. Moreover, the BIM tools, data and resources specially needed for construction site planning – i.e. objects and families of construction site elements – are insufficient (Schwabe *et al.*, 2016; Trani *et al.*, 2016).

There is therefore a need for more efforts towards implementing computational approaches for designing and optimizing construction sites. At new construction sites, structures, systems, workers, material and equipment flow need to be conceived, verified and managed before the start of work. This can reduce the gap between design and installation, and enhance high levels of safety for workers and efficiency on site.

This study aims at generating computational design solutions to construction site problems, which can assist construction site planners and engineers to optimize site plans, logistics and use of site equipment for building projects during the preliminary phase of a project. The developed Dynamo scripts are expected to help in a better management of site complexities before the actual construction starts. Furthermore, the dynamic solutions provided by the scripts are anticipated to help manage changes on site as the construction progresses. The proposed solutions could be implemented during tendering or on ongoing construction projects. The project team may use the generative scripts to generate different site scenarios and find the best solutions based on the prevailing site rules and constraints. The potential impact of the outcome of this study on the construction industry is a better-informed cost and logistical planning, increased productivity, improved safety on site and better coordination among the project stakeholders.

1.3. Objectives and scope of study

The main objectives of this study are to:

i) Investigate the potential and feasibility of adopting computational design in construction site planning.

ii) Develop generative scripts that can be used to plan and optimize a construction site using the Dynamo software as the main computational design tool. The elements to be planned/optimized include site spaces, positions of tower cranes, safety distances, shortest routes, site roads and manoeuvrability.

iii) Evaluate the feasibility of the developed generative scripts on a case study involving a building project.

iv) Identify potential areas of improvement and suggest developments for future similar works.

The scope of this study was limited to the following aspects:

i) The generative scripts were developed and evaluated using a building project, hence the proposed solutions are limited to building projects.

ii) Dynamo software was used as the main computational design tool. Other associated tools were MS Excel and Revit for the input of data and construction site components, and viewing of optimized results on the site BIM model.

iii) An abstract Revit site model was used to develop the Dynamo scripts based on conceptual site rules and constraints.

iv) The generation of solutions in the case study was limited to the prevailing site scenarios, rules and constraints.

v) The construction site planning process was BIM-based. The changes effected in Dynamo e.g. the site layout plan and updated positions of equipment, automatically reflected and could be visualized on the Revit site model.

vi) The focus of computation design on construction site planning was limited to site configuration, equipment management and transportation on site.

1.4. Dissertation outline

Chapter 1 presents an introduction to the dissertation, beginning with a theoretical background of the work. The motivation and significance of the study in the construction industry, and the scope and objectives of the investigation are also outlined in this chapter.

In *Chapter 2*, the state of the art of construction site planning and recent developments in site optimization is reviewed under three main areas. First is a review of construction site planning with focus on site layout design and planning of site equipment before the start of the construction process. The significance of construction site planning is also highlighted. Secondly, the role of computational design methods in construction site optimization is reviewed. The BIM-based approach to construction site planning is finally presented, covering the subjects of construction site configuration, 4D simulation and the management of health and safety.

Chapter 3 presents the theoretical basis and the proposed methodology of the computational design solutions to some of the problems encountered during the construction site planning process. Detailed Dynamo workflows and descriptions of the design experiments performed on an abstract construction site model are presented. The tools used are Revit, Excel, Dynamo and Dynamo extension packages.

In *Chapter 4*, the proposed computational design solutions developed in *Chapter 3* are applied to a case study. The Dynamo scripts are implemented on the case study BIM models to assess the consistency of proposed solutions. The main objective in this activity is to evaluate the feasibility of the proposed computational design solutions.

Chapter 5 presents conclusions drawn from the literature findings, a summary of the proposed solutions and their advantages, design limitations encountered during the study, and potential impact of the study on the construction industry. Also included in this chapter are suggestions on future developments are improvements.

The *Appendices* contain detailed information about the developed Dynamo scripts, and brief instructions for applying the scripts on Revit models. The load chart data used to optimize the positions of tower cranes in this study are also provided.

CHAPTER 2. STATE OF THE ART OF CONSTRUCTION SITE PLANNING

2.1. Introduction

Construction site planning is an essential aspect of construction project preparation. It has a significant impact on the safety and efficiency of the construction process. A properly planned construction site can minimize project delays, save costs, improve workers' safety and streamline site logistics. These benefits can be greater if a construction site planner is involved alongside the other designers during the preliminary design and project planning. The adoption of recent construction technologies e.g. the use of BIM and the parametric design method would enhance the benefits further.

Despite the widespread adoption of BIM in the AEC industry, construction site planning and optimization remains largely manual. However, there are recent and ongoing efforts leveraging computational design methods that aim to plan/design construction sites based on outcomes of qualitative and/or quantitative evaluation, rather than personal experience and rule of thumb. This chapter presents the state-of-the-art of construction site planning, and recent developments in the use of computational design methods to optimize construction sites.

2.2. Methodology for literature review

The purpose of this study was to explore the potential and possibility of using the computational design approach to plan a construction site. This included proposing a methodology that could be used to plan and optimize a construction site using the Dynamo software as the main computational design tool. A review of literature was carried out to assist in making sound procedural decisions in the third and fourth chapters. This section describes the approach that was adopted for literature review, in view of the study objectives highlighted in Chapter 1. The approach consisted of three main phases described below.

i) ***Exploration of literature***: this was the first phase which involved defining the relevant and required information based on the dissertation keywords i.e. computational design, construction site planning, construction site optimization. The search for literature, organizing and storing the relevant information was also performed in this phase.

ii) ***Analysis and interpretation***: this phase involved breaking down, studying and synthesizing the information in the selected literature in order to gain a better understanding of the concepts presented by the author(s). Also included in this phase was a discussion on the implications of the findings in the literature.

iii) ***Literature review presentation***: this was the final phase which involved presenting the synthesised work with more focus on construction site planning, construction site optimization, and computational design methods.

The Figure 2.1 below shows a graphical illustration of the phases described above.

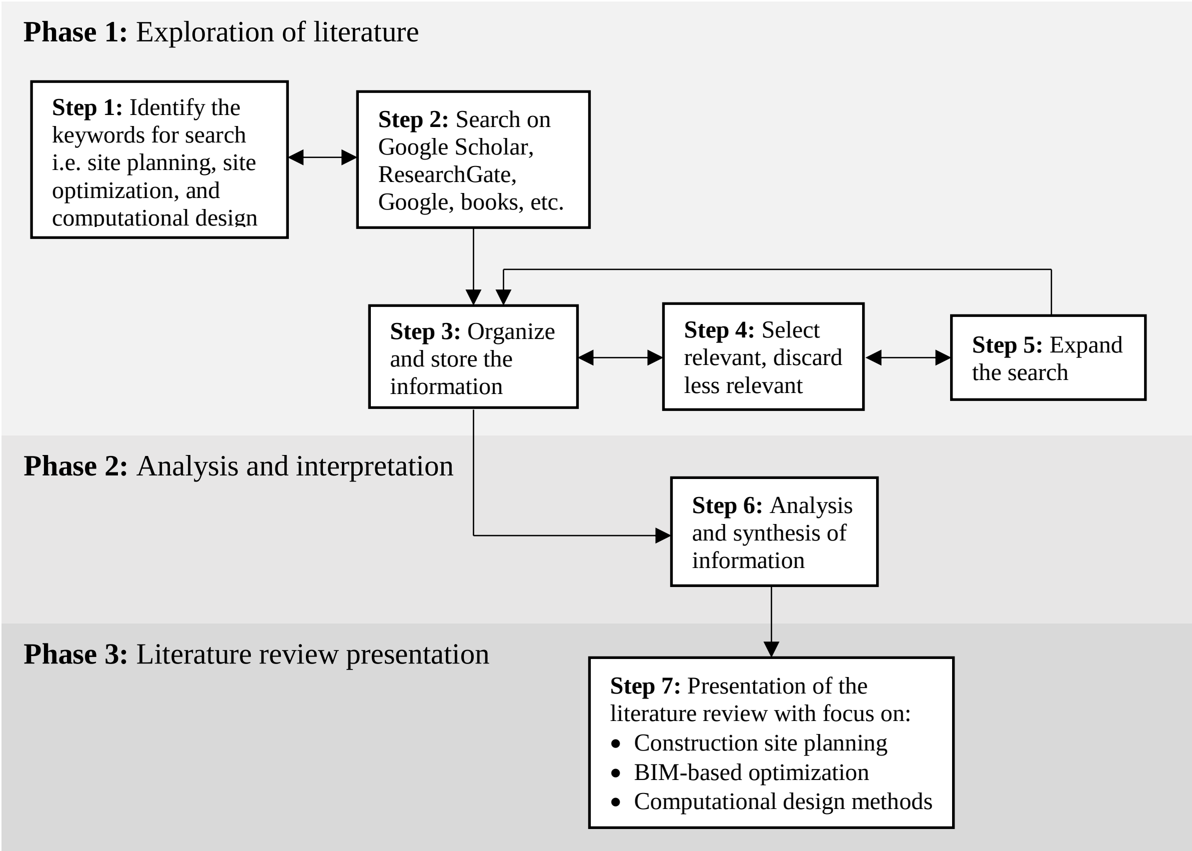

Figure 2.1: Methodology for literature review

A summary of the sources and their contributions to the literature review is presented in Table 2.1.

Table 2.1: Summary of sources and their contributions to the literature review

Author(s)	Main subject	General contribution
Astour & Franz (2014), Cheng & Kumar (2014), El-Rayes & Khalafallah (2005), Elgendi (2016), Jahr & Bormann (2017), Schwabe *et al*. (2016), Teizer *et al*. (2010), Zolfagharian & Irizarry (2014)	Construction site planning	Frameworks for planning various elements of a construction site, e.g. space, safety, equipment, flows and cost.
Alan (2013), Alothaimeen & Arditi (2019), Farmakis & Chassiakos (2018), Francis (2019), Fridgeirsson & Roslon (2017), Kaveh *et al*. (2018), Kaveh & Talatahari (2010), Omar (2019), Oral *et al*. (2018), Papadaki &Chassiakos (2016), Prayogo *et al*. (2018), Soltani & Fernando (2004), Venkrbec *et al*. (2018), Dynamo Team (2019), Kim *et al*. (2011), Vermeulen (2019)	Construction site optimization	Use of optimization methods such as Genetic Algorithms to optimize the site layout plan, construction site facilities and workflows.
Galic et al. (2015), Kanan *et al*. (2018), Khatib *et al*. (2007), Rischmoller & Alarcon (2002), Swallow & Zulu (2019), Zhang *et al*. (2013)	Simulation and virtual reality	Process modelling and scenario simulation i.e. for processes planning and safety management.
Bryde *et al*. (2013), Cassano & Trani (2017), Doumbouya *et al.* (2016), Dowsett & Harty (2013), Feng & Lu (2017), Kim *et al*. (2013), Mesároš & Mandičák (2017), Shin *et al*. (2018), Trani et al. (2015), Trani *et al*. (2016), Trani *et al*. (2016)	BIM-based design workflows	Significance and role of BIM in construction site planning and management.
British Standards Institution (2018), Council of European Communities (2007), Health & Safety Executive (2015), Reese & Eidson (2006), BIMForum LOD, International Labour Office (1992), International Labour Office (1995), Occupational Safety & Health Administration	Construction guidelines	Specifications, regulations and guidelines for construction workflows to ensure safety at construction sites.
Peroni (2018), Serra & Hage (2020)	General computational design	Information on the fundamentals of computational design

2.3. Construction site planning

The Council of European Communities (2007) defines a construction site as an area where buildings or civil engineering works are built. A non-exhaustive list of works referred to in the directive include excavation, earthworks, construction, assembly and disassembly of prefabricated elements, alterations, renovation, repairs, demolition, and drainage. The activities involved in the construction site design process can be subdivided into two categories, namely construction site pre-design activities, and construction site execution activities (Trani *et al.*, 2015). Table 2.2 below summarises the activities in each category. The first activity is performed by the site planner during the design phase, while the latter activity is performed by contractors and subcontractors (Trani *et al.*, 2015).

Table 2.2: Construction site design activities (Trani *et al.*, 2015)

Construction site pre-design
Project contextualization Functional-spatial design (productive site) Technological-plant design (productive site) Process analysis (construction phase) Process planning (construction phase) Organizational modelling Health and safety coordination planning
Construction site execution design
Site organization Site operational management Production operational design Operational safety planning

The design activities are limited within the site area, which can be classified into two main spaces, i.e. the available space and the unavailable space. The available space comprises the area where the construction facilities and equipment can be placed. The facilities installed in the available space are often temporary in nature, i.e. installed to facilitate construction operations e.g. site offices and storage yards, and hence they are not part of the long-term facilities. The unavailable space, on the other hand, is occupied with permanent facilities e.g. the building under construction. The temporary site facilities and equipment cannot be positioned in this space (Elgendi, 2016; Oral *et al.*, 2018). Construction site optimization involves defining the available and unavailable spaces, then finding the optimal layout based on required facilities, duration of activities, site rules and constraints.

2.3.1. Construction site layout design

The construction site layout design process determines the best locations for the required spaces and facilities on site (Cheng and Kumar, 2014). It involves working with multiple and often conflicting spatial requirements and constraints that interrelate. The solution is usually a compromise that attempts to satisfy these requirements as much as possible, based on the complexity of the problem and the available time budget (Kaveh *et al.*, 2018; Oral *et al.*, 2018). As the number of required spaces/facilities and constraints increase, it becomes more complex to figure out an optimal solution. Typically, no specific solution is perfect, thus a few different alternatives can be explored to obtain the desired design (Dynamo Team, 2019).

Many construction projects however, more so the large-scale and/or complex ones, often experience delays, cost overruns, decline in productivity and accidents due to poor site design and planning. This is commonly experienced in congested and disorganized sites. Effective planning of site layout is therefore vital and beneficial to all aspects of the construction process i.e. the flow of materials, safety of workers, optimized utilization of equipment, project time and cost (Kim *et al.*, 2011; Cheng and Kumar, 2014; Omar, 2019). Site space design links the spatial and temporal aspects of construction (Francis, 2019). Construction time and cost, for example, can be reduced as a result of appropriate location of facilities and construction materials i.e. a design that minimizes relocation needs.

Construction site planning relies on variables and constraints that are unique for each project, such as work spaces, available construction equipment, facility locations and the requisite logistics. Figure 2.2 shows some of the common variables and constraints at a typical construction site.

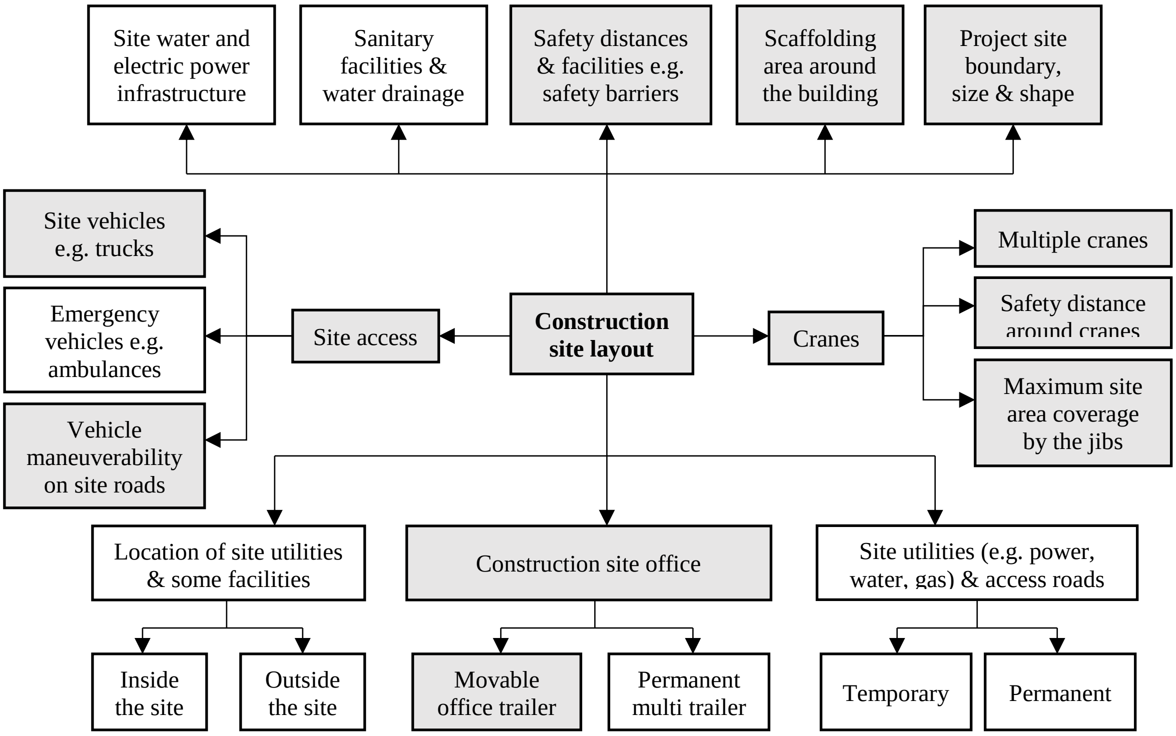

Figure 2.2: Common site variables and constraints (modified from Zolfagharian and Irizarry, 2014)

The highlighted variables and constraints in the above diagram are the elements that were considered for construction site planning and optimization in this study, since they have significant influence on the general site layout and productivity during the construction process.

2.3.2. Planning of construction site equipment and facilities

The planning of site equipment and facilities involves identifying the required equipment and determining their best locations at the construction site. Construction site facilities may be fixed or temporary. The fixed facilities e.g. the building under construction are permanent and the locations are fixed prior to construction. The temporary site elements are facilities without permanent locations prior to construction (Cheng and Kumar, 2014). Their location is determined by the site conditions and the construction requirements, and should be allocated space during the site planning process.

The purpose of planning for site facilities and equipment is to facilitate an orderly, productive and safe execution of tasks during construction, reconstruction, or demolition of a structure. The facilities planning process entails placing the site equipment and facilities on the generated site layout plan within the site area. Jahr and Barrmann (2017) classify site equipment and facilities into the following groups:

i) Construction machinery e.g. hoists and concrete pumps
ii) Social and office facilities e.g. office and sanitary containers
iii) Storage areas e.g. tool sheds, open and closed storage
iv) Traffic areas and transport routes i.e. temporary construction roads, entrances and exits
v) Media supply and disposal e.g. power and water supply, and waste disposal
vi) Site security e.g. fences, gate and lighting
vii) Excavation support

Figure 2.3 illustrates the general workflow for planning construction site facilities and equipment.

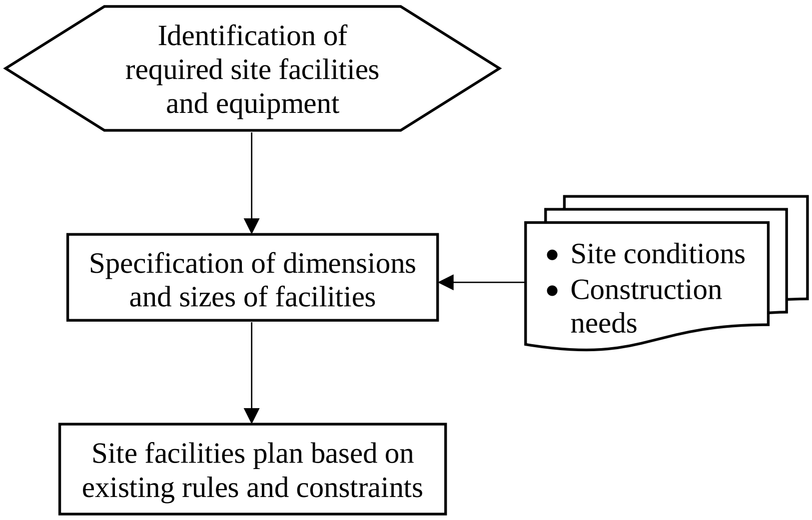

Figure 2.3: General workflow for planning construction site facilities and equipment

The first step of site facilities planning is to identify the required site facilities and equipment, and thereafter specify their dimensions. The dimensioning of site equipment and facilities according to site conditions and requirements is crucial for efficiency. For instance, under-dimensioning, on the one hand can lead to delays in the construction progress e.g. work stoppage in order to reposition tower cranes as a result of insufficient crane reach. On the other hand, over-dimensioning can incur additional costs which could be avoided e.g. when the crane is much higher than the required height. The facilities are also dimensioned to facilitate optimized material storage, safe work conditions for workers, and efficient running of the facilities/equipment. Production facilities such as the batching plant ought to be sized based on their production capacities (Cheng and Kumar, 2014).

Thereafter, the facilities and equipment are arranged within the site area. For many cases, planning has largely been manual, and at times with little digitalization. The dimensioning of equipment and spaces is commonly based on rule of thumb and experience of site planners (Prayogo *et al.*, 2018), thus often lacking the qualitative or quantitative perspective. The quality of outcome therefore relies on the expert knowledge and experience of the site planner. The use of construction site design tools which utilize computational approach can ease and expedite the planning process, as well as yield better results (Jahr and Borrmann, 2017).

2.3.3. Significance of construction site planning

Construction site planning has a large impact on the construction process of a project. The beneficial effects of site planning, particularly when carried out in the preliminary phase of the project, are discussed below.

a) ***Increased safety of construction workers*****:** The safety of construction workers is a priority. Workers at a construction site are exposed to risky environments and equipment that may cause accidents. Construction site hazards such as extreme heights/depths, machinery failure, unguarded risky machinery, structural collapse, falling objects, and toxic fumes or materials may result in fatal injuries, health conditions or death. Safety programs and identification of safety distances during construction site layout planning can mitigate injuries and deaths (Khatib *et al.*, 2007; Elgendi, 2016).

b) ***Productivity at the construction site*****:** The level of safety on site and the layout plan have a substantial influence on productivity. A safe environment increases the confidence and motivation of the workers, and therefore increases productivity. A careful positioning of site facilities and equipment based on adjacency requirements has been proven to increase productivity on site (Khatib *et al.*, 2007; Elgendi, 2016).

c) ***Project cost and time*****:** Construction site planning has a significant impact on the project cost and time. Proper design for example, minimises or eliminates the need to relocate facilities, equipment or construction materials, thus saving time and preventing incurring financial losses (Khatib *et al.*, 2007; Elgendi, 2016; Shin *et al.*, 2018).

d) ***Flow of materials, workers and accessibility of site area*****:** Site planning determines the ease with which site areas can be accessed and the ease of delivering materials, facilities. etc (Elgendi, 2016). In addition, the shortest routes can be determined thus minimizing transportation costs.

e) ***Material storage and waste management*****:** Planning for the locations of temporary storage spaces or facilities to accommodate construction materials and also handle waste materials at the site can improve accessibility and productivity (Elgendi, 2016).

2.4. BIM-based construction site planning

The use of BIM in construction site planning can help site planners to efficiently organize the spatial layout plan, identify and manage potential safety hazards and conflicts on site, and simulate the existing site constraints and positions of facilities.

2.4.1. Construction site configuration

A BIM-based generation of 3D-site layout plan can be carried out in a BIM environment using a BIM-authoring tool such as Autodesk Revit. A 3D parametric library containing BIM elements used as basic components of the site layout plan is required during this process. However, due to insufficient number of BIM resources for site elements (Schwabe *et al.*, 2016; Trani *et al.*, 2016), the designer may have to develop some of the BIM objects and families, completed with the related technical and cost parameters (Astour and Franz, 2014).

An optimization technology may then be used to automate dimensions and locate the site facilities depending on the available equipment for the project, construction methods, available space, and the necessary safety measures at the site (Astour and Franz, 2014). The optimization process involves the determination of optimal or near optimal locations and dimensions of site facilities while considering the prevailing site rules and constraints.

The site rules are determined by site elements such as safety distances, spatial plan, facility and equipment positions. Information on site rules may be obtained from company level documentations, or from the relevant codes at industry level. Site constraints, on the other hand, are the invariable site factors e.g. property boundary, size and position of the building under construction, and the site area (Astour and Franz, 2014).

2.4.2. 4D simulation

Studies on 4D scheduling began several years ago with the implementation of 3D computer aided design (CAD) systems over time to visualize the progress of work. The evolution of BIM has enabled the inclusion of the 'time' dimension, thus automating the link between 3D objects and work schedule (Kim *et al.*, 2013; Trani *et al.*, 2015). The 4D simulation process involves the integration of 3D CAD models with the construction activities in order to visualize the construction progress over time. A 4D model is thus a visualization tool that simulates the scheduled construction activities and shows the components of the project and the order in which they will be constructed (Rischmoller and Alarcon, 2002).

The process of simulation determines the effect of input variation in a system or its local parts. Process modelling and simulation allows the comparison of constraints and procedures, and hence improves the understanding of procedures and scenarios. This enables decision-making based on quantitative data. Virtual models and process simulations are also important tools in production and logistics. They add value through the simulation of scenarios which may involve changing input parameters. This results in the generation of multiple scenarios that can be used to improve decision-making, site layout design and quantitative assessments (Galić *et al.*, 2015).

Construction is a dynamic process, and changes in site conditions and requirements are often expected as work progresses. (Cheng and Kumar, 2014; Jahr and Barrmann, 2017). 4D simulation can be useful in managing the dynamic construction site plan. The simulation of site layout and activities using 4D models can provide a dynamic view of the construction site (Zolfagharian and Irizarry, 2014) and provide a better understanding of the workflow beforehand.

2.4.3. Management of health and safety at construction site

The construction sector is one of the industries with high risk working environments. Therefore, the health and safety of construction workers is an aspect that must be considered during the construction activities (Swallow and Zulu, 2019). Figure 2.4 shows a framework for implementing a rule-based safety analysis in BIM proposed by Zhang *et al.* (2013).

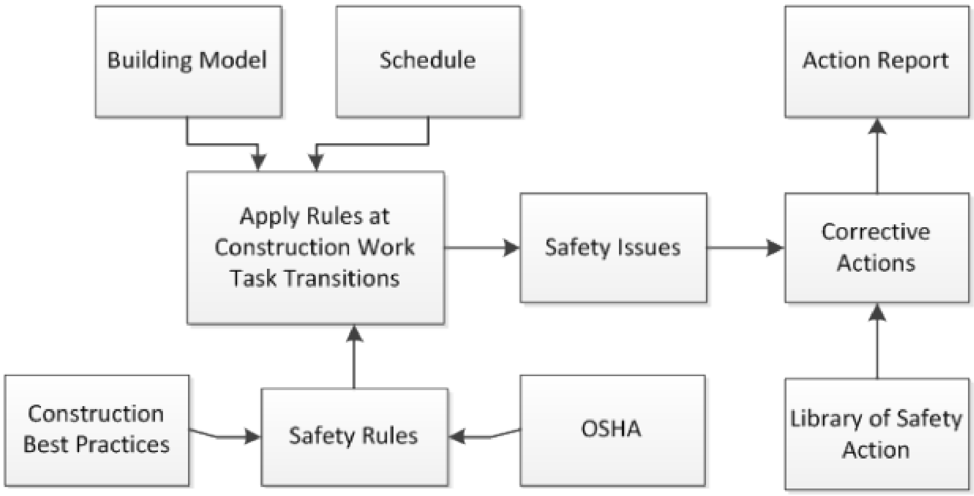

Figure 2.4: Framework for implementing a rule-based safety analysis in BIM (Zhang *et al.*, 2013)

In this framework, the risk factors that may be encountered in a construction site are analysed, and then the BIM model elements are matched to relevant regulations to establish a framework for BIM application in the safety regulatory system (Zhang *et al.*, 2013).

2.4.3.1. Selected guidelines on health and safety in construction

Several guidelines on the improvement of safety in the construction industry exist. The PAS1192-6:2018 document published by the British Standards Institution (2018) forms a part of the BIM level 2 framework, and it highlights the collaborative sharing and use of structured health and safety information. This standard advocates for the digitalization of health and safety management by using 3D or 4D construction scheduling models to facilitate the visualization and planning of safe working environments (Swallow and Zulu, 2019). Also, the directive on 'the introduction of measures to encourage improvements in the safety and health of workers at work' authored by the Council of the European Communities (2007) is based on principles that focus on the assessment and prevention of risks, protection of safety and health of workers, elimination of risks and accident factors, and the informing or training of workers. Similarly, visualization aided by 4D models can be beneficial in realizing these principles. Other publications such as the documents published by the International Labour Office (1992 and 1995) provide directives on health and safety training.

The safety aspects of a construction project can be better addressed beforehand using a 3D or 4D BIM model (Health and Safety Executive, 2015). Visualization can play an important role in identifying the health and safety issues at the construction site and the required safety distances to machineries and areas of potential risk. The training of workers on safe use of equipment and the positions they will take or work from at the construction site can also be carried out by 3D visualization.

2.4.3.2. Scaffolding planning

Many injuries and deaths at the construction site are caused by scaffold-related accidents. According to the Occupational Safety and Health Administration (OSHA), 72 percent of American construction workers get injured or die from scaffold-related accidents caused by planking, support giving way, workers slipping or being struck by a falling object. All these accidents can be managed by compliance with construction safety guidelines and standards such as the OSHA standards, the PAS1192-6:2018 directives, and the Council Directive 92/57EEC guidelines on the implementation of health and safety at construction sites.

Visualization and 4D simulation can be useful in identifying and analysing scaffold related hazards. This should be done in the project planning phase using the 4D BIM model by conducting simulations on the scaffolding system and potentially hazardous activities (Feng and Lu, 2017). In addition, the 4D BIM model can serve as a tool for educating or training the construction workers on safety practices and use of machineries at the site.

2.4.3.3. Safety distances and zones

Safety distances and zones should be clearly defined within the construction space to manage accidents. Safety barriers should be installed around areas that are potentially risky e.g. deep excavations, and machineries such as cranes and excavators, to indicate areas of only authorised access. Clear signs should also indicate the probable dangers that workers are exposed to at the construction site. Some studies (Teizer *et al.*, 2010; Kanan *et al.*, 2018) have proposed the use of an autonomous real-time safety alert system for workers at construction sites, which can play a significant role in enforcing safety distances.

Also, residential facilities such as the site office should be positioned away from potential health and safety risks e.g. falling objects, excessive noise and dust. The site offices, for example, ought to be away as much as possible from the reach of tower cranes to minimize the possibility of accidents due to falling objects. In addition, accidents can be managed by setting out paths for workers, vehicles and mobile plants, which avoid high risk areas (Soltani and Fernando, 2004).

2.4.4. The CoSIM approach

The construction site information modelling (CoSIM) is an approach developed by Trani *et al.* (2016) which uses technology to establish a virtual construction site based on information obtained from an actual construction site. The virtual model may contain information such as material and site equipment data, processes and operational information. In this approach, construction site planning is considered during the project preparation stage when decisions on the technical and organizational aspects are made. This concept can also be useful in the estimation of work timelines.

2.4.4.1. Construction site design workflows

The CoSIM approach integrates site design into the BIM design process during the preliminary phase of a construction project. This enables the identification of risks and critical aspects of the construction project that may affect the implementation phase. Information sharing and coordination with the building designers is the core of workflow in the design of a construction site. (Trani *et al.*, 2015; Trani *et al.*, 2016). The BIM design workflows for a construction site can be categorised in three phases as shown below.

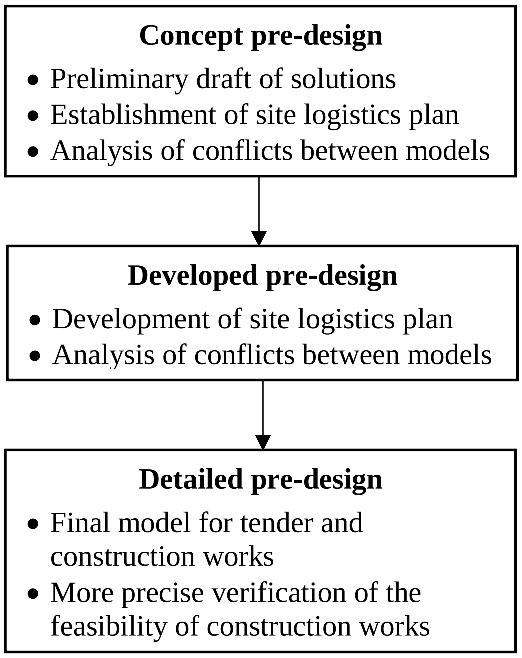

Figure 2.5: BIM design workflows for construction site

a) ***Concept pre-design*****:** This phase involves a preliminary draft of solutions. The main task of the construction site planner is to model a master plan of the construction site around volumes. A plan for logistics is then established in order to verify the suitability of available zones and site scenarios. Conflicts between the site model and models from other designers are also analysed at this stage (Trani *et al.*, 2016).

b) ***Developed pre-design*****:** This phase involves the development of a construction site logistics plan. The model at this stage has an adequate number of site elements containing material information needed to plan building operations and inform the choice of site equipment. Conflicts between the site model and models from other designers are also analysed at this stage (Trani *et al.*, 2016).

c) ***Detailed pre-design*****:** The main objective at this stage is to generate a final model for tender and construction works. The site planner exchanges information with the other designers about detailed technological choices, and generates a 4D work plan that manages operational information. The site planner can thereafter verify the feasibility of works in a more precise context and revert to the designers. The final CoSIM model containing all elements is then used to manage construction (Trani *et al.*, 2016).

2.4.4.2. Level of development for construction site design

The BIMForum (2020) website defines the Level of Development (LOD) Specification as "the reference that enables practitioners in the AEC industry to specify and articulate with a high level of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process". LOD depends on the information needed at various phases of design. Its purpose is to define the required information in order to meet the expectations of BIM operators at various stages of design (Cassano and Trani, 2017). The LOD requirements at two main phases of construction site design – i.e. construction site pre-design and construction site execution design are presented below.

a) ***Construction site pre-design*****:** This phase is implemented before tender, and its objective is to show the main needs on a construction site. Constructability issues based on the building design choices are also considered at this stage. The LOD at this stage should be accurate since these critical issues have significant impact on the entire process of site design. Moreover, the LOD of the CoSIM model should be high enough to facilitate the evaluation of safety and costs, and the generation of solutions if required (Trani *et al.*, 2015). The developed and detailed design have almost the same level of detail i.e. LOD 300/350. The developed phase describes the site layout in general while the detailed phase describes the layout of work zones (Cassano and Trani, 2017).

b) ***Construction site execution design*****:** This phase involves the implementation of the CoSIM pre-design. The elements prepared for this phase represent the 3D models of the actual equipment and facilities used at the construction site. The graphical and informational LOD should be detailed for each element. LOD 400 should be applied to facilitate the visualization of tasks, the examination of the feasibility of individual operations, and visual training for safety practices (Trani *et al.*, 2015; Cassano and Trani, 2017).

2.5. Optimization in construction site planning

Optimization entails finding the best solution to a problem while considering a specific objective(s). An optimization problem can be solved by maximizing or minimizing a function based on a given range of input values.

2.5.1. Fundamentals of optimization in construction

The study by Venkrbec *et al.* (2018) broadly classifies a range of optimisation problems in construction into two groups based on their optimization objectives, namely the resource-oriented optimization problems, and the layout and route-oriented optimization problems. These two are also the main domain of tasks during construction. The optimization procedure determines the optimum site layout that maximizes productivity, cost and safety of a project (Kim *et al.*, 2011; Zolfagharian and Irizarry, 2014).

2.5.1.1. Principles of optimization

The optimization methods can be categorised into three classes, namely mathematical, heuristic and metaheuristic. The three categories of optimization methods are briefly described below to improve an understanding of their principles. More information can be found in the literature (Fridgeirsson and Roslon, 2017; Farmakis and Chassiakos, 2018).

a) ***Mathematical (exact) methods*:** These are methods that are commonly used to find global optimum. Examples include the linear programming (LP), constraint programming (CP) and dynamic programming (DP). Their search for solution covers the whole solution space, and the solution is achieved by breaking down the problem into simpler parts. The drawback of this method however is the exponential increase in the number of optimum solutions with increase in variables (Papadaki and Chassiakos, 2016; Fridgeirsson and Roslon, 2017).

b) ***Heuristic methods*:** The heuristic methods offer a practical solution with no guarantee of an optimal solution, though it is sufficient for the goals under consideration. They can also yield good solutions with relatively less effort. Heuristic methods are often used to solve complex real-life problems in construction among other fields. They are problem-oriented methods and can be adapted to a particular problem. They can be used to determine sub-optimal solutions in a specific time duration, though the drawback at times as a result is that they fail to recognise the global optimum solution. Also, their complications increase with complex schedules. Moreover, this method does not guarantee an optimal solution to a particular problem. The categories of various heuristics discussed in the literature (Fridgeirsson and Roslon, 2017) include the decomposition methods, inductive methods, reduction methods, constructive methods and local search methods.

c) ***Metaheuristic methods*:** Metaheuristic methods are the most used in solving construction site layout planning problems (Oral *et al.*, 2018). They are problem independent techniques and can be applied to solve almost any optimisation problem. Metaheuristics explore the solution space more thoroughly and as a result find a better solution. However, they required some fine-tuning of the input parameters in order to apply the algorithms to the considered problem. Examples of these methods include: Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Genetic Algorithms (GA), and Simulated Annealing (SA), among others (Papadaki and Chassiakos, 2016; Fridgeirsson and Roslon, 2017)

2.5.1.2. Recent use of computational design for construction optimization

Various optimization techniques have been proposed or used for construction site planning in the recent past. Kim *et al*. (2011), for example, presented a methodology for optimizing the fabrication process of a caisson structure. In this method, a genetic algorithm (GA) was used to control the locations of construction equipment and prefabrication facilities. A virtual construction site layout was modelled using a software application based on the spatial information of the actual construction site and thereafter, the rules and constraints of the site were also modelled to reflect the conditions on site. Finally, a genetic algorithm was used to determine the optimum layout of the construction site. A similar study by Alan (2013) also used an optimization process by genetic algorithm to obtain an optimum solution for construction site planning problems.

In an extended construction site planning approach, Francis (2019) proposed a hybrid solution that was based on spatiotemporal techniques that combine graphical, procedural, and algorithmic aspects of optimization. By integrating construction site spaces and operations, this optimization technique performs beyond the commonly used algorithmic optimization approach. Cheng and Kumar (2014) presented an automated framework that could create a dynamic construction site layout model using BIM technology. The framework created a dynamic layout model for construction site optimization using information in the BIM models and the construction schedules. Their approach used a genetic algorithm heuristic method together with a custom-developed algorithm.

Metaheuristic methods have also been widely used to solve construction site planning problems. Oral *et al.* (2018) used a metaheuristic genetic algorithm – the multi-objective Particle Swarm Optimization – based on pareto dominance approach to mitigate construction safety risks in crane operated projects and minimize the travel distances between the temporary site facilities. Another study by Kaveh *et al.* (2018) used two meta-heuristic algorithms introduced in a previous work by Kaveh and Talatahari (2010). The algorithms optimised the site layout for different types of site space modelling. Their study then compared results with those of Particle Swarm Optimization (PSO), Charged System Search (CSS) and Magnetic Charged System Search (MCSS). Their results highlighted the capabilities of CSS and MCSS in solving the construction site layout problems.

Further comparisons are made in the work by Prayogo *et al.*, (2018) who compared the performance of Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC) and Symbiotic Organisms Search (SOS) algorithms in optimizing site layout problems. According to their results, the SOS outperformed the other two algorithms. Jahr and Barrmann (2017) developed an approach to automate the generation of facilities at a construction site. It mainly involved the identification and dimensioning of each site equipment. Their method used a 'knowledge-based system', which refers to computer programs that contain 'permanent knowledge' which can be structured in rules and facts. The programs employed methods from the field of artificial intelligence to solve complex tasks. Schwabe *et al.*, (2016) also presented an automated rule-based checking algorithm for site layout planning embedded in a commercial BIM platform.

These works highlight the evolution of the construction site planning process from the largely manual practices that rely on rule of thumb and experience of the construction site planner, to automated approaches that use computational methods. However, a gap that remains is a BIM-based standard framework that can be used to solve the construction site planning problems.

2.5.2. Optimization methods

Some of the optimization methods proposed by the various studies (some of them mentioned in Section 2.5.1) have been used by practitioners in the construction industry in the recent past. These include single-objective and multi-objective optimization techniques. Single-objective optimization entails optimizing one criterion at a time, e.g. minimizing project time while ignoring other objectives. The objectives of construction projects often conflict with each other, thus the single-objective optimization approach rarely offers practical solutions. This is because optimizing one criterion often adversely affects the other criteria that are not being optimized.

Tools have therefore been developed to efficiently plan and manage construction works and achieve anticipated objectives using multi-objective optimization approaches. The study by Alothaimeen and

Arditi (2019) compares some of the recent multi-objective optimization approaches as shown in Table 2.3, which were used to simultaneously optimize multiple objectives, ranging from two to seven.

Table 2.3: Comparison of optimization methods from recent studies (Alothaimeen and Arditi, 2019)

Optimization method	**Number of objectives**					
	2	**3**	**4**	**5**	**6**	**7**
Genetic algorithms (GA)	2	3	-	-	-	-
Differential evolution (DE)	1	3	-	-	-	-
Strength Pareto evolutionary algorithm (SPEA)	-	1	-	-	-	-
Non-dominated sorting genetic algorithm-II (NSGA-II)	8	6	-	-	-	-
Niched Pareto genetic algorithm (NPGA)	-	1	-	-	-	-
Multi-objective genetic algorithm (MOGA)	1	-	-	-	1	1
Particle swarm optimization (PSO)	3	3	-	2	-	-
Ant colony optimization (ACO)	1	-	-	-	-	-
Analytic network process (ANP)	-	-	1	-	-	-
Shuffled frog-leaping algorithm (SFLA)	-	1	-	-	-	-
Simulated annealing algorithm (SA)	1	-	-	-	-	-
Plant growth simulation algorithm (PGSA)	1	-	-	-	-	-
Hungarian algorithm (HA)	1	-	-	-	-	-
Mixed-integer nonlinear programming (MINLP)	2	-	-	-	-	-
Hybrid methods	6	6	-	-	-	-
Total	**27**	**24**	**1**	**2**	**1**	**1**

According to the reviewed studies, most methods optimised two or three objectives simultaneously. Also, the most used optimisation approach was NSGA-II, followed by the Hybrid method which pairs two or more approaches for the optimization process. In the study of 55 publications, the optimized objectives were distributed as shown in Table 2.4

Table 2.4: Distribution of optimized objectives in the studies (Alothaimeen and Arditi, 2019)

Optimization objective	**No. of times used**	**Percentage (%)**
Cost	51	93
Duration	23	42
Energy and environment	17	31
Resources	7	13
Safety	6	11

The two optimization methods mentioned above i.e. multi-objective optimization and single-objective optimization are discussed in the following sections.

2.5.2.1. Single-objective optimization

The single-objective optimization (SOO) approach selects one objective and finds the optimal solution according to it (Fridgeirsson and Roslon, 2017), for example minimizing project cost or maximizing the utilization of an equipment. The optimal solution is obtained by ignoring other factors, or by combining all the factors of the problem into one objective (Oral *et al.*, 2018; Vermeulen, 2019). It is however worth noting that both the global optimal solution and the local optimal solution - i.e. optimal solution in a subspace – may exist for an objective under consideration as illustrated in Figure 2.6 below.

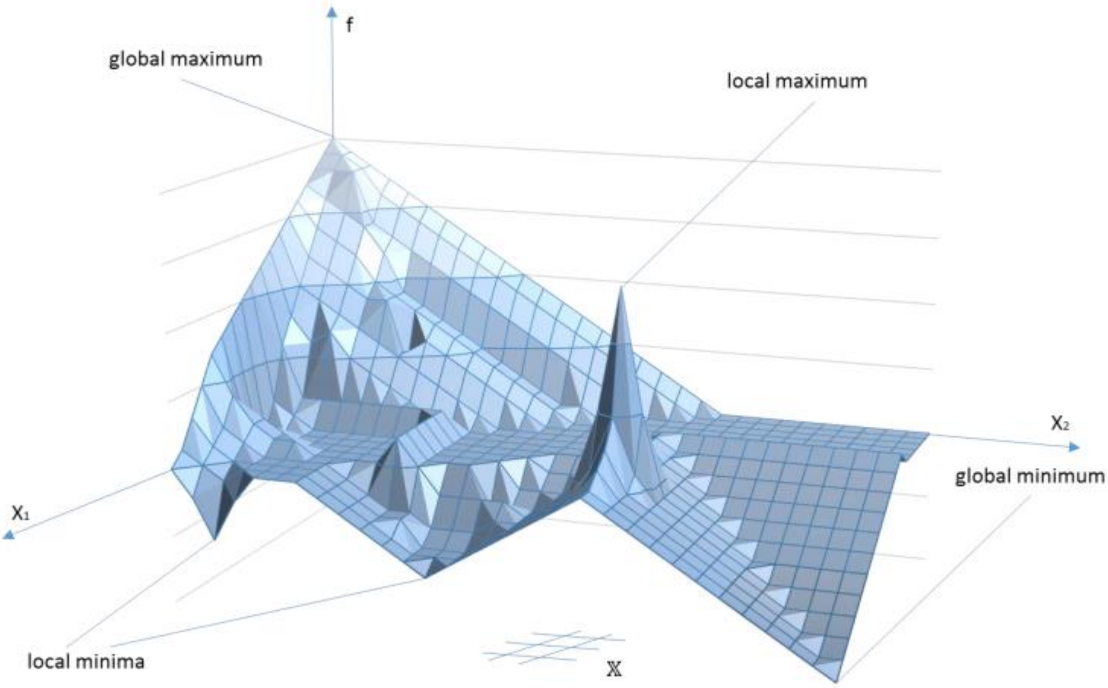

Figure 2.6: An illustration of local and global optimal solutions (Fridgeirsson and Roslon, 2017)

The single-objective optimization approach is however rarely used in the AEC industry since most optimization problems usually involve multiple competing objectives, some of which may be adversely affected if ignored (Papadaki and Chassiakos, 2016).

2.5.2.2. Multi-objective optimization

In the multi-objective optimization (MOO) approach, problems involving more than one objective/criterion are optimized concurrently. This approach is applied where an optimal decision is required and trade-offs can be made between two or more conflicting objectives, for example, maximizing storage while minimizing area of space (Fridgeirsson and Roslon, 2017; Vermeulen, 2019).

Many multi-objective optimization problems are nontrivial in nature. This implies that they lack a single solution that simultaneously optimizes each objective. The objective functions are thus considered to be conflicting, and there exists an infinite number of pareto optimal solutions. A solution is considered to be pareto optimal or non-dominated if an improvement of any objective function results in the degradation of other objective values. This is illustrated in Figure 2.7. A design in the pareto optimal set cannot be dominated by another solution (Fridgeirsson and Roslon, 2017; Oral *et al.*, 2018; Vermeulen, 2019).

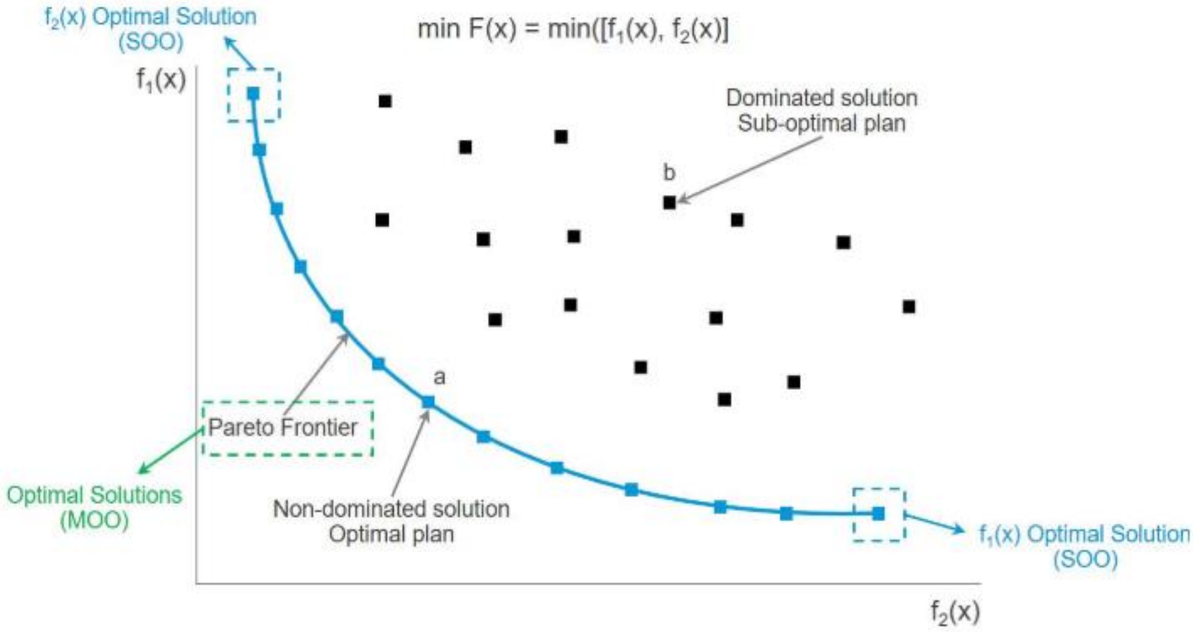

Figure 2.7: An illustration of pareto optimal solutions (Vermeulen, 2019)

The pareto frontier refers to the curve connecting the pareto optimal solution (see Figure 2.7 above). Decision making is usually based on the solutions on the pareto frontier.

2.5.3. Optimization techniques

The commonly used optimization techniques in the construction industry are the generative design, genetic algorithm, and brute force search. These techniques are presented in this section.

2.5.3.1. Generative design

Generative design is an iterative design process in which a computer program generates several outputs that meet certain rules and constraints. The designer thereafter refines the feasible region by altering the minimal and maximal values of an interval in which a variable meets the set of constraints, in order to reduce or augment the number of outputs to choose from (Vermeulen, 2019). Figure 2.8 below demonstrates the generative design process.

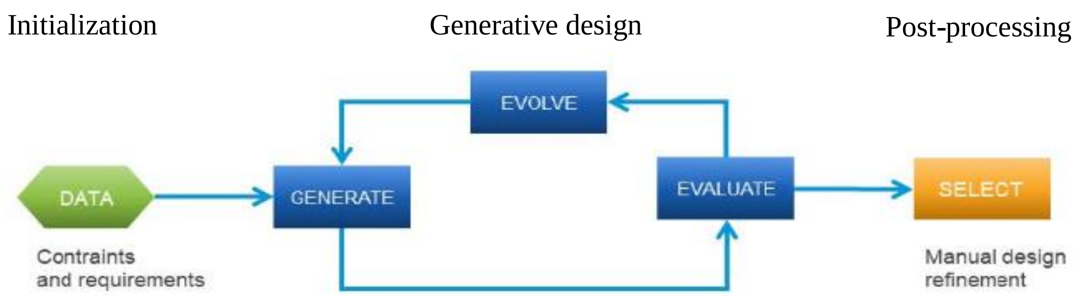

Figure 2.8: Generative design process (Vermeulen, 2019)

2.5.3.2. Genetic algorithms

Genetic algorithm (GA) is a search-based technique that uses the principles of natural selection. It is often used to obtain optimal or near optimal solutions to complex problems. GA is appropriate for solving multi-objective optimization problems since more pareto optimal solutions can be efficiently localized in a large solution space. The tools used in this technique utilize the NSGA-II evolutionary algorithm (El-Rayes and Khalafallah, 2005; Vermeulen, 2019). Examples of GA solutions in AEC workflows include optimized positions of construction equipment (Kim *et al*., 2011), optimized site layout plan (Alan, 2013; Kaveh *et al.*, 2018) and enhanced safety of workers on site (Oral *et al.*, 2018). Figure 2.9 shows a typical workflow in the GA process.

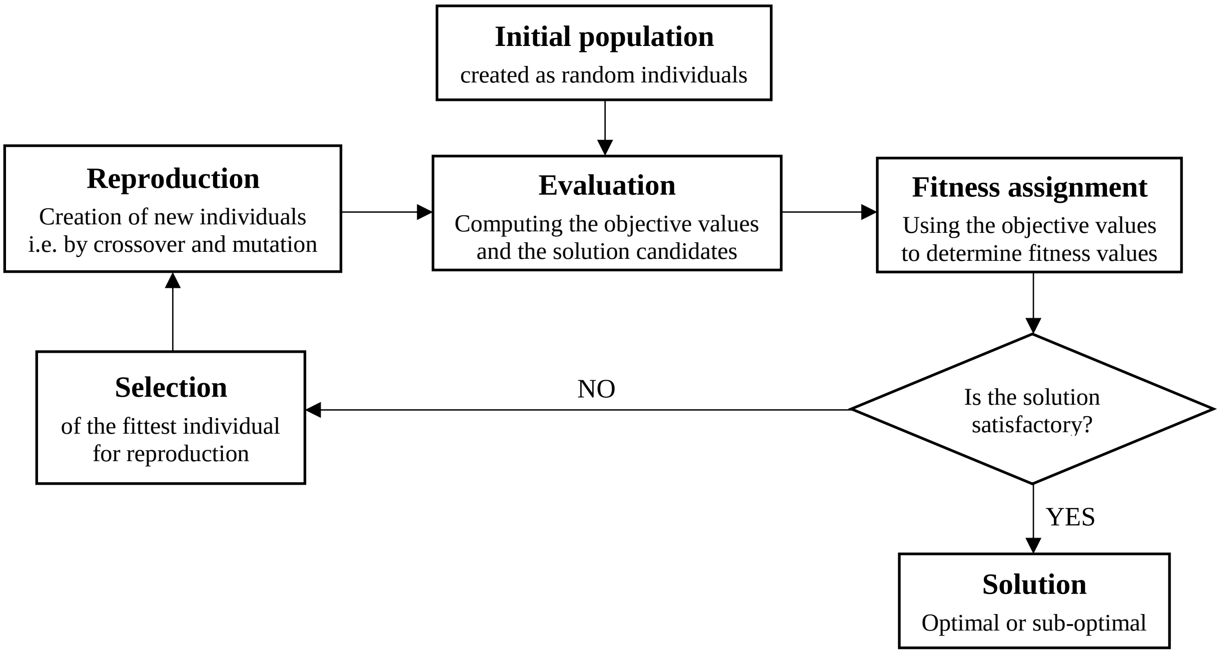

Figure 2.9: GA principles and typical workflow in the GA process (Fridgeirsson and Roslon, 2017)

a) ***Initialization*:** The initialization stage involves defining the population size, which relies on the nature of the problem. The population contains a set of possible solutions and is generated randomly. At times, the solution may be ‘seeded’ in areas where the optimal solution is expected to be found (El-Rayes and Khalafallah, 2005; Fridgeirsson and Roslon, 2017; Vermeulen, 2019).

b) ***Selection*:** For each successive generation, a part of the existing population is selected to breed a new generation. Fitter solutions – as determined by the fitness function – are selected from the solutions through a fitness-based process. The fitness function is always problem dependent, and it measures the quality of the represented solution (El-Rayes and Khalafallah, 2005; Fridgeirsson and Roslon, 2017; Vermeulen, 2019).

c) ***Genetic operators*:** A second generation population of solutions is thereafter generated from those selected through a combination of genetic operators i.e. crossover and mutation. A pair of ‘parent’ solutions are chosen from the initial selection for breeding. The ‘child’ solution is created which typically contains characteristics of the ‘parents’. The process continues as a new population of solutions is generated. This procedure improves the average fitness of the subsequent population. The generation process is terminated when: (i) a solution satisfying minimum criteria has been obtained, (ii) the fixed number of generations has been reached, (iii) the highest-ranking fitness has been achieved (El-Rayes and Khalafallah, 2005; Fridgeirsson and Roslon, 2017; Vermeulen, 2019).

2.5.3.3. Brute-force search

The brute-force or exhaustive search is a technique that systematically enumerates and scrutinizes all possible candidates for the solution. It is simpler to implement and an existent solution to the computational problem is guaranteed. However, it is slow and generally inefficient for practical problems with huge solution space (Peroni, 2018; Vermeulen, 2019). Thus, the effectiveness of this approach is limited to computational problems that are small.

2.5.4. BIM-based construction site optimization

The generative BIM technology often uses the optimization technique to facilitate the generation of multiple design alternatives in the construction industry. Starting with the desired outcome, a range of design possibilities can be explored and optimal designs produced promptly (Galić *et al.*, 2015; Vermeulen, 2019). Through optimization, multiple options, ideas and scenarios can be generated rapidly, thus quickly exploring design options.

Few studies in the recent past establish the connection between optimization and BIM. The review by Venkrbec *et al.* (2018) for example, summarises the BIM methods, models and tools applied for various optimization problems. Some of the tools highlighted include expert systems such as the geographical information system (GIS) Arc/Info, computer-aided design packages and other custom programs for specific tasks in site planning. Methods that employ genetic algorithms have also been widely utilised to solve problems such as construction site layout planning, location of cranes and facilities, and minimization of transportation costs. For most of these studies, the process of analysis was based on BIM generated data.

2.6. Closure

A state of the art of construction site planning and optimization in the AEC industry has been presented in this chapter, with focus on implementation during the preliminary design phase of a construction project. The use of BIM to assist construction site planners in site layout configuration, 4D simulation and management of health and safety have also been covered to highlight the BIM perspective and the important role it plays in construction site planning. In addition, optimization methods commonly applied in the BIM environment are presented. The purpose of these discussions is to assist in making procedural decisions in the next chapter. They provide a basis for the following:

i) Development of Dynamo workflow scripts in Chapter 3 that will seek to solve construction site optimization problems.
ii) A better understanding of optimization principles and process for a more informed application in the experimental scripts.
iii) A better definition of construction site rules and constraints, and formulation of the site problems to be solved.
iv) Application of the proposed solutions to the case study in Chapter 4.

CHAPTER 3. THEORETICAL BASIS AND METHODOLOGY OF SOLUTIONS

3.1. Introduction

The process of construction is dynamic. This implies a continuous evolution of the building or infrastructure during its construction. In addition, changes in logistics, required machineries, labour and resource allocation, among other elements, are anticipated as construction progresses. A dynamic construction site plan is therefore needed to cope with these changes. The complex and dynamic nature of the construction process can be efficiently managed by developing a dynamic construction site plan during the initial design phase of a construction project when the construction site is being planned.

This chapter presents the theoretical basis and methodology of the proposed computational design solutions to some of the problems experienced during the construction site planning process. Design experiments were performed on an abstract site BIM model using the Dynamo software and Artificial Intelligence (AI), with the purpose of managing the complex and dynamic nature of construction. The optimization of construction site elements such as spatial configuration, positions of tower cranes, safety distances around machineries and areas of risk, flow of materials within the construction site and the shortest path between locations are explored in this chapter.

3.2. Requirements for computational design solutions

The preliminary step in obtaining the computational design solutions was to define the problem to be solved. Thereafter, the required construction site elements and facilities were identified and then their sizes and dimensions determined. The anticipated construction site logistics also played a key role in determining the site configuration and equipment. The construction site layout plan was then generated by placing the equipment and facilities on the available spaces in accordance with the prevailing site rules and constraints.

3.2.1. Problem definition

The main aim of this study was to investigate the potential and feasibility of applying the computational design method in planning the construction site. The focus was on adopting the method during the project planning stage. Generative scripts that can be used to plan and optimize the construction site were developed using the Dynamo tool by following the workflow illustrated in Section 3.3.3, in order to solve problems that were related to spatial allocations, positioning of facilities and equipment, material flows and vehicle movement, and safety on site. The construction site rules, constraints and relationships between various parameters were defined to perform the following:

i) Configure the construction site i.e. set the site boundary; allocate facilities and spaces within the construction site based on adjacency needs, and model the site roads or paths.

ii) Manage safety on site by demarcating safety distances and zones e.g. around excavations, machineries and the building under construction.

iii) Assess the manoeuvrability of the site vehicles e.g. trucks and manage accessibility between site facilities and spaces.

iv) Optimize the positions of multiple tower cranes in order to achieve maximum coverage of the building under construction and the building materials, with minimum conflicts.

v) Coordinate and optimize the flow of materials and movement of workers by establishing manoeuvrable and shortest routes within the construction site.

3.2.2. Input data and objects

In this experiment, an abstract construction site model was created and then used to develop the Dynamo scripts. Inputs to the Dynamo scripts from the abstract BIM model consisted of the site boundary, building elements, site excavations, and site machineries e.g. cranes and trucks. In addition, spatial and crane data was extracted from Excel tables by the Dynamo scripts. Detailed information about the inputs used in this experiment are presented in Section 3.4.1.

In other cases where a BIM model of the existing construction site situation needs to be modelled, the data required will include.

i) Images and descriptions about the construction site
ii) Existing site plans and program of works
iii) Existing BIM models of buildings and facilities on site
iv) List of zones or spaces making up the site
v) Construction equipment and facilities on site, and their descriptions
vi) Required sizes and adjacency of spaces on site
vii) Flows for people and construction materials i.e. both horizontal and vertical
viii) Safety distances to excavations, risky equipment and buildings under construction

3.2.3. Design tools

The Dynamo software and the Dynamo third-party packages were the tools used for computational design together with Autodesk Revit as the BIM authoring tool to generate the solutions in this study.

a) Autodesk Revit

Autodesk Revit (version 2020) was the BIM authoring tool that was used to model the abstract construction site. The parametric objects representing site equipment or facilities such as tower cranes, trucks and excavators were also created or had been existing as Revit objects. Also, Revit was the platform for visualizing updated optimized results.

b) Dynamo

The Dynamo application was used for generative design of the site through scripting, and for optimization. The rules and constraints that define relationships were established through visual scripting. These rules, constraints and relationships were organised into algorithms, defined as a set of instructions that can be followed to solve a problem. In Dynamo, the sequence of instructions is organized using blocks known as ‘Nodes’ while the predefined tasks are joined sequentially using ‘Connectors’ as shown in Figure 3.1. Intermediate human readable languages such as Python facilitate the computer’s understanding of the algorithms in to execute a task (Serra and Hage, 2020).

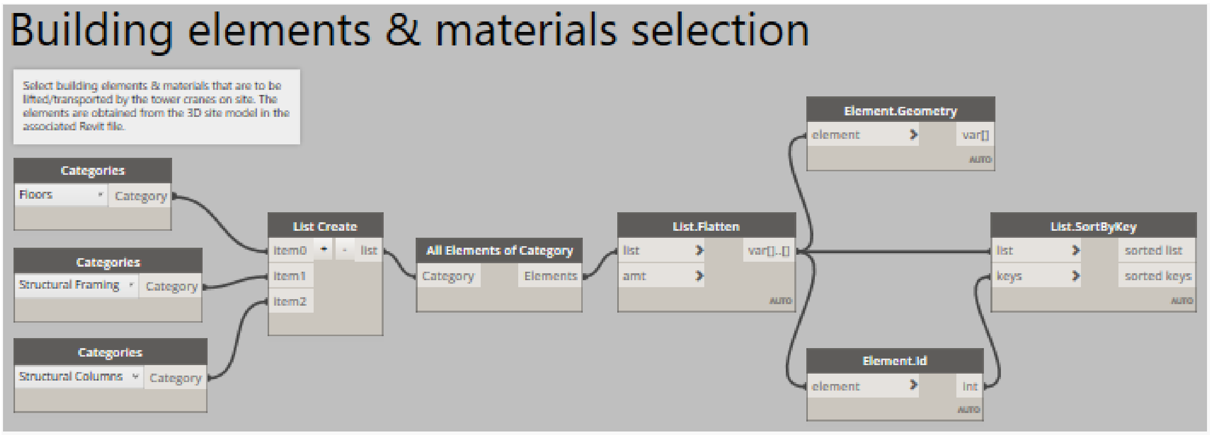

Figure 3.1: Nodes and Connectors from Dynamo script

c) Dynamo packages

This study used third-party Dynamo packages listed in Table 3.1 below, which are available in the Autodesk Revit Online Package repository.

Table 3.1: Details of the Dynamo packages used in this study

Dynamo package	Version	Website	Accessed
DynaShape	0.6.1.0	forum.dynamobim.com/t/dynashape/11666	14/07/2020
BIM4Struc.CraneAnalysis	2.0.0	www.autodesk.com/autodesk-university/class/Construction-Dynamoite-Explode-Productivity-Dynamo-2016	05/07/2020
Refinery Toolkit for Space Planning	2.0.1	-	22/07/2020
Dynamo Text	1.0.0	dynamobim.org/	16/07/2020

A brief description of the packages listed in the table is presented below. Illustrations of the processes and use of the packages are presented in Section 3.5.

i) ***DynaShape (version 0.6.1.0)***: an open-source package for constraint-based form finding and optimization. DynaShape tool is a generative Dynamo extension developed by the Dynamo Team (2019). It uses computational design power to address space planning problems using a combination of *bubble diagram*[1] and algorithms for geometric constraint. This combination can

[1] A diagram that comprises circles/ellipses that represent spaces, often used by architects and urban planners to sketch up space variations for a space planning problem. The size of each circle/ellipse is approximately proportional to the area of space.

be used to generate and optimize a space plan based on space entities and their inter-relationships.

ii) ***BIM4Struc.CraneAnalysis (version 2.0.0)*****:** a tool for analysing the position of tower cranes developed by Vermeulen (2019). It contains a custom node that analyses the building elements to be lifted by the crane according to the set requirements, then sorts the elements based on *Lift Status Values*[1].

iii) ***Refinery Toolkit for Space Planning (version 1.0.0)*****:** a package used in generative space planning workflows. It can be used to analyse and return the shortest path between points while considering the existing obstacles.

iv) ***Dynamo Text (version 2.0.1)*****:** a package that is used to create text in Dynamo from a list of *strings*[2] and their corresponding positions.

3.3. System set-up and workflow

The set-up for methodology of the proposed solutions, the definition of site rules, constraints and relationships, and the computational design workflow followed to arrive at the solutions are discussed in the following subsections.

3.3.1. System set-up

The solution set-up of the system was divided into two main phases as shown in Figure 3.2.

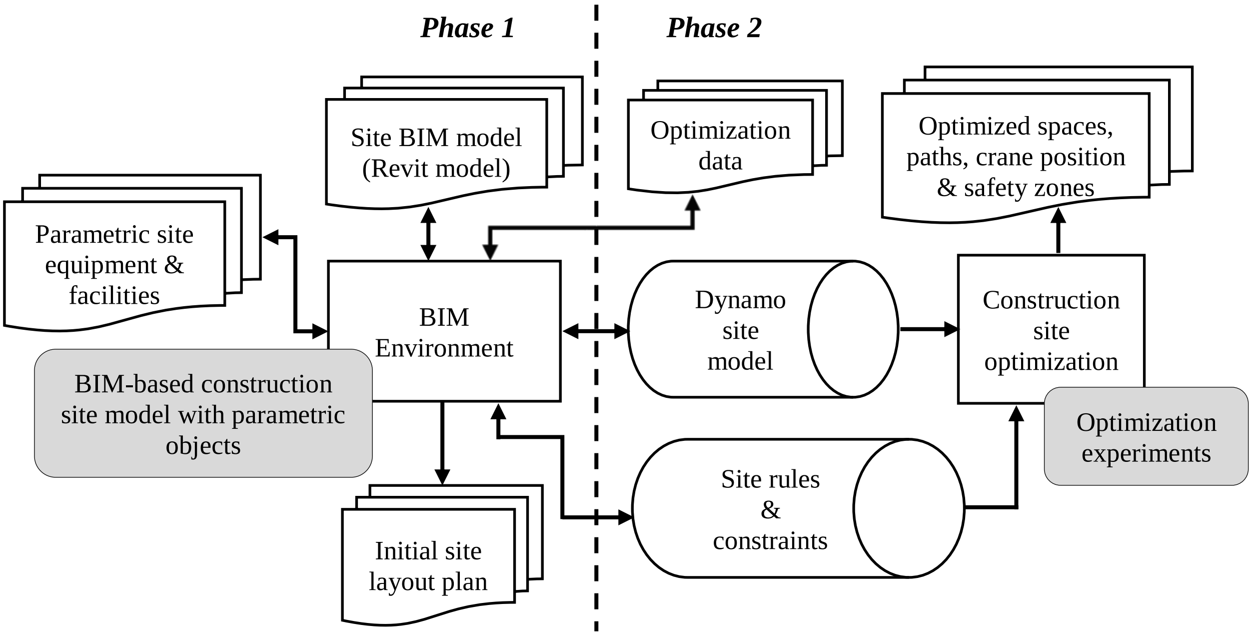

Figure 3.2: A schematic of the system set-up

[1] A value assigned to each element, which determines its capability to be lifted based on its weight and distance to the tower crane.

[2] Data type used to represent text.

Phase one comprised a BIM-based generation of a 3D site plan in Revit. The sub-tasks in this phase included: (i) the modelling or obtaining of site geometry, elements, boundaries and parametric site objects, and (ii) the identification of risky areas e.g. deep excavations and machineries. The object parameters such as density of building elements were also assigned in this phase.

Phase two comprised the optimization of the site BIM model in Dynamo. Input data was extracted from Excel tables and the Revit model from Phase one. The data included site geometry and objects/equipment, building elements, site spaces data tables, and crane capacity data tables. The parameters of the building elements were automatically read by the script from the BIM environment. The script thereafter generated optimized solutions according to the defined rules and constraints. Based on the generated optimized solutions, the safety zones could be identified, the site spaces could be efficiently located, and the site roads, facilities and equipment placed at optimum positions.

3.3.2. Definition of site rules and constraints

The site rules were determined by the quantifiable metrics such as safety distances, facilities and equipment positions, spatial plan and location of site road/paths. In this study, this information was conceptual and for experimental purpose. However, for an actual construction site, this information may be obtained from internal company documentations or from the relevant codes at industry level. The site constraints, on the other hand, are the invariable site factors e.g. site boundary, size and position of the building under construction, and the construction site area. Table 3.2 shows the attributes of the construction site equipment and facilities implemented as rules and constraints in this experiment.

Table 3.2: Attributes of site equipment and facilities implemented as rules and constraints

Site equipment or facility	Attributes (Input parameters)
Constraints	
Site boundary (fixed)	Coordinate points at corners, enclosed area (site acreage)
Building under construction (unavailable space)	Position of the building, area occupied by the structure, scaffold area around the building
Rules	
Tower crane	Crane capacity (loads at different ranges), jib length, crane position, reach, *crane base host area*[1]
Crane base host area	Position on site, surface area
Site machinery e.g. excavators and trucks	Point of location on site, safety distance/radius
Storage spaces	Size (length and width), space position, adjacency requirements
Site roads and paths	Width, curvature at bends, length, accessibility needs, material flows
Temporary works and installations	Safety distances or zones around areas such as excavations, scaffolding area

[1] The area or platform within which the base of the tower crane is to be installed

Further information about the site rules and constraints considered in this study follows below.

i) ***Property boundary*****:** The property or site boundary is a constraint that defines the extents within which modelling and optimization of space and equipment can be implemented. In Dynamo scripting, the boundary is modelled by joining corner points imported from the Revit site model. Alternatively, 'Property Line' defining the boundary in Revit can be imported as a family in Dynamo.

ii) ***Space layout*****:** Site space layout is a variable that relates to the configuration of spaces/zones within the boundary for maximum productivity and efficiency. In most cases, the aim is to minimize storage spaces and maximise workspace. Logistics and procedures are often considered when making decisions on locations and adjacency of spaces. For example, the construction materials/elements storage yards ought to be efficient enough to avoid relocations, and within the reach of cranes. Also, the construction materials/elements should be near the workspace, and should not impede flows on site.

iii) ***Location of site roads*****:** The position, size and length of the site road(s) on site is important for site logistics e.g. the management of the flow of building materials and workers, and the general accessibility within the site. The objective is to reduce the travel or flow path, and to determine the best route that will enhance accessibility with minimum interference.

iii) ***Safety distances and zones*****:** Safe distances to risky areas e.g. deep excavations, and equipment that can inflict injuries is crucial for productivity among construction workers. The type of barriers and the minimum safety distances depends on the level of risk posed.

iv) ***Site equipment and facilities*****:** The management of site equipment and facilities involves determining appropriate locations for their maximum and efficient utilization. Details of construction equipment e.g. dimensions, technical and cost related data are vital for BIM modelling. The facilities should be sufficient, easily accessible, and efficiently positioned. For example, the site office and other facilities for human residency should be located away from excessive noise and dust, and at safe locations with enough space and adequate access.

v) ***Crane operation areas and distances*****:** Maximum utilization of tower cranes implies maximum coverage of the main construction and the building material stockpiling areas. This ought to be implemented within the crane capacity i.e. range and load capacities.

vi) ***Temporary installations*****:** Temporary installations such as scaffolds and safety barriers are key to safety on site. They boost workers' confidence in view of safety and thus contribute to increased productivity.

3.3.3. Computational design workflow

The preliminary tasks in computational design of a construction site include coordinating the building model, the terrain model and logistical requirements in order to set the base for site planning. Thereafter, the site planning activities follow, which include collecting data e.g. spatial and crane capacity data and building elements. The collected data is then used in the Dynamo script to automate the BIM model, which is later optimized. The flowchart in Figure 3.3 illustrates the computational design workflow adopted in this study.

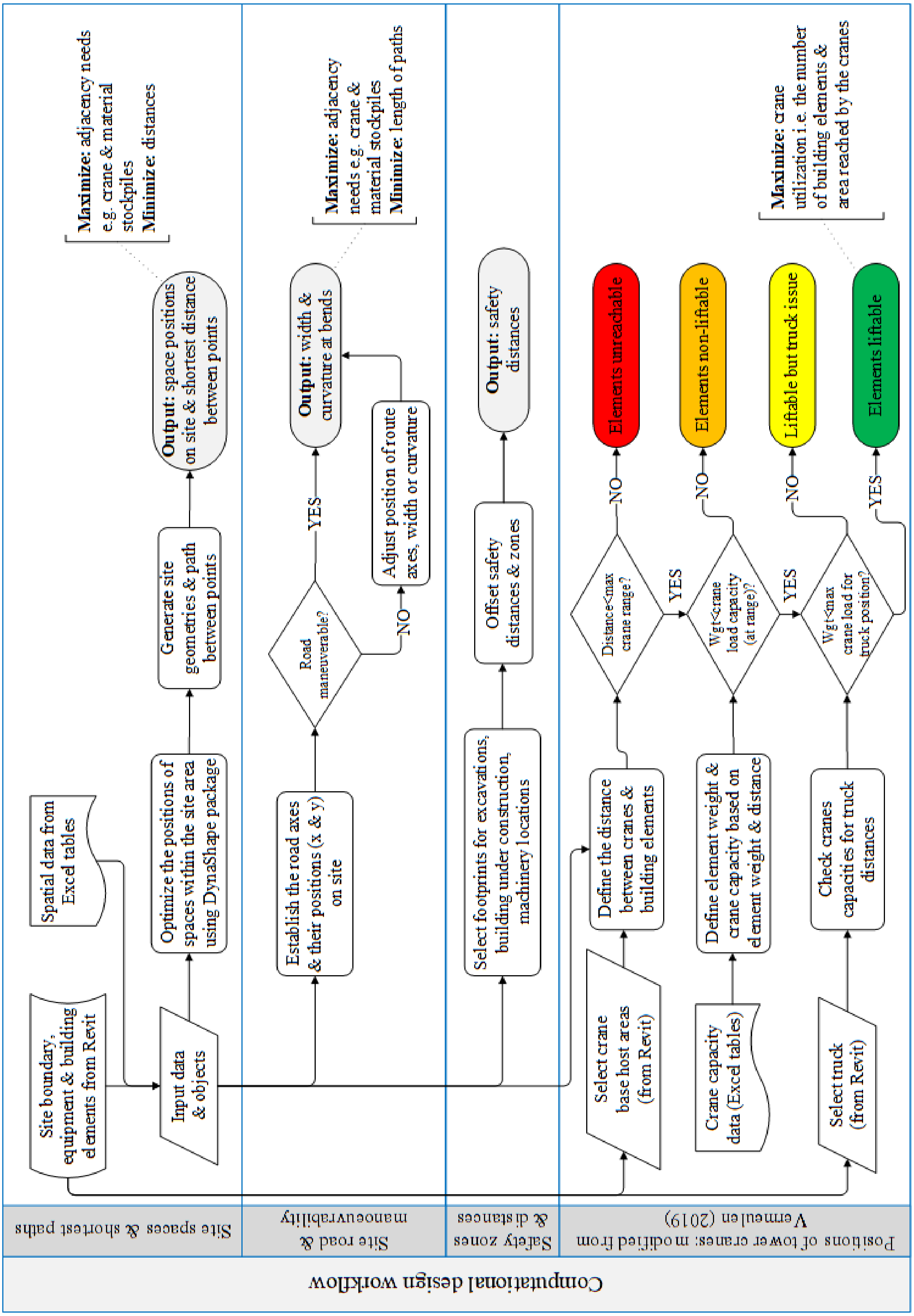

Figure 3.3::Computational design workflow

3.4. Computational solution process

Figure 3.4 illustrates the computational design process adopted in the experiments.

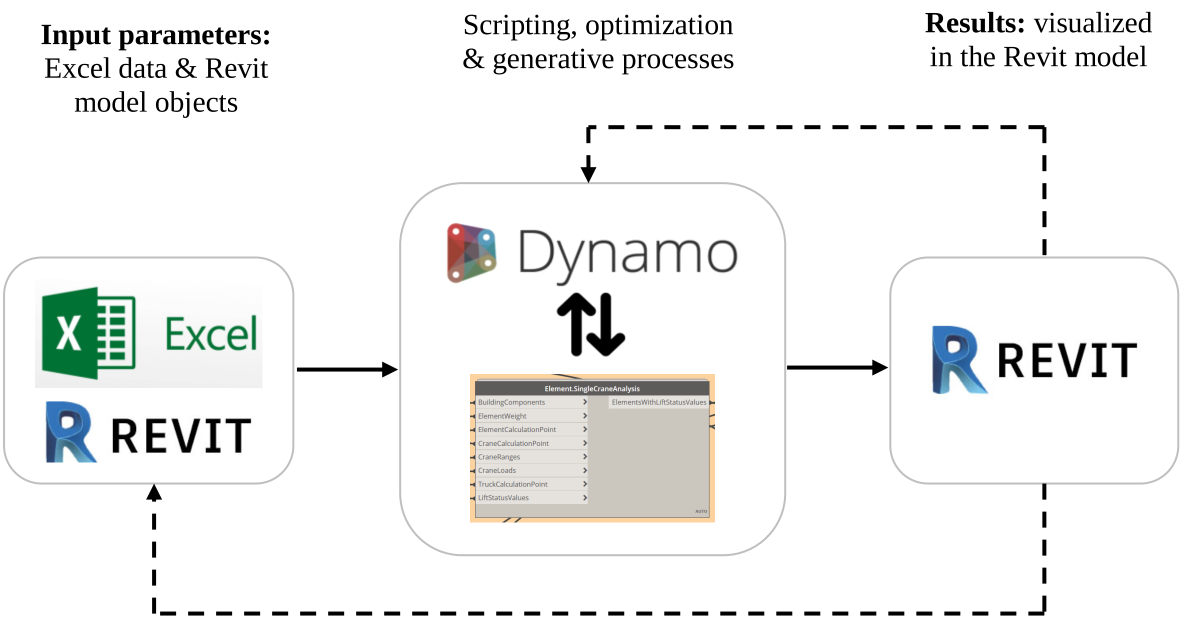

Figure 3.4: An illustration of the computational design solution process

Comprehensive illustrations and details of the design process are given in the sections that follow.

3.4.1. Input and initialization

As illustrated in Figure 3.4 above, the Dynamo scripts extract data from the Excel tables and also from the construction site BIM model. The input of data and initialization of parameters in the Dynamo scripts is enabled by the functionalities that:

i) Select objects directly from the construction site BIM model or based on property or class e.g. elements of the same family type
ii) Obtain property and associated metadata or parameter values of objects in the construction site BIM model
iii) Update the site BIM model and also the type property or parameter values

Table 3.3 summarises the data and parameters that are extracted from the Revit BIM model and the Excel data tables.

Table 3.3: Information obtained from the Revit BIM model and Excel tables

Source	Site information category	Information
Revit BIM model	Construction site area	Site boundary, site area (acreage)
	Planned construction (building)	Building footprint, position on site (area), building elements, area of construction
	Building elements	Density, volume, distance between each element and the crane
	Excavations	Excavation footprint, position on site (area)
	Site machinery e.g. tower cranes, trucks and excavators	Locations on site (coordinate points)
	Crane base host area	Surface area, location on site
Excel data tables	Spatial data	Space/facility IDs, names, sizes, adjacency requirements and departments
	Crane capacity data	Crane capacity i.e. crane loads at different jib ranges

3.4.2. Analysis and optimization

After the initialization of parameters, the Dynamo scripts are then run to generate optimized solutions. Optimization is largely implemented by specific nodes from the third-party Dynamo packages. The Dynamo nodes were used to analyse and optimize the following:

i) The positions of multiple cranes
ii) Manoeuvrability of site vehicles such as trucks on the site road
iii) Site spatial configuration
iv) The shortest route between locations

3.4.3. Results output and visualization

The optimized results are finally displayed on the generated model in the background 3D preview navigation workspace in Dynamo and updated on the Revit site model. For a more refined and/or practical output, manual adjustments may be required in the Revit site model and/or in the Dynamo scripts, and the process repeated. It is important to note that human input/intervention may also be needed to obtain the best solution among the generated options.

3.5. Proposed computational design solutions

The computational techniques applied to the design workflow comprises defining and scripting the entire process through which an object is created, instead of simply modelling the fixed shape of the object. This technique not only enhances design flexibility but also significantly reduces the time needed to explore other design options.

The computational design method adopted was based on algorithms[1] that use the power of the computer to execute tasks. The design process involved the expression of parameters, rules and constraints that collectively define the relationship between the design intent and outcome (see Section 3.3.2 for the defined site rules, constraints and relationships).

3.5.1. Construction site configuration

The construction site configuration involved the organization and management of the spatial plan layout, installation of site facilities and equipment, and the design of site roads within the construction site boundary.

3.5.1.1. Construction site boundary

The construction site boundary was scripted in Dynamo using the polygon coordinate points – i.e. corner points of the site geometry in the Revit BIM model. Alternatively, the site boundary can be scripted using the *Property Line*[2] feature created in the Revit BIM model. Figure 3.5 shows the Dynamo script with the site boundary output.

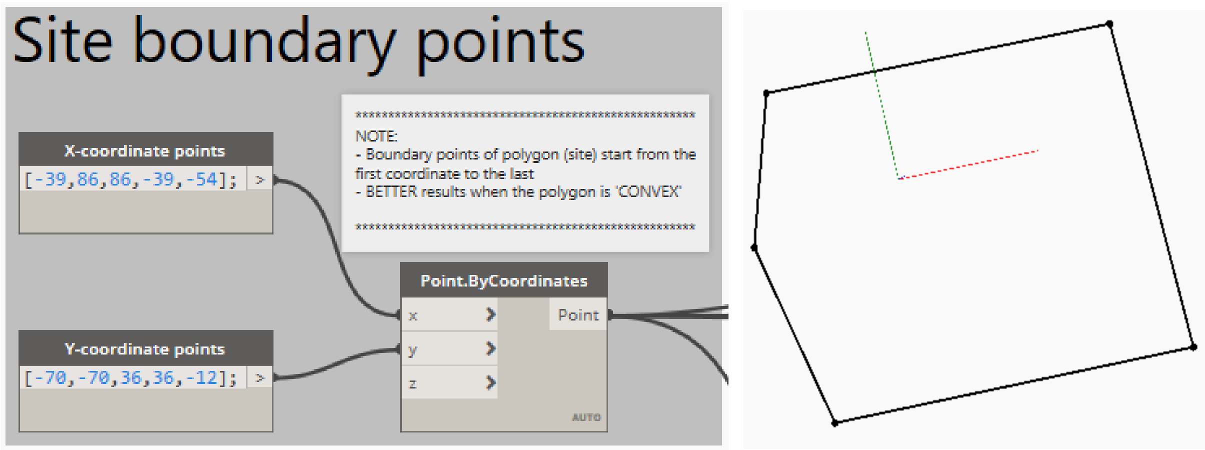

Figure 3.5: Input for construction site boundary

The site boundary line was created by joining the coordinate points of the corners of the polygon (construction site geometry). The shape of the construction site geometry determines the number of points to be input in the Dynamo scripts.

3.5.1.2. Spatial plan layout

The spatial plan was generated using the *DynaShape* package (Dynamo Team, 2019) by arranging the site spaces within the construction site boundary. The spatial data that was required to generate the construction site layout plan was retrieved from an Excel table organized as shown in Table 3.4.

[1] A defined process and set of rules followed in order to solve a problem.

[2] Add property line from the *Massing & Site* tab in Revit ► *Modify Site* panel ► *Property Line*

Table 3.4: Organization of spatial data in an Excel table

Space ID	Space or Facility	Department	Department ID	Quantity	Width (m)	Height (m)	Area (m^2)	Total Area (m^2)	Preference	Adjacent Spaces
0	Building under construction	Construction	0	1	65	57	5000	5000	1	3.4.9
1	Site office & meeting room	Management	1	1	10	10	150	150	2	0
2	Sanitary rooms	Waste	2	1	10	10	150	150	3	0
3	Crane area A	Construction	0	1	10	10	250	250	1	0.5.9
4	Crane area B	Construction	0	1	10	10	250	250	1	0.7.8
5	Fabricating workshop	Fabrication	3	1	10	10	400	400	4	
6	Equipment store	Storage	4	1	10	10	400	400	5	0
7	Batch plant	Construction	0	1	10	10	800	800	1	10.8
8	Material stockpiling	Storage	4	2	10	10	1000	2000	5	
9	Scaffold and formwork yard	Storage	4	1	10	10	800	800	5	
10	Cement silo	Storage	4	1	10	10	300	300	5	
11	Waste holding area	Waste	2	1	10	10	1500	1500	3	0

The facilities and spaces on site were represented by circles (also known as bubbles) organized on a plane as shown in Figure 3.6, with their sizes roughly matching the actual areas of the represented spaces and facilities.

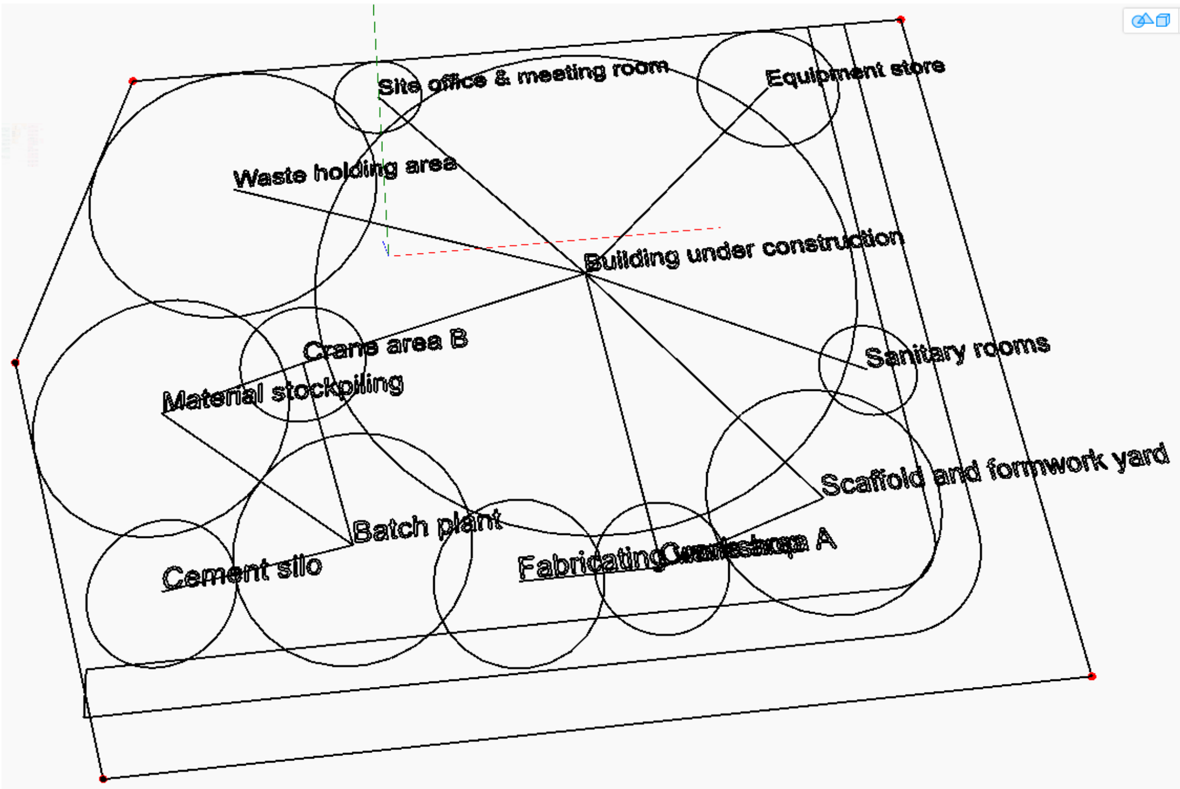

Figure 3.6: Site spaces and facilities represented by circles within the site boundary

The lines joining the centres of the circles indicate the adjacency relationships as defined in Table 3.4 in the 'Adjacent Spaces' field. The space circles and the adjacency relationships are generated by the *Engine.Execute*[1] node in Dynamo as shown in Figure 3.7.

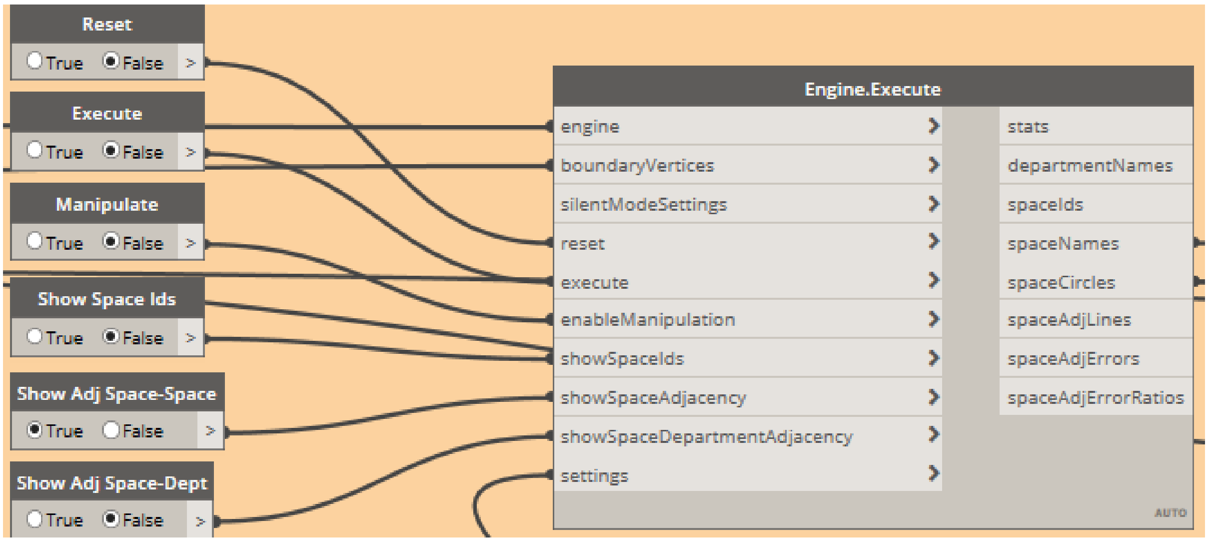

Figure 3.7: The *Engine.Execute* node for generating space circles

The set of instructions for running the *DynaShape* engine are provided on the package developers' webpage (Dynamo Team, 2019), though a summarized set of directions as implemented in this study are as follows:

i) Set the *Reset* node to 'True' to initialize the engine based on the space specifications from the Excel table. Reset it to 'False'.

ii) Set the *Execute* node to 'True' to enable the free movement of the circles. Also, set the *Manipulate* node to 'True' to facilitate the manipulation of the spaces by dragging them around while in the background viewport mode.

iii) Repeat the procedure to run the engine again. At this stage, the Dynamo geometries are not yet generated. Set the *Execute* node to 'False' to pause the engine and generate Dynamo geometries.

The advanced settings parameters can be used to improve the results. More information about manipulating the advanced settings can be found on the Dynamo Team (2019) website. It is worth noting that the *Engine.Execute* node generates better results when the geometry of the polygon is *Convex*[2]. However, if the construction site geometry is not convex, some points may be ignored or adjusted slightly while still maintaining the general shape of the polygon in order to create a convex polygon just for the purpose of spatial planning. Though the Dynamo geometry may be inaccurate, the *Engine.Execute* node will generate better results which can be refined at a later stage.

[1] A node from the DynaShape package, used to generate space circles

[2] A convex polygon curves outward such as in a circle

3.5.1.3. Construction site facilities and spaces

The site elements and geometries in the background 3D preview navigation work screen in Dynamo were generated from the Excel data table and also imported from the Revit site model. The geometries from the Excel data table were simple extrusions of shapes of the dimensions given in Table 3.4, and their main purpose was to roughly represent the site spaces and facilities. The geometries imported from the Revit site model were families of construction elements such as structural columns, beams and site machinery e.g. tower cranes. Figure 3.8 shows the Dynamo geometries of some of the site facilities, spaces and equipment generated by the Dynamo script.

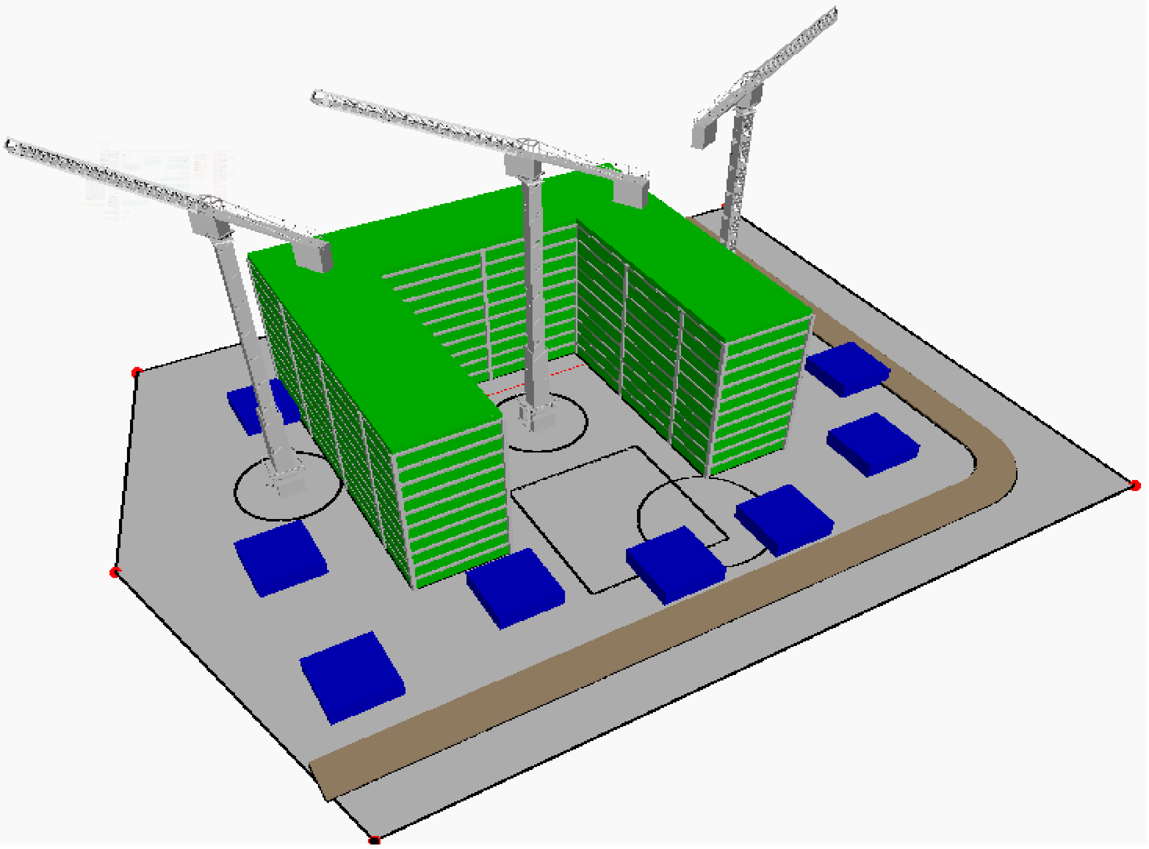

Figure 3.8: Site elements and geometries generated by the Dynamo script

Some site machineries such as excavators were represented by instance points that would be used later to generate safety distances/radius. Also, the instance point for trucks would be used to simulate the movement of trucks so as to manage vehicle manoeuvrability.

3.5.1.4. Site road

The parameters used to generate the road at the construction site were the route axis positions, road width and the degree of curvature at bend as shown in Figure 3.9.

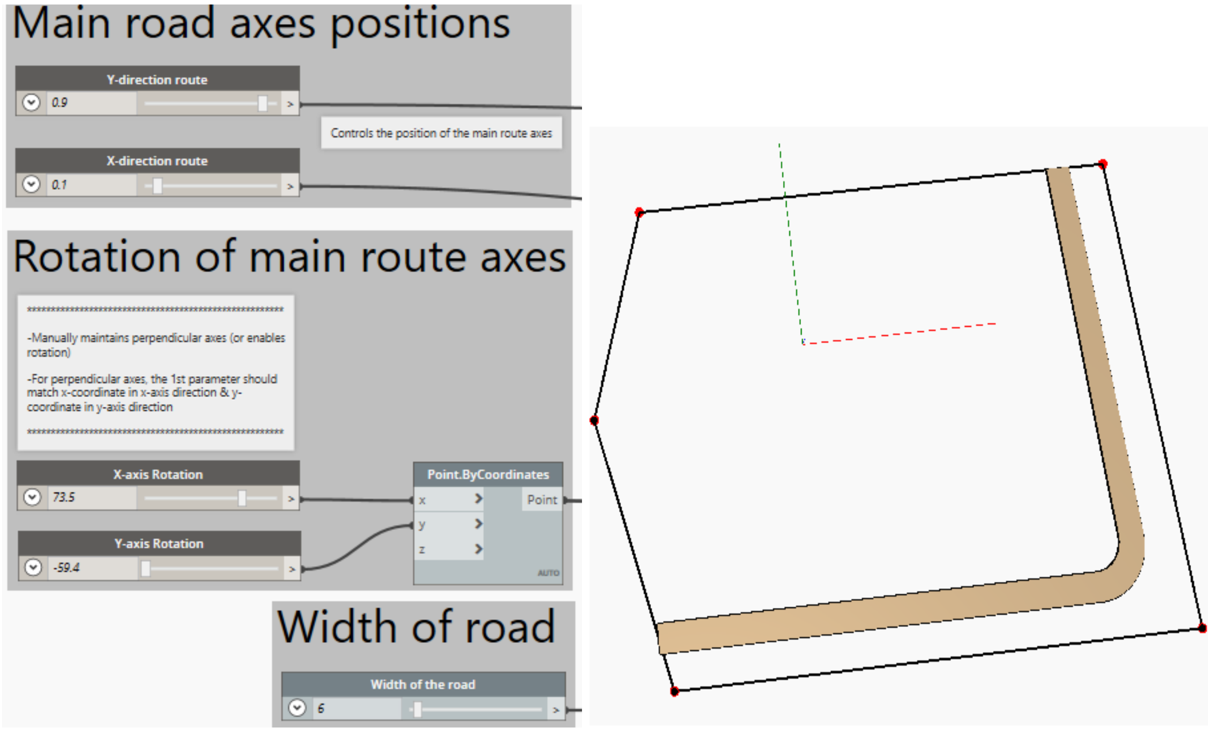

Figure 3.9: Input parameters for the site road

The positions of the horizontal and vertical sections of the road can be moved by adjusting the axes parameters. The axes can also be rotated to change the orientation of a section of the site road.

3.5.2. Manoeuvrability of site vehicles

Easy manoeuvrability of site vehicles facilitates accessibility to site spaces and facilities, and also the efficient movement of building materials within the construction site. The Dynamo script contained a parameter for the degree of curvature with values that vary from 2 to 10 as illustrated in Figure 3.10. This parameter was used to manage the vehicle manoeuvrability on the site road.

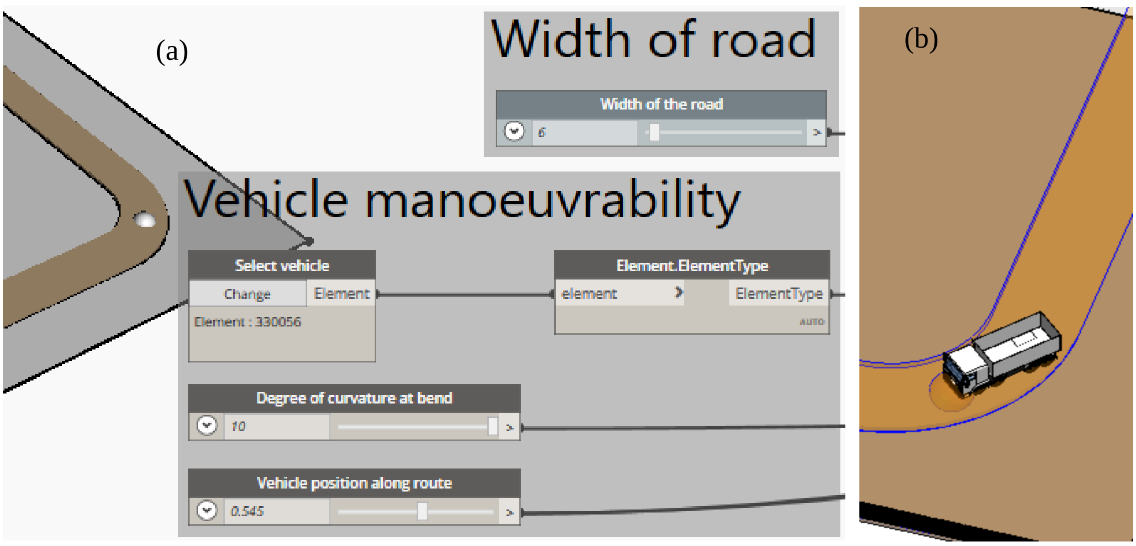

Figure 3.10: (a) Input parameters for vehicle manoeuvrability, (b) visualization in the Revit model

For the degree of curvature at bends, the minimum curvature is obtained when the parameter is close to 2, whereas the curvature is maximum when the parameter is close to 10.

3.5.3. Optimization of the positions of tower cranes

An efficient location of tower cranes at a construction site ensures maximum reach to the building elements and materials without exceeding their lifting capacities. Moreover, it helps to minimize or eliminate potential conflicts among the tower cranes. The crane optimization results can be used to foresee potential hoisting problems and also eliminate the need for future relocations of materials and site facilities, thus saving project time and costs.

In this study, the *BIM4Struc.CraneAnalysis* package was used to optimize the locations of multiple tower cranes at the construction site. The aim was to achieve maximum reach to building elements and materials while considering two main constraints i.e. the lifting capacities of the cranes, and crane base host areas. A summary of the optimization procedure for multiple cranes that was adopted in this study is described below. Detailed procedures and additional information on the use of the Dynamo package can be found in the literature (Vermeulen, 2019).

a) Method description

The optimization method uses *Lift Status Values* calculated and assigned to each building element depending on its weight and proximity to the tower crane (see Figure 3.3 for the flowchart). The input data to the Dynamo script are:

i) Lifting capacity of a tower crane with a total jib length of 35 metres, indicating loads liftable at each jib length. This data was obtained from an Excel table organized as shown in Table 3.5.

Table 3.5: Data for the 35-metre-jib tower crane (Source of data: ALL Tower Crane)

Crane Ranges (m)	Crane Loads (kg)
4	20000
10	20000
16	20000
20	20000
22	20000
24	20000
26	20000
27	18950
29	17420
31	16090
33	14930
35	14400

ii) Building elements such as structural columns, beams and slabs, which were imported from the construction site BIM model.

iii) Crane base host areas selected from the construction site BIM model. This refers to the area or platform upon which the crane base is to be installed.

iv) Trucks for delivering materials or building components to the area reachable by the tower cranes. These were selected from the Revit site model and represented as instance points.

v) Tower cranes selected from the site BIM model.

A custom node from the *BIM4Struc.CraneAnalysis* package shown in Figure 3.11 was then used to calculate the *Lift Status Values* for the building elements. The custom node also indicates the required input data. For each crane, a separate node was used for analysis and then the individual analysis results were joined for a combined evaluation of the final *Lift Status* results.

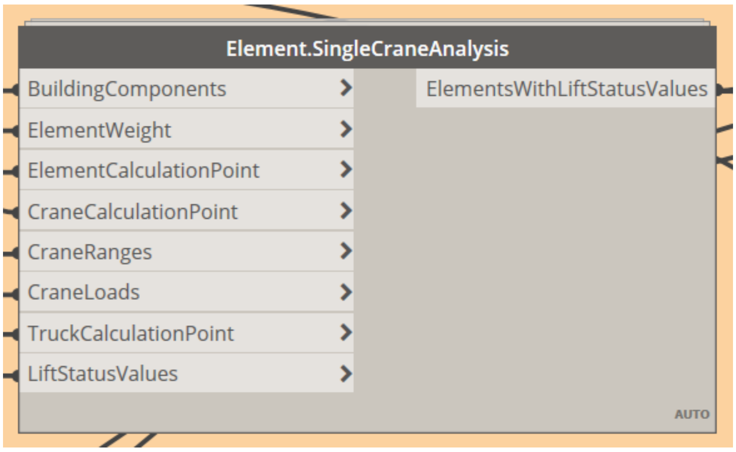

Figure 3.11: The custom node for calculating *Lift Status Values* for building elements

The Dynamo script then determined the *Lift Status* of the building elements based on the calculated *Lift Status Values*. Table 3.6 shows the *Lift Status* categories and their interpretations.

Table 3.6: Interpretation of the *Lift Status* of building elements (Vermeulen, 2019)

Lift Status	Colour code	Description	Lift Status	Lift Score
Liftable	Green	Element within crane capacity when lifting from truck or placing on building	0	0
Liftable but Truck Issue	Yellow	Element within crane capacity when placing on building but delivery truck is too far from the crane	1	5
Non-Liftable	Orange	Element heavier than the crane capacity at its distance	2	20
Unreachable	Red	Element too far away from the crane	3	100

The *Lift Status* of the building elements could be visualized in the Revit site model using the colour code by assigning the generated *Lift Status* results for each building element to the created *Lift Status* project parameter in the Revit site model. Figure 3.12 illustrates the optimization results for the positions of towers cranes in the Revit site model.

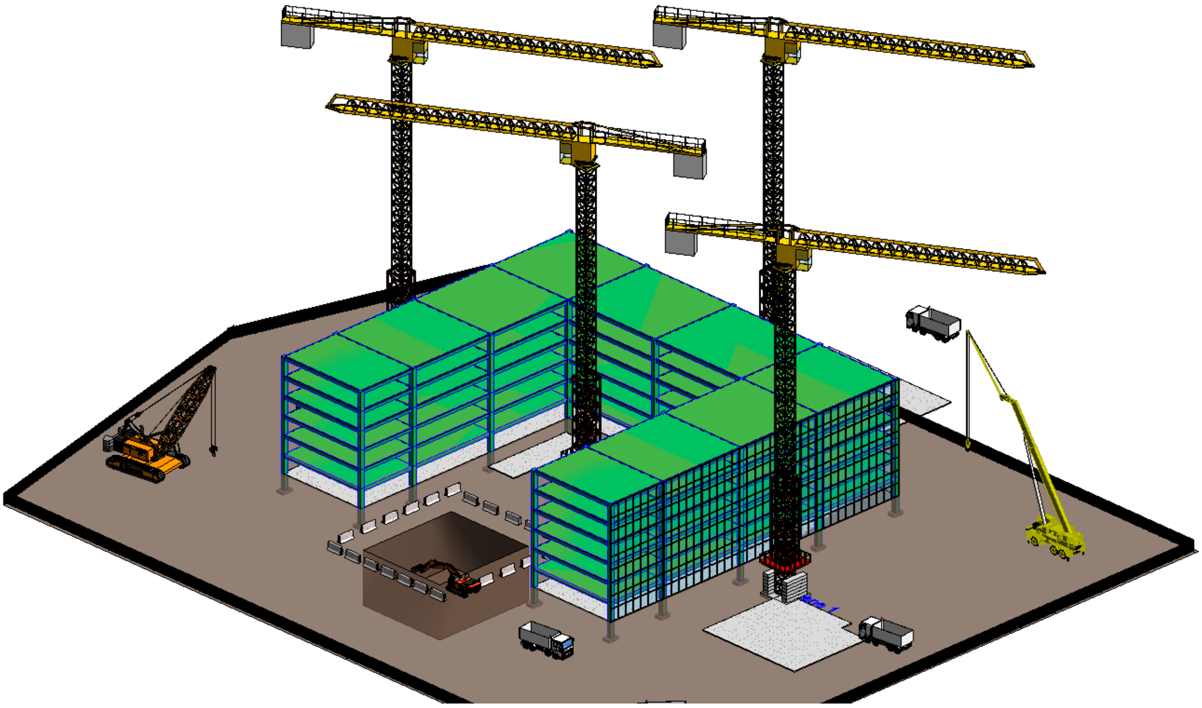

Figure 3.12: Optimized positions of tower cranes on the abstract site

The optimization results in Figure 3.12 indicate that all the building elements were within the combined reach of the tower cranes. In addition, all the building components could be lifted by the tower cranes. The positions of the tower cranes could also be displayed in the Dynamo script using the *Watch* node as shown in Figure 3.13.

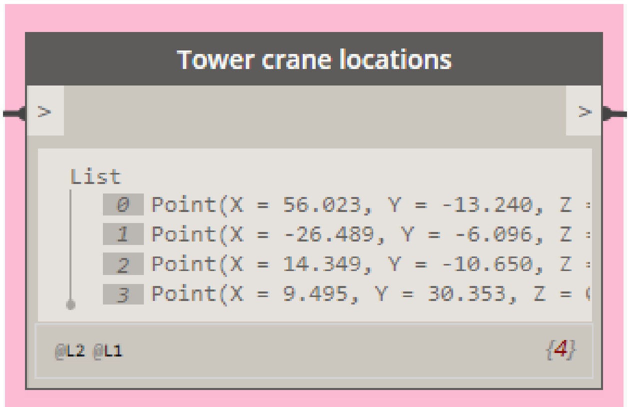

Figure 3.13: Coordinate points showing positions of the tower cranes

b) Lift Score Results Evaluation

The objective of the analysis was to find a solution with minimal *Lift Score* – a value based on the *Lift Status* of each building component in the analysis set i.e. a total of scores. A decrease in the value implies a better crane position, with ‘0’ being the optimal value. After the analysis, the script automatically updates the optimal positions of the tower cranes in the Revit model according to the calculated minimum *Lift Scores*.

3.5.4. Safety distances and zones

The areas and machineries of potential risk at the construction site should be identified and safety distances or zones demarcated around them to protect workers from accidents. This was implemented around the building under construction (scaffolding area), around a deep excavation, tower cranes and an excavator as shown in Figure 3.14.

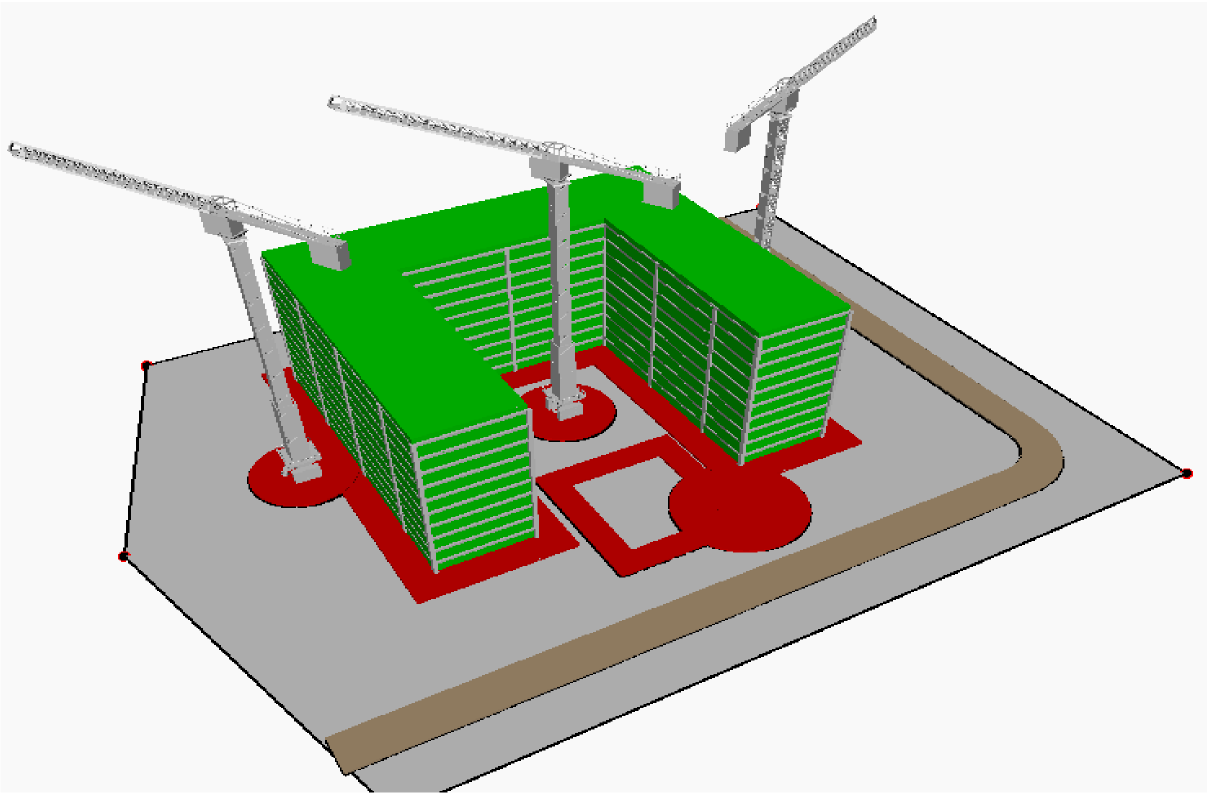

Figure 3.14: Safety zones around areas and machineries of potential risk

The actual footprints of the building and excavation, and the instance locations of the machineries were used to determine the safety distances.

3.5.5. Shortest route between site facilities

The *PathFinding.ShortestPath* node from the *Refinery Toolkit for Space Planning* package was used to evaluate the shortest path between points or facilities at the construction site. Figure 3.15 shows the input parameters that controlled the locations, the executing node and the analysis results.

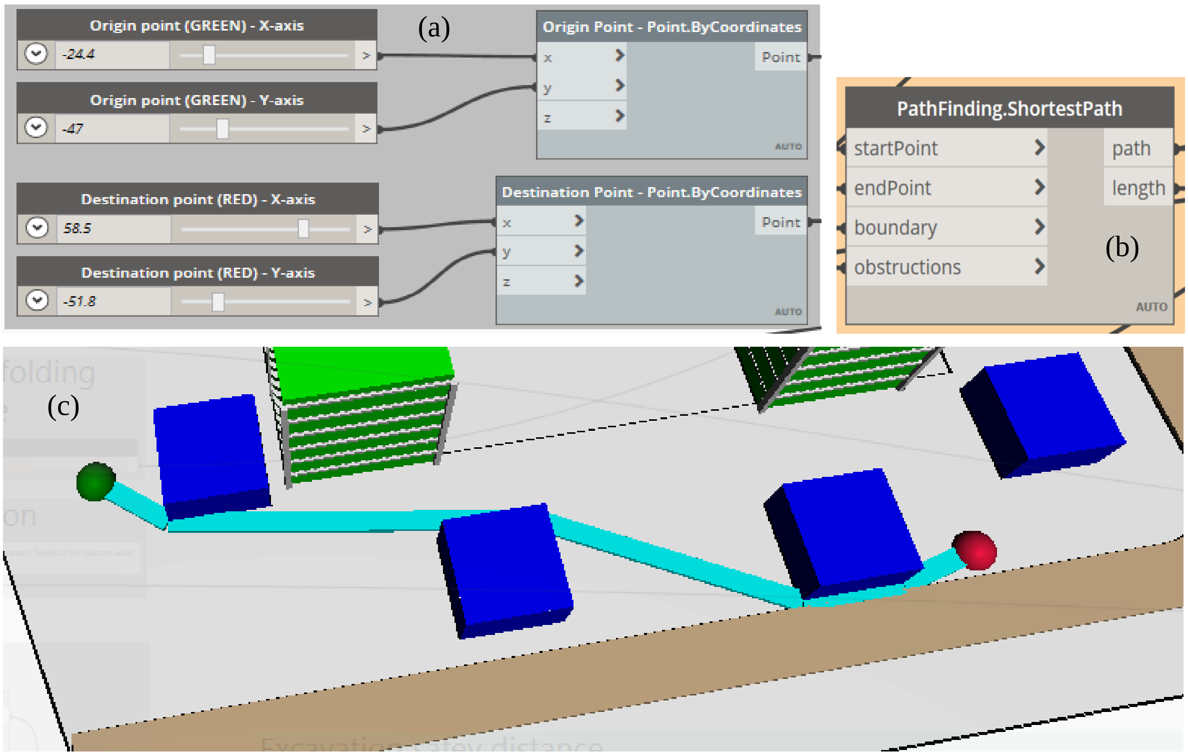

Figure 3.15: (a) Input parameters, (b) the *PathFinding.ShortestPath* node, and (c) analysis results

3.6. Closure

The construction site optimization problems in the abstract experimental site in this chapter comprised spatial layout planning, optimization of the positions of multiple tower cranes, manoeuvrability of site vehicles on site road, maximization of safety through safety distances and determination of the shortest paths. The Dynamo scripts developed with the aid of the BIM-based site model could generate solutions to the abovementioned problems. The proposed solutions can be implemented in the initial design phase of a construction project to plan and optimize a construction site. They are also more efficient with a dynamic construction site i.e. they can be used to manage changes on site as construction progresses. However, potential areas of improvement still exist, which will be suggested for future similar works.

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CHAPTER 4. CASE STUDY: HOSPITAL BUILDING PROJECT

4.1. Introduction

In this chapter, the Dynamo solution scripts developed in Chapter 3 were applied to a case study to automate construction site planning. The case was a project that involved the construction of a hospital building. The BIM models of the project were provided by WeBuild S.p.A. – an industrial group specializing in construction and civil engineering works. Technical advice regarding Dynamo workflows and the construction site planning process were also provided. The main objective of this case study was to evaluate the feasibility and consistency of the proposed computational design solutions in planning a construction site.

4.2. Site description

The project site was located in a metropolitan area, and surrounded by a built environment situated on a generally flat terrain. Figure 4.1 shows the context of the project site in the Revit BIM model.

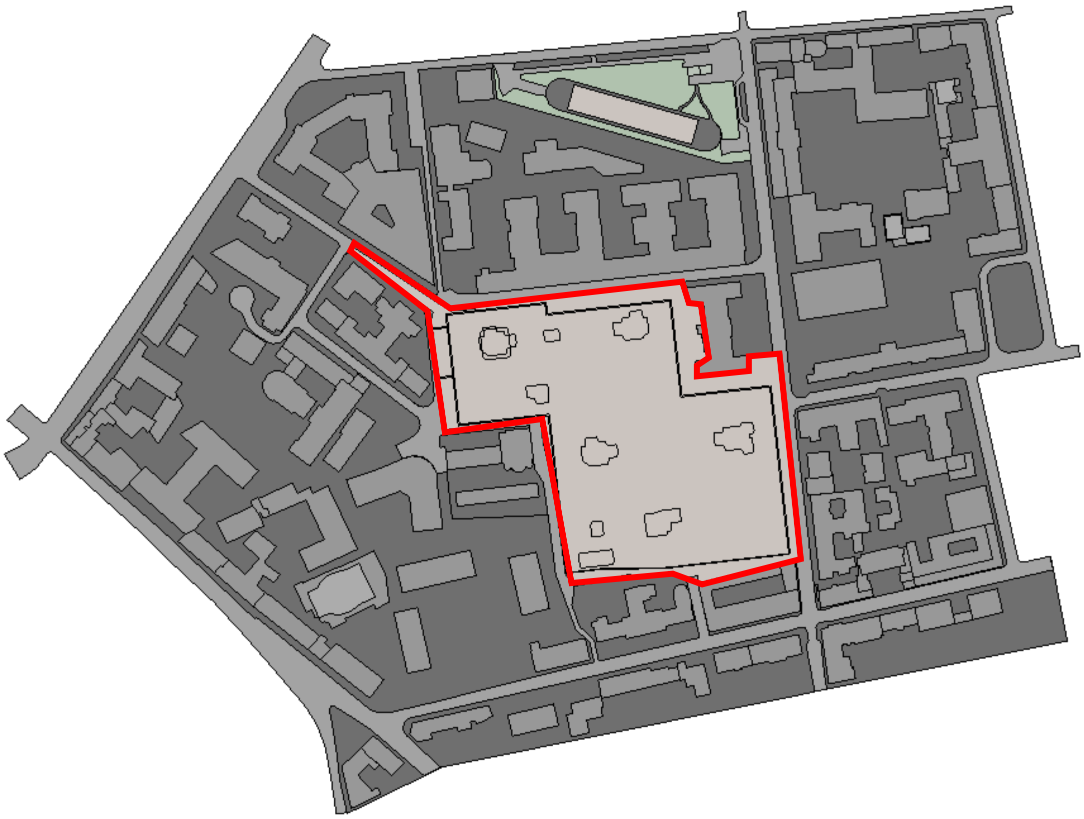


Figure 4.1: Context of the project site in the Revit BIM model (Source: WeBuild S.p.A.)

The project involved the construction of a proposed multi-storey hospital building in a limited available space, hence the need to optimize the use of available space, operation of construction equipment, site logistics and construction processes. The size and shape of the hospital building is shown by the Revit BIM model in Figure 4.2.

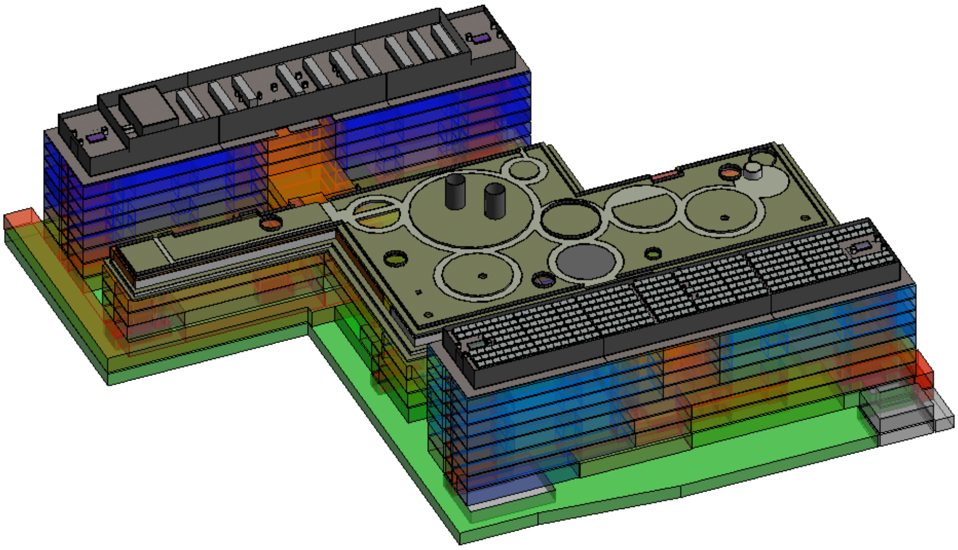


Figure 4.2: Size and shape of the proposed hospital building (Source: WeBuild S.p.A.)

The building elements and materials for use in the project included concrete, reinforcing steel, structural steel, prefabricated curtain walls and materials for façade and finishes. MEP components were also to be installed in the building.

4.2.1. Problem definition

The problems to be addressed by the computational design approach in this case study are as listed below:

i) Construction site configuration: this involved setting the site boundary, allocating the required facilities and spaces within the site based on adjacency needs, and designing the site road or paths.

ii) Safety management on site by demarcating safety distances and zones e.g. around machineries, deep excavations, and the building under construction.

iii) Management of accessibility between construction site facilities and spaces. This also involved evaluating manoeuvrability of site vehicles on the site road.

iv) Optimization of the locations of multiple tower cranes: this involved maximizing the reach of multiple cranes on site concurrently with the aim of achieving maximum area coverage.

v) Flow optimization: this entailed coordinating the flow of materials and movement of workers by establishing shortest routes within the site.

4.2.2. Scope of Dynamo scripts application

The application of the developed Dynamo scripts to generate solutions in this case study was limited to the following aspects:

i) The construction site rules and constraints, and the optimization requirements were limited to those of the Revit BIM models that were provided.

ii) A standard value was assumed if the actual values for required parameters were missing, e.g. the density values of the building components.

iii) Only the construction site problems that had feasible computational design solutions were considered for optimization.

iv) Due to unavailability of work schedule or program of works, assumptions were made about some of the construction activities required for site optimizations.

4.2.3. Site rules and constraints

The constraints at the project site based on the availed Revit BIM models of the case study were as follows:

i) Fixed site boundary. All the planning, construction operations and allocation of spaces for site facilities and machineries were to be implemented within the construction site boundary.

ii) The space occupied by the hospital building under construction was unavailable for the allocation of temporary facilities. Spatial planning therefore had to consider the available spaces at the superstructure level of construction.

iii) Due to limited available space within the construction site, the site road for use by delivery vehicles was designed to extend from the site entrance to the front area of the site as shown in Section 4.4.1.3. The tower cranes would then be used to move the materials within the construction site once delivered by trucks.

The site rules that governed the optimization processes were as follows:

i) Allocation of spaces and positioning of facilities while considering adjacency requirements in order to minimize distances of material movements on site, e.g. locating the batch plant within the reach of tower cranes.

ii) Maximize the reach of tower cranes by optimizing their positions. Building components and materials on site would be transported mainly by tower cranes.

iii) Ensure high levels of safety by demarcating safety distances/radii from machineries and areas of potential risk.

iv) Enhance or maximize safety around the building under construction by demarcating scaffolding distance which follows the building footprint.

v) Reduce flow paths by determining the shortest path between locations.

vi) Offload and stockpile building materials at locations that can be easily accessed by the delivery trucks and tower cranes, and at liftable crane range.

4.3. Input data

The construction site BIM model contained the required facilities and machinery as shown in Figure 4.3, which were to be managed and organized within the construction site area. The central model in this case study was created from the site BIM model (Figure 4.3) in order to make it the coordination point for all alterations made on the construction equipment and layout plan. The Project Coordinate System was used to coordinate the positions of the models.

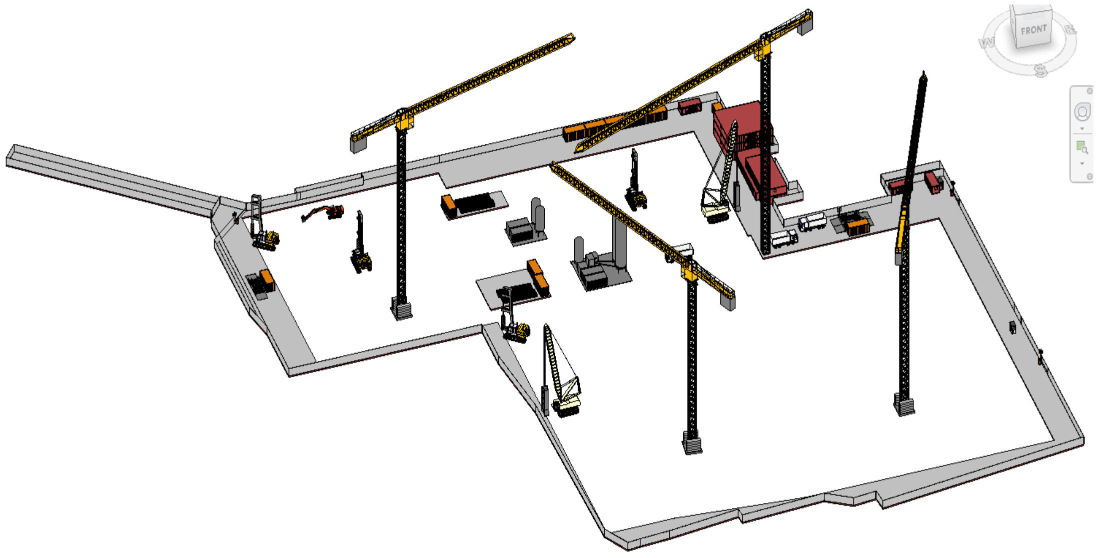


Figure 4.3: Site BIM model with required facilities and machineries (Source: WeBuild S.p.A.)

The Revit objects – representing site facilities and equipment – and the boundary points were used to model the construction site in Dynamo. Table 4.1 summarizes the data imported from the Revit objects, and their significance in the Dynamo script.

Table 4.1: Input data from the Revit site model and their significance

Revit object	Input data to Dynamo	Significance of input data
Site boundary	Polygon (boundary) points	Generate the construction site boundary
Building elements (columns and walls)	Location and weight of the elements	Optimization of positions of tower cranes
Building footprint	Polygon (boundary) points	Position of the building under construction, Demarcation of scaffolding area or safety zone
Tower cranes	Location and jib length of cranes	Optimization of positions of tower cranes
Crane base host areas	Area and location of the host surfaces	Optimization of positions of tower cranes
Light trucks	Point of location	Optimization of positions of tower cranes, site road, assessment of site vehicle manoeuvrability
Excavators, piling machines	Point of location	Demarcation of safety distances
Office containers, storage containers	Size, adjacency, space ID	Spatial allocation
Bentonite plant, grouting plant	Size, adjacency, space ID	Spatial allocation

The input data for spatial planning and tower crane capacity was imported into the Dynamo scripts from Excel tables that were organized as shown in Sections 4.4.1.2 and 4.4.5 respectively.

4.4. Computational design solutions

The solutions generated by the Dynamo scripts include site layout and facilities layout plan, demarcation of safety distances, vehicle manoeuvrability on site road, analysis of shortest paths and optimization of the positions of tower cranes. These are discussed in the subsections.

4.4.1. Construction site configuration

The configuration of the construction site involved setting up of site boundary, organizing the spatial plan layout and installing site facilities and equipment within the construction site as described in the following sections.

4.4.1.1. Construction site boundary

The construction site boundary was scripted in Dynamo using the coordinate points of the site geometry obtained from the Revit site model shown in Figure 4.3, which was used as the central model. The vertices or coordinate points were joined by Dynamo curves to form an enclosed polygon as shown in Figure 4.4 below.

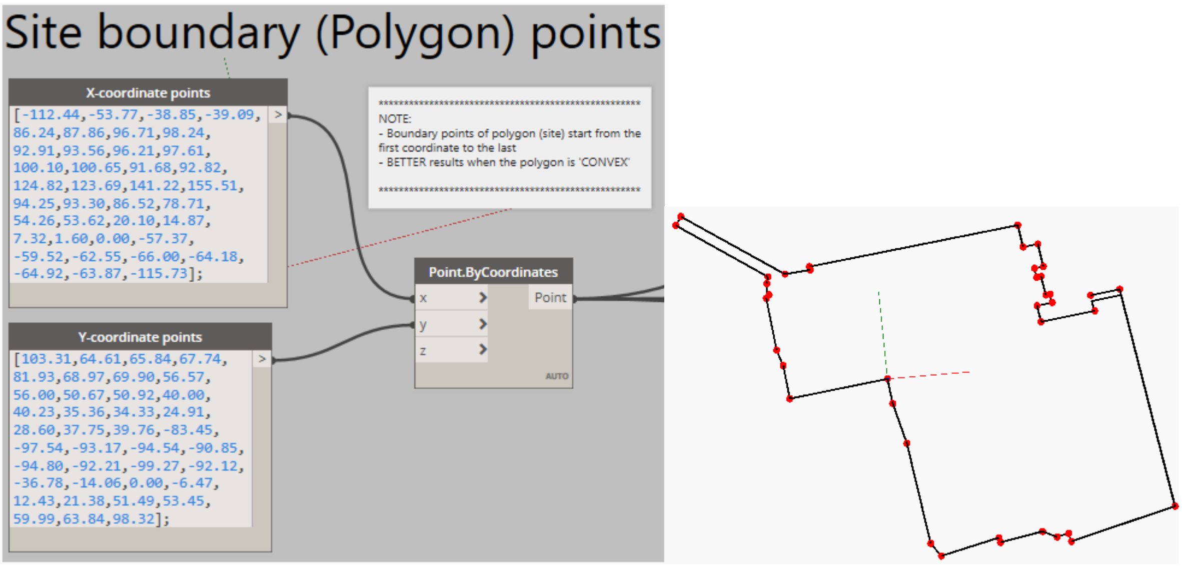


Figure 4.4: Input data for site boundary

The spatial layout plan – consisting of site facilities and equipment – was then organised within the generated construction site boundary.

4.4.1.2. Spatial plan layout

The *Engine.Execute* node from the *DynaShape* package was used to generate the spatial plan on the central site model. Detailed information about the site facilities was organized in an Excel table as shown in Table 4.2.

Table 4.2: Details of spatial data based on the hospital building project facilities and equipment

Space ID	Space or Facility	Department	Department ID	Quantity	Width (m)	Height (m)	Area (m^2)	Total Area (m^2)	Preference	Adjacent Spaces
0	Proposed hospital building A	Construction	0	1	100	100	10000	10000	1	
1	Proposed hospital building B	Construction	0	1	50	50	4000	4000	2	
2	Office container 1	Management	1	1	10	50	500	500	2	9
3	Office container 2	Management	1	1	10	10	150	150	2	9
4	Storage containers 1	Storage	2	1	10	5	100	100	2	10
5	Storage containers 2	Storage	2	1	10	5	100	100	2	11
6	Storage conatiners 3	Storage	2	1	10	5	100	100	2	12
7	Bentonite plant	Manufacture	3	1	10	10	150	150	1	10.11
8	Grouting plant	Manufacture	3	1	10	10	150	150	1	10.13
9	Parking kiosk	Management	1	2	5	5	30	60	4	
10	Crane base area 1	Construction	0	1	5	5	30	30	1	0
11	Crane base area 2	Construction	0	1	5	5	30	30	1	0
12	Crane base area 3	Construction	0	1	5	5	30	30	1	1
13	Crane base area 4	Construction	0	1	5	5	30	30	1	1

The spatial data was imported into the Dynamo script so as to organize the space layout as shown in Figure 4.5. The spatial layout plan was based on spatial adjacency requirements.

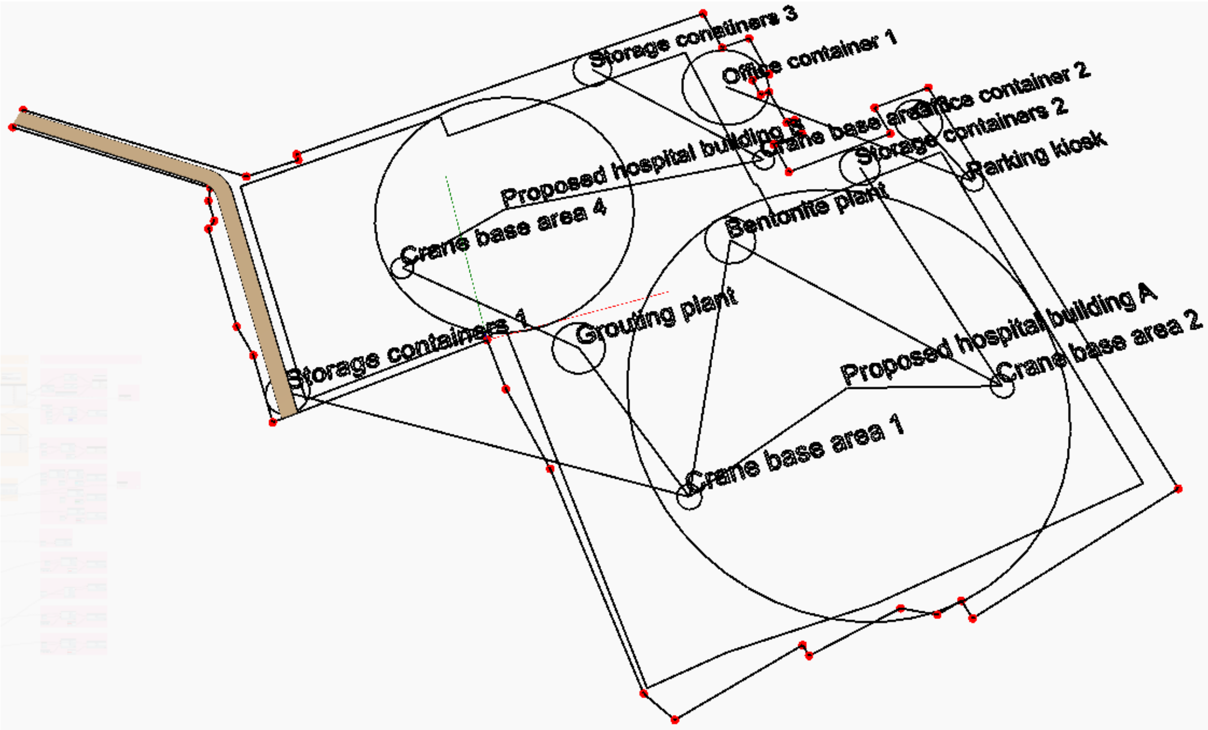


Figure 4.5: Site space layout for the hospital building project facilities and equipment

Two circles were used to represent the building under construction as shown above due to its protruding shape.

4.4.1.3. Site road

Due to limited available space on site, the road for delivery vehicles was designed from the site entrance to the front area of the site as shown in Figure 4.6. The tower cranes would then be used to move the materials within the construction site once delivered by trucks.

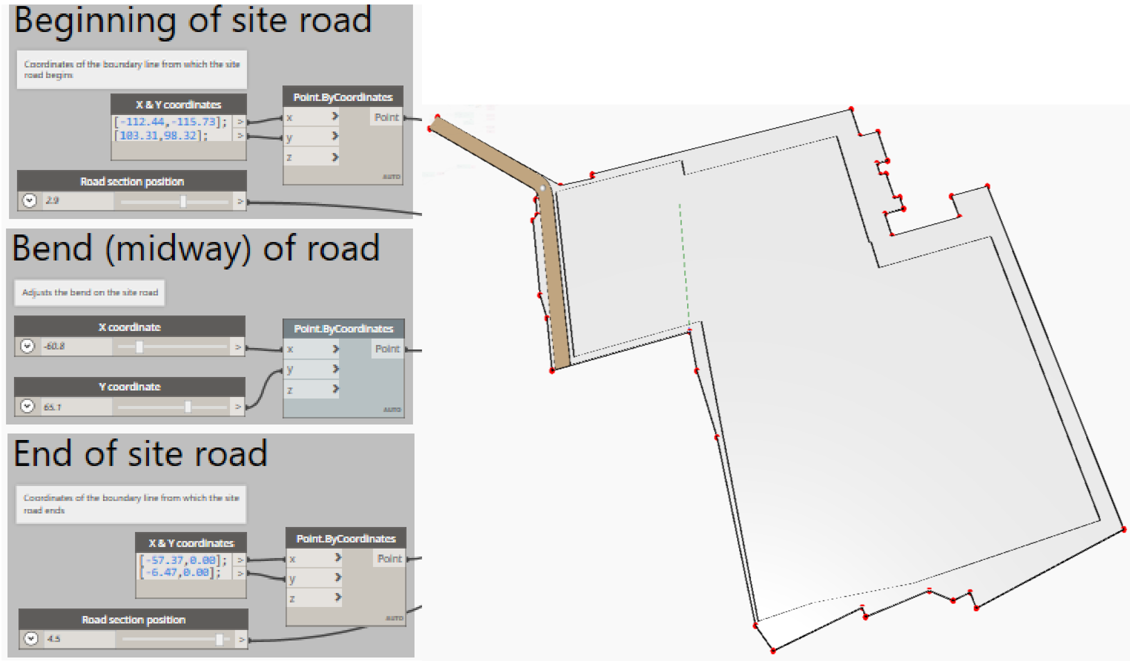


Figure 4.6: Site road extending from the entrance to the front area of the site

The parameters used to generate the road at the construction site were axes that were perpendicular to the boundary lines and coordinate points along the road. Control parameters could also be used to adjust the positions of road sections, width of road, and the degree of curvature at bend.

4.4.2. Manoeuvrability of site vehicles

The degree of curvature was used to manage site vehicle manoeuvrability at the bend on site road as illustrated in Figure 4.7.

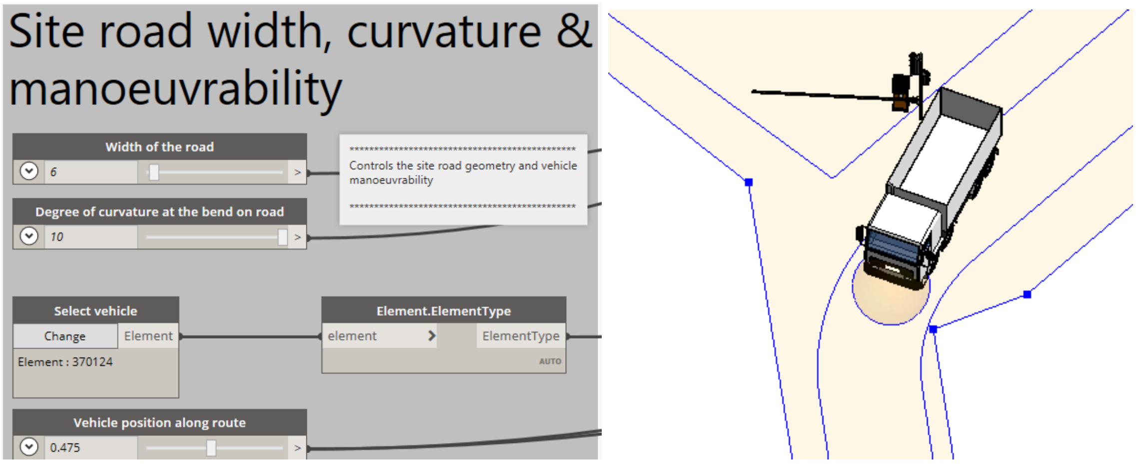


Figure 4.7: Site vehicle manoeuvrability at the bend of site road

For this case study, the optimum degree of curvature for manoeuvrability based on the site constraints was 10.

4.4.3. Safety distances and zones

The machineries and areas of potential risk at the construction site were identified on the central model, and safety distances demarcated around them. This was implemented around the tower cranes and piling machines at substructure construction phase as shown in Figure 4.8, and around the building under construction (scaffolding area) as shown in Figure 4.9.

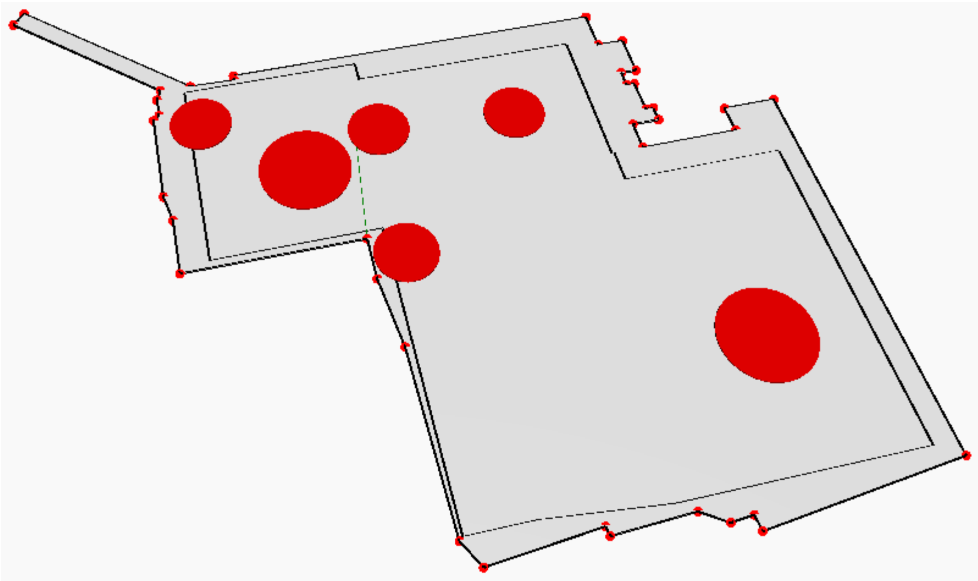


Figure 4.8: Demarcation of safety distances around machineries at substructure construction phase

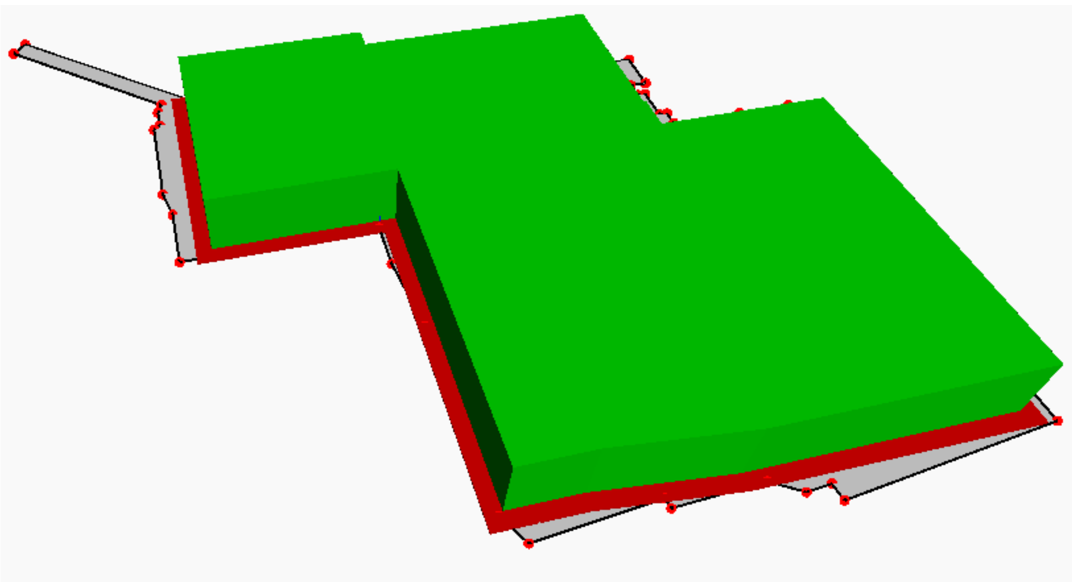


Figure 4.9: Demarcation of scaffolding area around the building under construction

For an optimum utilization of the available space, the actual footprint of the building under construction, and the exact locations of machineries were used to offset safety distances.

4.4.4. Shortest route between site facilities

The shortest distance around obstacles and between points or facilities on site were analysed to minimize flows before the construction of superstructure. Figure 4.10 shows the 3D preview of the shortest path determined between two points.

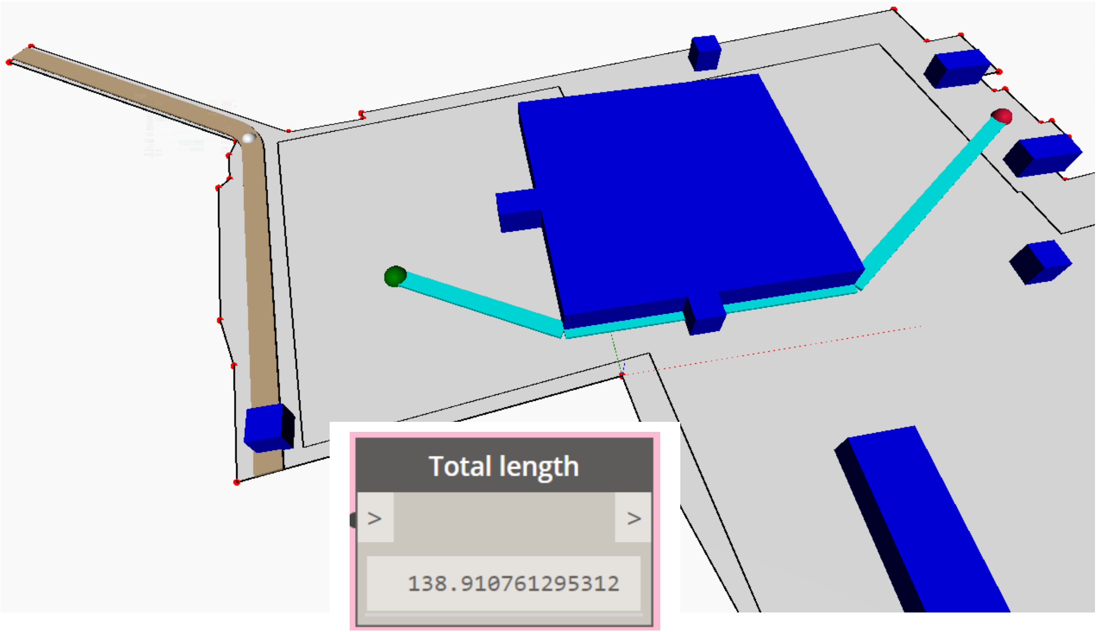


Figure 4.10: Shortest route around obstacles and between two points on site

The total length of the shortest path determined could also be displayed in the Dynamo script as shown in the figure above.

4.4.5. Optimization of the positions of tower cranes

The optimization of the positions of tower cranes was implemented on a federated structural BIM model. It was feasible to use the structural columns and walls only in the optimization process due to their practical sizes and weights in regard to hoisting, and also to reduce the time of executing the Dynamo scripts. The position of the site boundary from the central model and the position of the federated structural model were synchronized using the Dynamo script as shown in Figure 4.11, in order to coordinate the positions of all models, and also for a better understanding of the context.

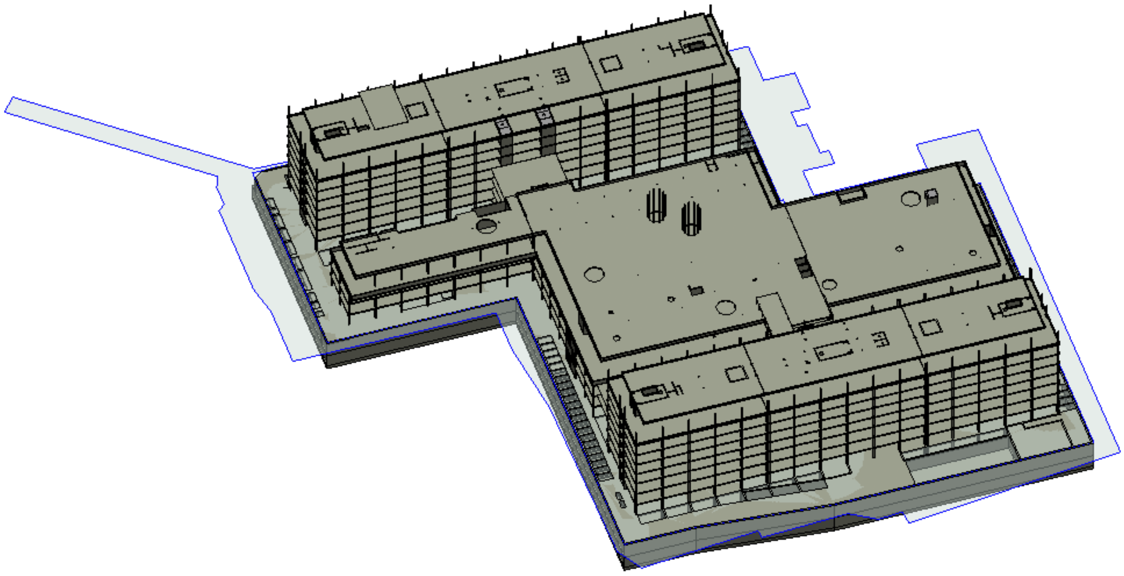


Figure 4.11: Federated structural model used for the optimization of the positions of tower cranes

The *BIM4Struc.CraneAnalysis* package was used to optimize the locations of multiple tower cranes. The input data from the federated Revit model to the Dynamo script were: (i) the crane base host area, (ii) the building elements containing density parameter, (iii) the trucks, and (iv) the lifting capacity of a tower crane with a total jib length of 60 metres organized in an Excel table as shown in Table 4.3.

Table 4.3: Data for the 60-metre-jib tower crane (Source of data: ALL Tower Crane)

Crane Ranges (m)	Crane Loads (kg)
4	20000
10	20000
14	20000
16	20000
20	20000
22	20000
24	18530
26	16840
28	15400
30	14170
34	12140
36	11300
38	10560
42	9280
45	8470
47	7990
50	7340
53	6770
55	6420
57	6100
60	5800

The crane base host areas, from which an optimum crane installation point was determined on each host area by the Dynamo script, were placed at locations that would minimize or avoid conflicts during the construction process as shown in Figure 4.12. Another key consideration in locating the crane base host areas was an even distribution of tower cranes around the site model for maximum reach.

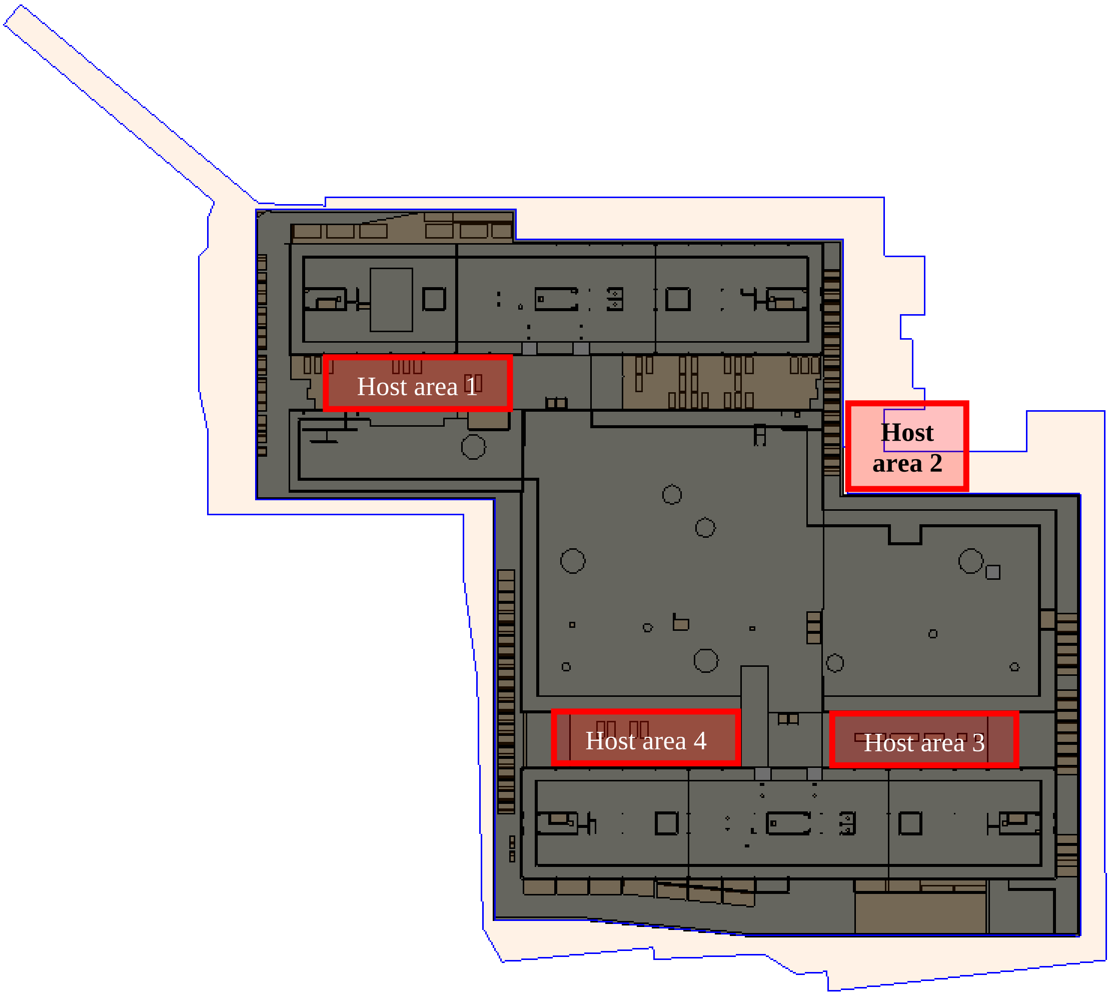


Figure 4.12: Tower crane base host areas placed at positions of probable maximum reach and minimum conflicts

Section 3.5.3 provides a description of the methodology used to optimize the positions of the tower cranes. This includes the input procedure, Dynamo workflows, results output, results interpretation and visualization. The results of tower crane positions optimization using the Revit federated structural model is shown in Figure 4.13. The pink circles indicate the total reach of the tower cranes.

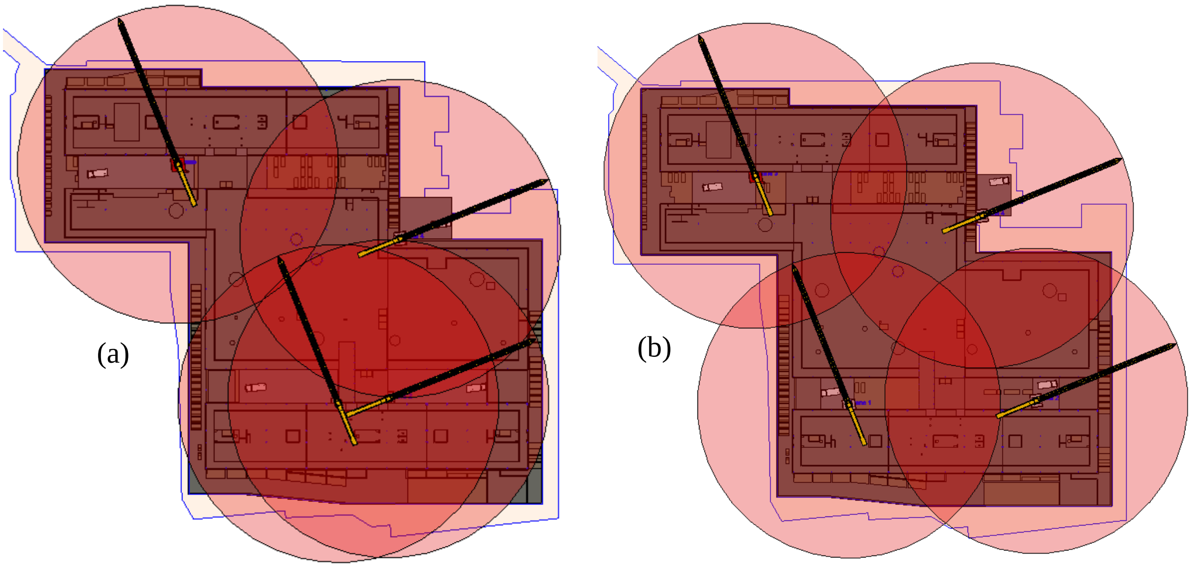


Figure 4.13: Optimized positions of the tower cranes: (a) initial optimization results, and (b) refined optimization results

The Dynamo script optimized the position of each tower crane individually but concurrently, and updated their locations in the federated Revit BIM model. To eliminate conflicts between tower cranes and also increase the area covered by the tower cranes if needed (and is feasible), the crane positions could be refined through manual intervention by moving the crane base host area in the Revit BIM model accordingly and then running the Dynamo script again. Figure 4.13(b) illustrates refined optimized positions of the tower cranes from Figure 4.13(a). The coordinate points of the positions of the cranes could also be displayed on a Dynamo node as shown below.

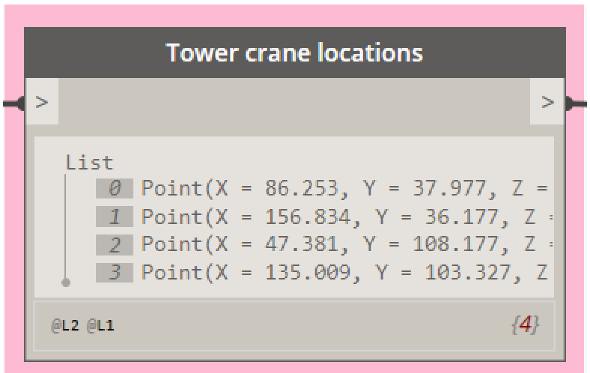


Figure 4.14: Coordinate points showing the optimized positions of the tower cranes

A better optimization approach however, would involve a combined analysis of the multiple tower cranes with little or no manual intervention.

4.5. Results visualization on the Revit BIM models

The *Lift Status* of the building elements could be visualized in the Revit views using the colour code used (see Table 3.6 for the colour code and interpretations). The colours were assigned to each building component based on its ability to be lifted and/or its distance from the tower crane as shown in the federated BIM model in Figure 4.15.

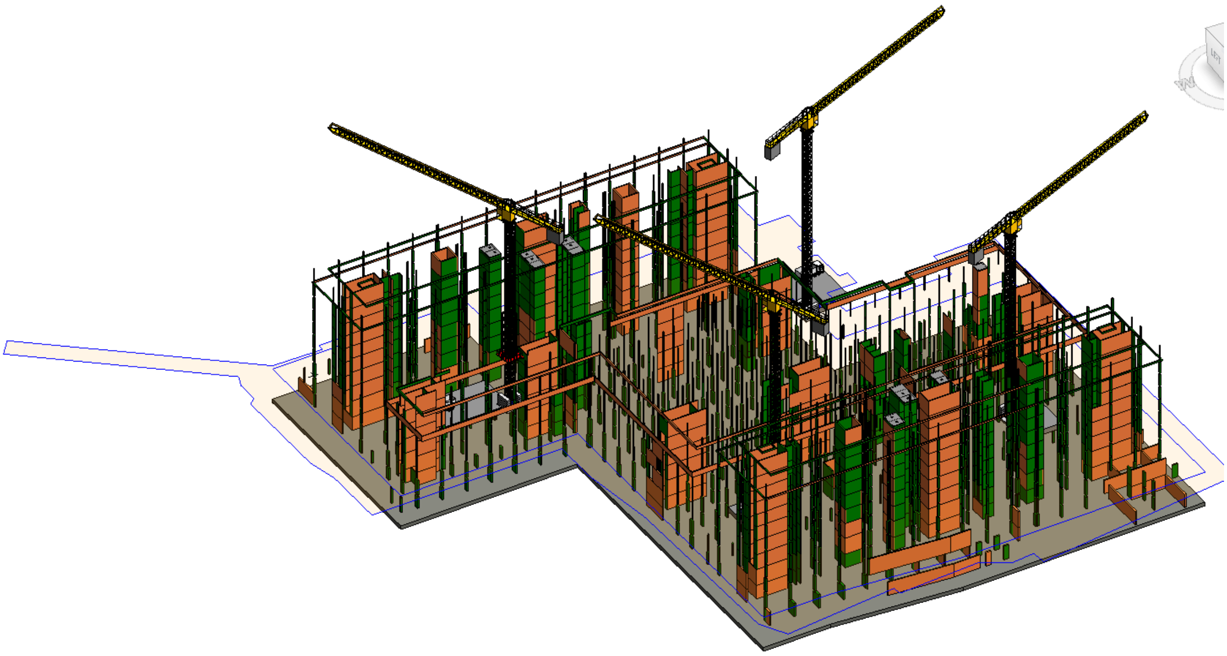
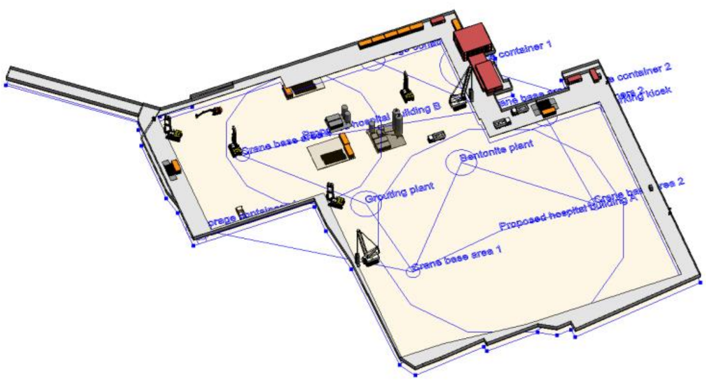


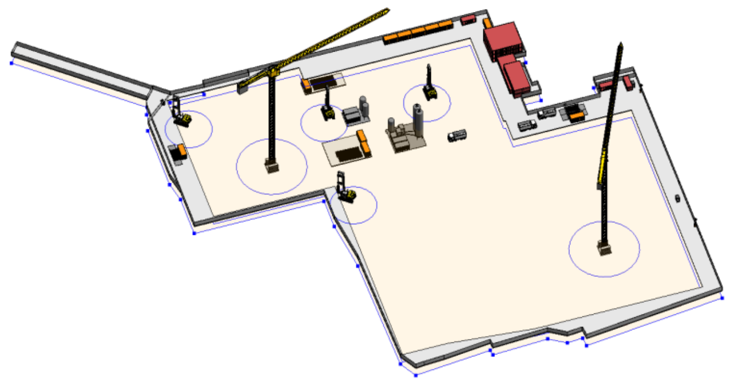
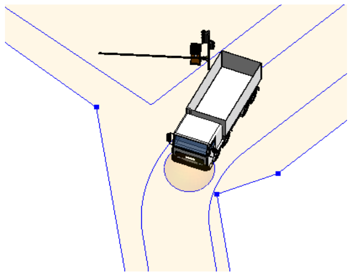
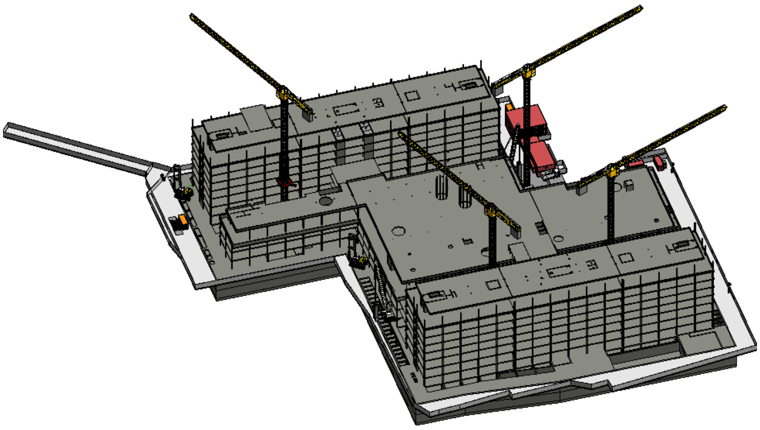
Figure 4.15: Visualization of the *Lift Status* of the building elements in the Revit BIM model

The optimization results above indicate that all the building components used for crane position optimization – i.e. structural columns and walls – could be reached by the tower cranes (see Table 3.6 for colour code and detailed interpretation). The elements coloured green (all structural columns and some walls) could be lifted by the cranes while the elements coloured orange (some walls) were heavier than the capacity of the tower cranes. Increasing the lifting capacities of the cranes would improve the ability to hoist the elements.

Other results from the Dynamo scripts could be replicated on the Revit BIM models. Table 4.4 summarizes some of these results.

Table 4.4: Summary of Dynamo output result replicated in the Revit BIM models

Dynamo output	Revit model visualization	Description
Spatial plan		Spatial allocation within the site boundary represented with circles.

Dynamo output	Revit model visualization	Description
Safety distances		Demarcation of safety radii/distances from site machinery.
Site road and manoeuvrability of site vehicles		Simulation of truck motion around the bend of site road.
Optimized tower crane positions		Positioning of the tower cranes at locations of maximum reach.

4.6. Closure

The proposed Dynamo solution scripts were used to generate optimized solutions for the case study in this chapter. The addressed site problems were based on the specific site rules, constraints and context of the case project. The proposed solutions included optimized construction site configuration, optimized flows and manoeuvrability on the site road or paths, optimized positions of multiple tower cranes, and enhanced safety through the demarcation of safety distances. However, there still exists areas that require future improvements. These are discussed in the next chapter.

CHAPTER 5. CONCLUSION

5.1. Summary of findings and solutions

The aim of this study was to develop a BIM-based solution to some of the problems encountered in construction site planning using the computational design method. The intention was to optimize the use of spaces and equipment/machineries on site, and manage site logistics and the dynamic nature of construction during the initial planning stage of a construction project. After performing computational design experiments using Dynamo scripts on an abstract BIM site model, the developed solutions were applied on a case study which involved the construction of a hospital building. The study findings, limitations, proposed solutions and their potential impact on the construction industry are summarised in this section.

a) Computational design in construction site planning and optimization

The computational design method is increasingly being used in the construction industry. A variety of computational design tools for this purpose are existent. Many studies have also been conducted on ways of efficiently using the existing computational techniques. While most of these design tools and studies focus on architectural and structural design, little attention has been accorded to construction site planning, particularly at the project planning phase. Therefore, more studies are needed on the use of computational design methods for construction site planning, and the application of available computational design tools on construction site planning.

This study used the computational method within the BIM environment to plan a construction site, thereby bridging the gap between construction site planning and project execution. In view of the study objectives highlighted in Chapter 1, the results show consistency in the application of the proposed Dynamo solutions, thus indicating a high feasibility in adopting the computational design approach for construction site planning.

b) Limitations of the computational design approach

The limitations of using the computational design approach to generate solutions as experienced in this study were as follows:

i) The efficiency and effectiveness of the generated solutions was limited to the level of skills in scripting/programming and in operating the design tools. Hence, solutions of greater efficiency and effectiveness can only be achieved with greater knowledge in scripting as well as operating the tools.

ii) The commercially available computational design tools and the BIM environment required to generate the solutions are expensive. They would also require specialized training to operate.

iii) Some specialized tools e.g. the *Engine.Execute* node from the *DynaShape* package, were rigid in their applications i.e. they did not allow modifications to suit the design requirements.

iv) BIM data and resources that were specially required for construction site planning e.g. families of construction site elements, were insufficient.

c) Proposed solutions and their advantages

The Dynamo tool was used to plan and optimize an abstract experimental site BIM model based on rules and constraints that were conceptual. The site elements that were optimized included site layout plan, site road and manoeuvrability of vehicles, positions of multiple tower cranes, safety distances, and shortest paths between site facilities. Consistent results were obtained with the application of the developed Dynamo scripts to the case study, based on the prevailing site rules and constraints. Some of the advantages of the proposed solutions include:

i) Efficient construction site planning process: multiple design options and scenarios were generated rapidly, hence enabling quick exploration of design options.

ii) Dynamic site planning solutions: the proposed solutions could be used to efficiently manage the changing requirements in construction machineries, resource allocation, labour and logistics as the construction process evolves.

iii) Site scenarios for different design options could be visualized, and hence assist in making better informed decisions on the health and safety of workers. This also helped in minimizing or eliminating conflicts between site equipment such as tower cranes.

iv) Solutions to complex site planning problems such as the optimization of multiple tower cranes could be generated faster and with greater precision.

d) Potential impact of the study on the construction industry

The proposed computational design solutions to construction site problems could assist construction site planners and engineers to optimize site plans, logistics and the use of site equipment for building projects during the preliminary stage of a project. The Dynamo scripts are expected to assist in better management of construction site problems before the actual construction starts, and also help to manage changes on site as the construction progresses.

The project team may use the generative scripts to generate different site scenarios and find the best solutions based on the prevailing site rules and constraints. The potential impact of this study on the construction industry is a better-informed cost and logistical planning, increased productivity, improved safety on site and better coordination among the project stakeholders.

5.2. Future developments and improvements

The proposed solutions are anticipated to address or provide a framework for solving some of the construction site problems during the initial design phase of a project using the computational design approach. However, further developments and future improvements are still needed. These are suggested in this section.

i) The *Engine.Execute* node from the *DynaShape* package used in this study for spatial layout optimization generated better results with convex site geometries as explained in Section

3.5.1.2. Future improvements should consider developing a script that equally generates good results with site geometries of any shape including a concave outline.

ii) The generative scripts for spatial planning in this study used simple geometries for rough positioning of site facilities. Future improvements could involve automatic and accurate update of positions of the actual site facilities and machinery on the site BIM model.

iii) In the optimization of the locations of multiple cranes, the script optimizes the position of each crane separately though concurrently. In addition, further manual intervention was needed to ensure maximum coverage by the tower cranes as highlighted in Section 4.4.5. However, a better optimization approach would involve a combined analysis of the multiple tower cranes with little or no manual intervention.

iv) The Dynamo scripts, particularly for the optimization of tower crane positions, take a lot of time to execute especially when many building elements and site equipment are involved. To improve efficiency, scripting methods that are more superior e.g. Python coding could be employed.

v) Future works could also explore other computational design and optimization tools such as the Grasshopper software. Though not within the scope of this study, some of these tools have demonstrated good optimization capabilities. A potential problem that would need to be addressed is interoperability issues when using these tools to optimize a Revit site model.

vi) The generative solutions could also be improved or modified so that they could be applied on infrastructure projects as well.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D, 4D, 5D	3-, 4-, 5-dimensional
ABC	Artificial bee colony
ACO	Ant colony optimization
AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
BIM	Building Information Modelling / Model
CAD	Computer-aided Design
CoSIM	Construction site information modelling / model
GA	Genetic Algorithm
GIS	Geographical information system
GUI	Graphical user interface
LOD	Level of Development
MEP	Mechanical, electrical and plumbing
MOO	Multi-objective optimization
OSHA	Occupational Safety and Health Administration
PSO	Particle swarm optimization
SA	Simulated annealing
SOO	Single-objective optimization
SOS	Symbiotic organisms search
VR	Virtual Reality

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APPENDICES

APPENDIX A: DYNAMO SCRIPTS

A1: COLOUR CODE FOR DYNAMO WORKFLOWS

The colour code shown in Table 5.1 was adopted as a standard in this study for workflows in the Dynamo scripts to improve readability and implementation of the Dynamo graphs.

Table 5.1: Colour code for functions in the Dynamo scripts

No.	Function	Colour
1.	***Grey colour*** indicates input. Input data can be collected from the Revit BIM model, Excel tables or other interoperable format. The inputs can be changed per project and should be set before running the scripts.	
2.	***Green colour*** indicates the assigning of initial values to objects and variables. Functions are involved in the preliminary positioning.	
3.	***Orange colour*** denotes analysis and optimization operations based on the provided input data.	
4.	***Pink colour*** indicates visualization of results, geometries and evaluation of the output.	
5	***Blue colour*** denotes the title block containing descriptions of the script, file names, associated files and platforms, required Dynamo packages, and the project units.	
6.	Notes about the processes and descriptions of the Dynamo nodes are written on a ***white background***.	

For additional information and a better understanding of the Dynamo graphs:

i) Nodes that performed the same function were grouped and a title provided to indicate the task performed.

ii) Commentaries about the logic have been added for some groups.

iii) Specific nodes obtained from the Dynamo packages have been pointed out, and their sources mentioned in the notes.

A2: FACILITIES AND SPATIAL PLANNING SCRIPTS

This section contains the Dynamo scripts for spatial planning. Some modifications were implemented in the script for the case study due to varying site rules and constraints. This was done only in the input and initialization sections of the Dynamo graphs. The first section below presents the graphs in all the sections, while the second section shows the two sections where modifications were made.

a) Spatial planning script for the abstract site model – graphs in all sections

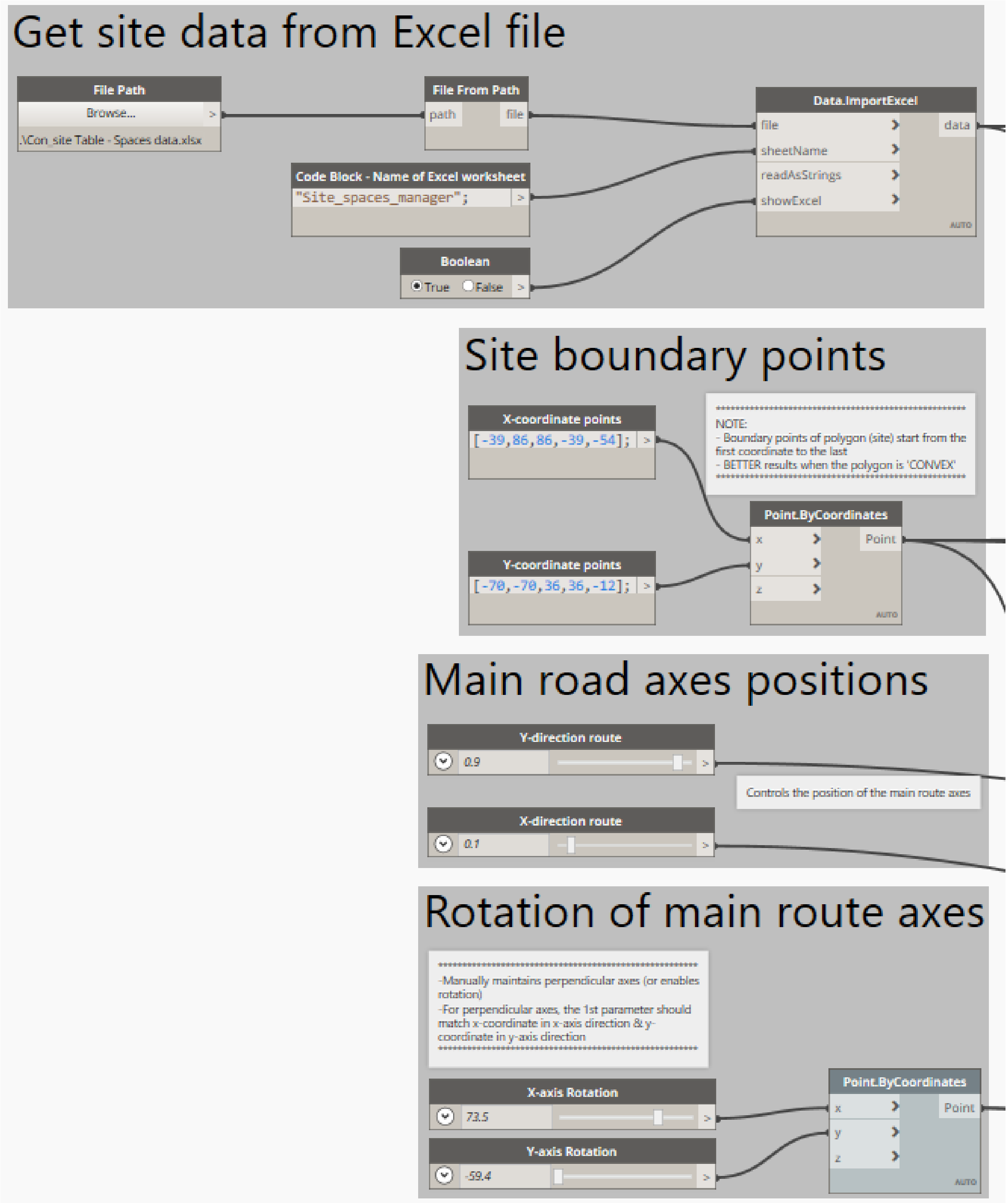

Figure 5.1: Input graphs for the abstract site model – 1

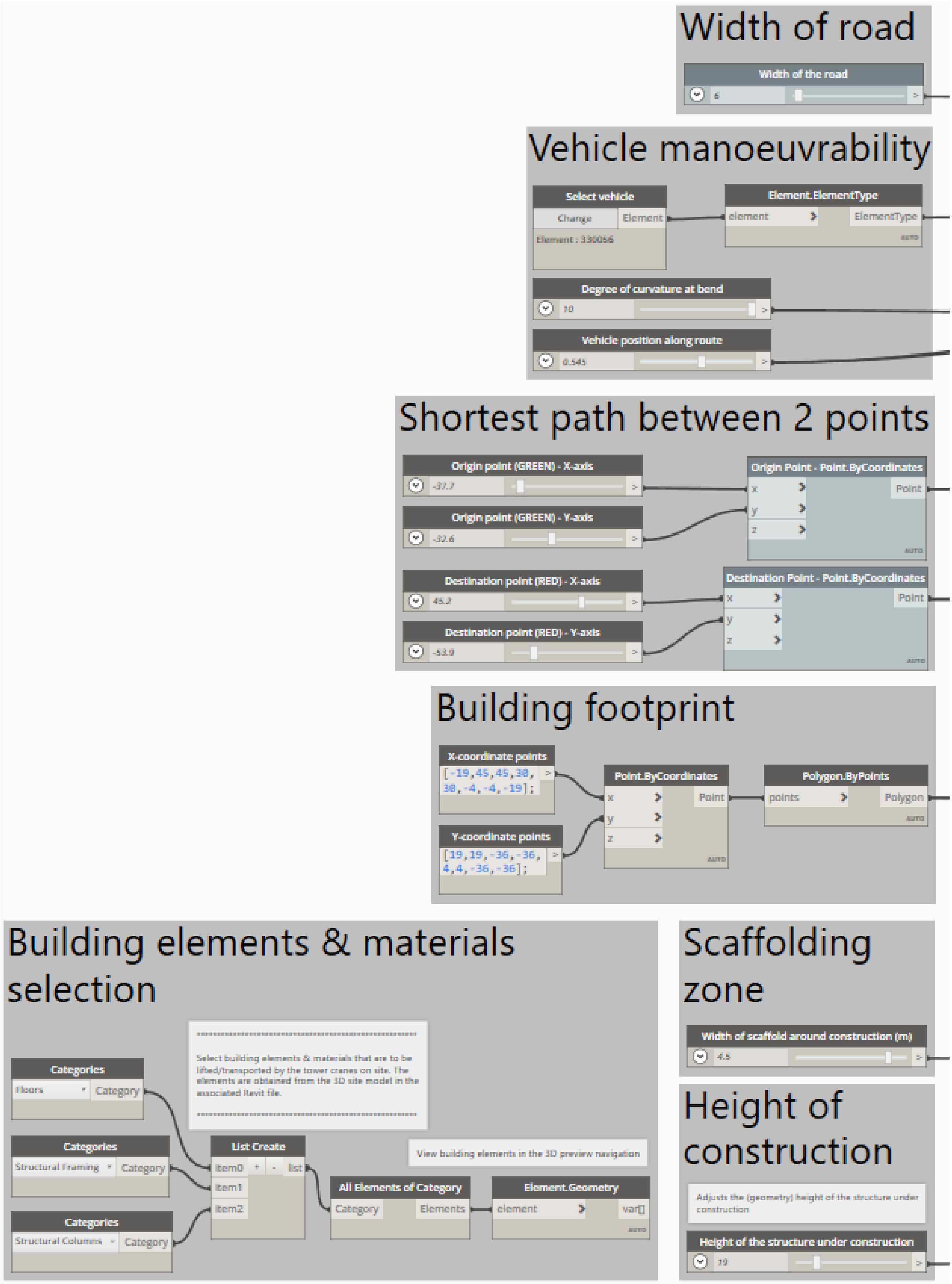

Figure 5.2: Input graphs for the abstract site model – 2

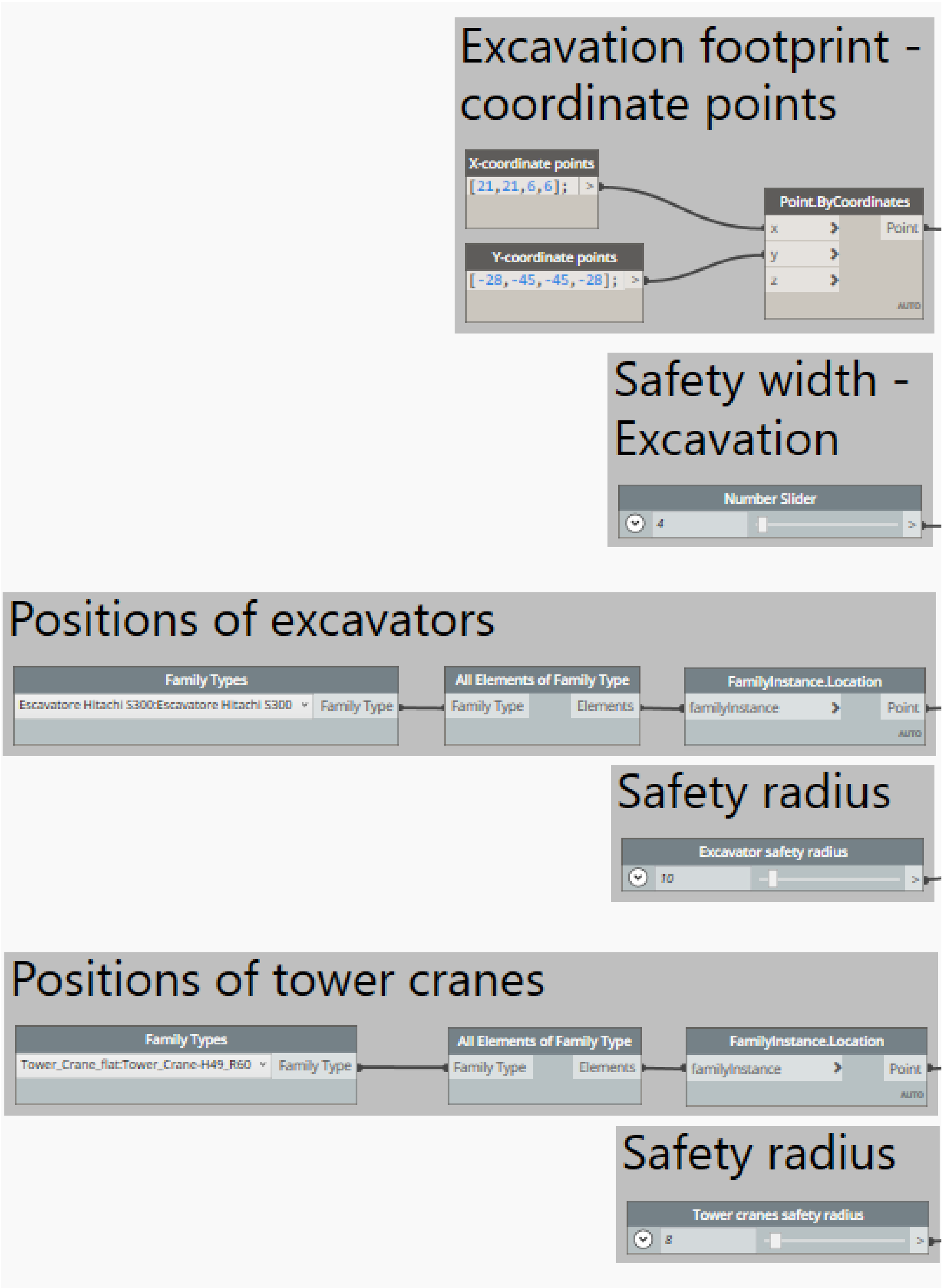

Figure 5.3: Input graphs for the abstract site model – 3

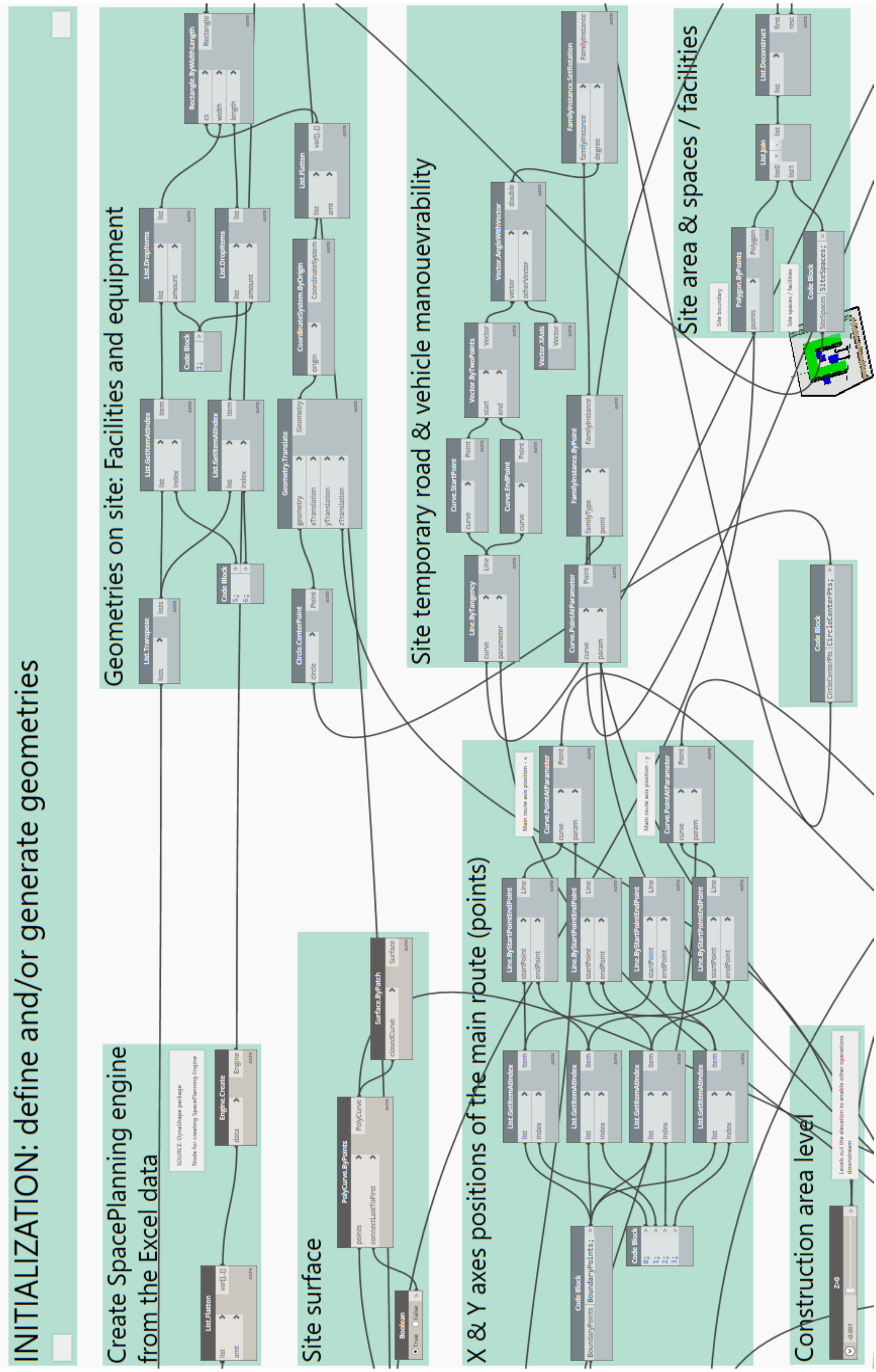

Figure 5.4: Initialization graphs for the abstract site model – 1

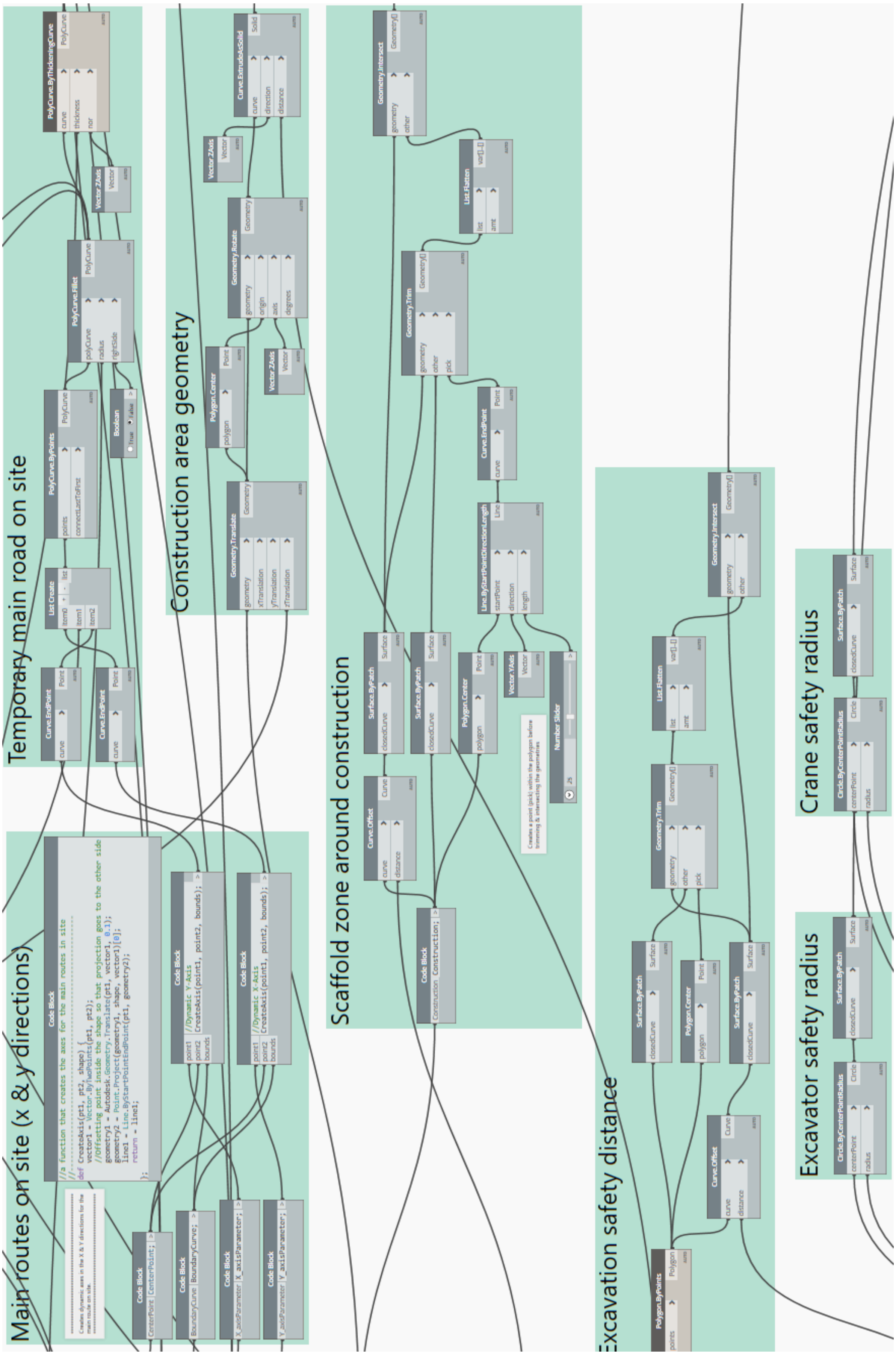

Figure 5.5: Initialization graphs for the abstract site model – 2

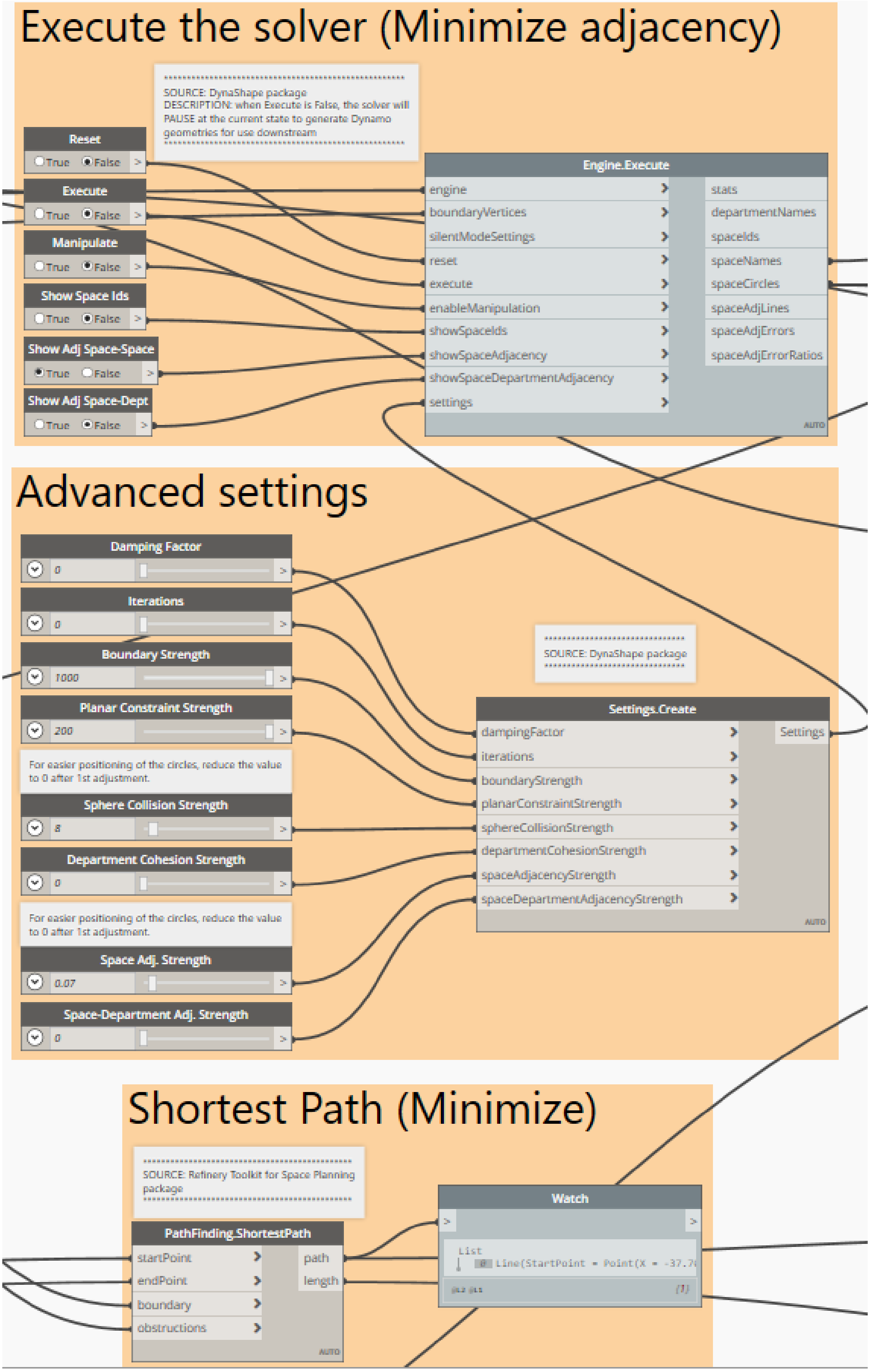

Figure 5.6: Analysis graphs for the abstract site model

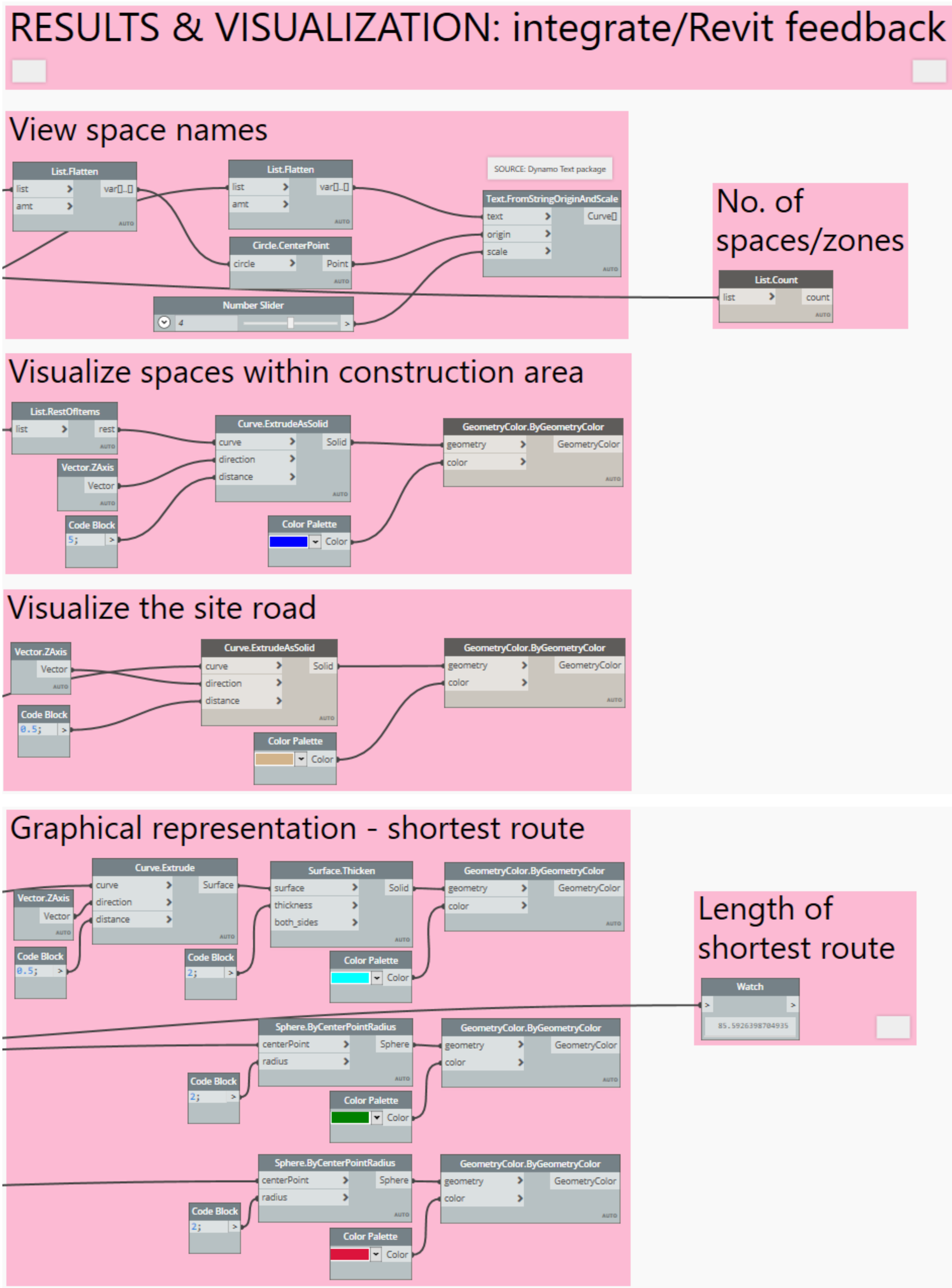

Figure 5.7: Results and visualization graphs for the abstract site model – 1

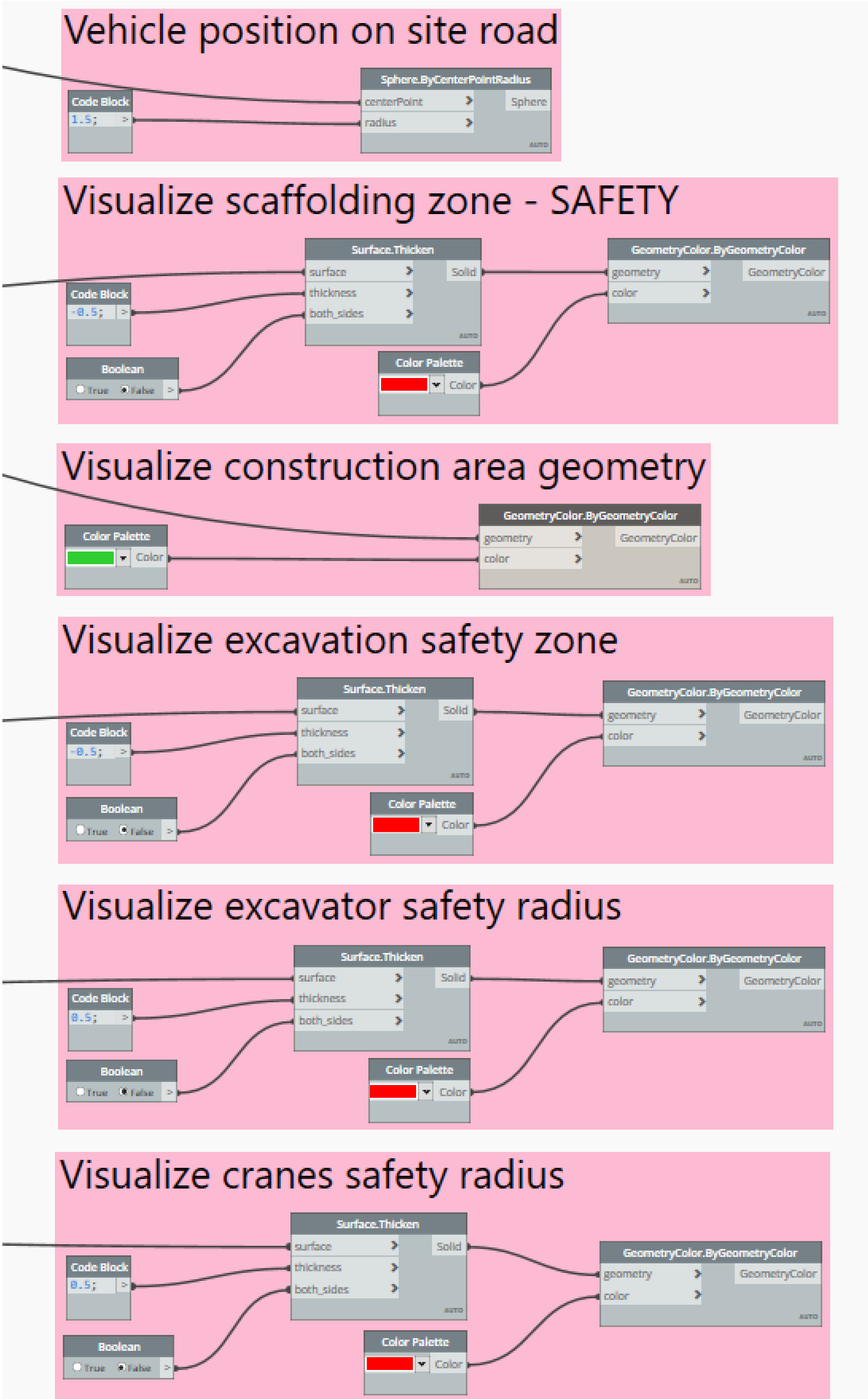

Figure 5.8: Results and visualization graphs for the abstract site model – 2

b) Spatial planning script for the case study site model – modified input and initialization

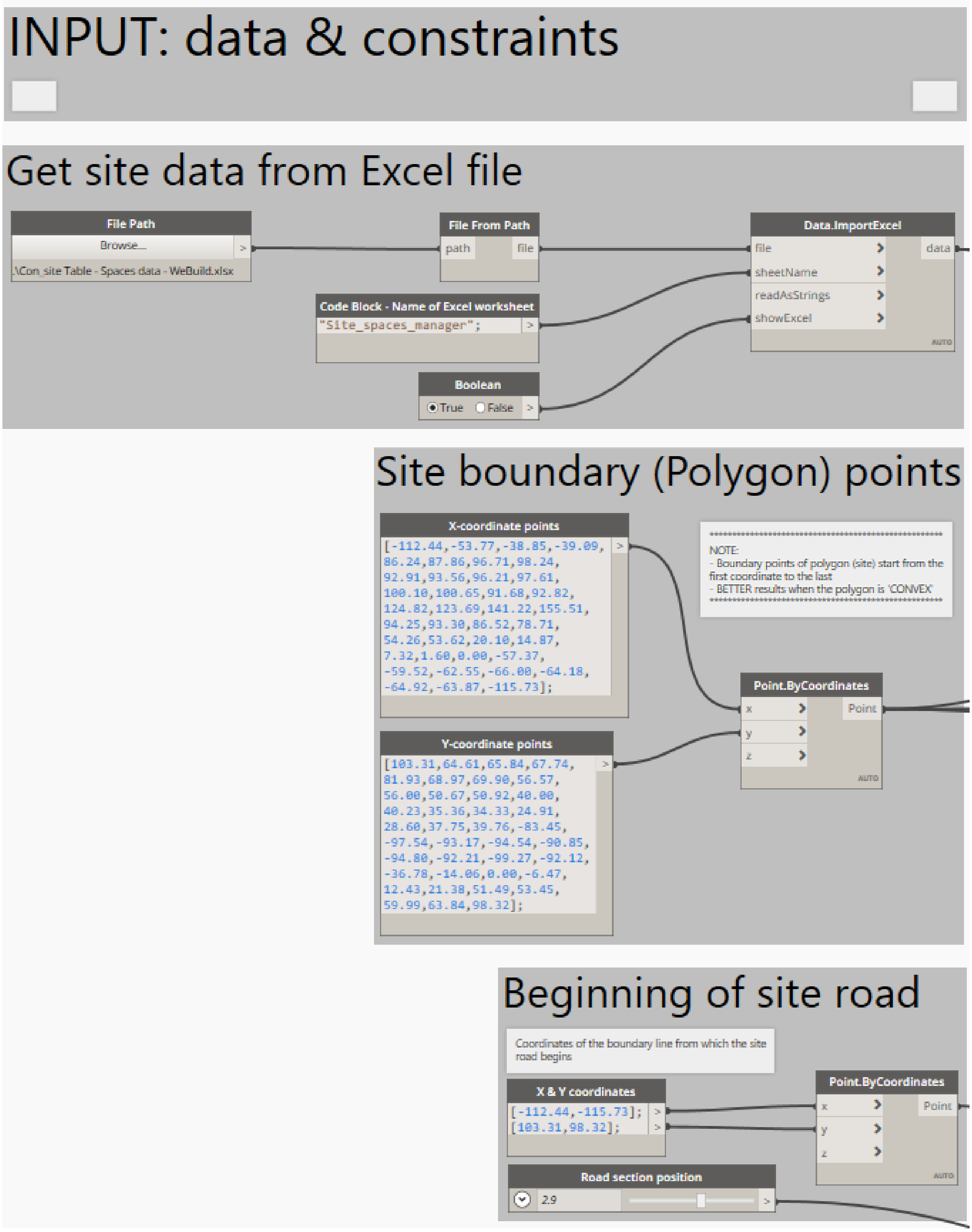

Figure 5.9: Input graphs for the case study site mode – 1

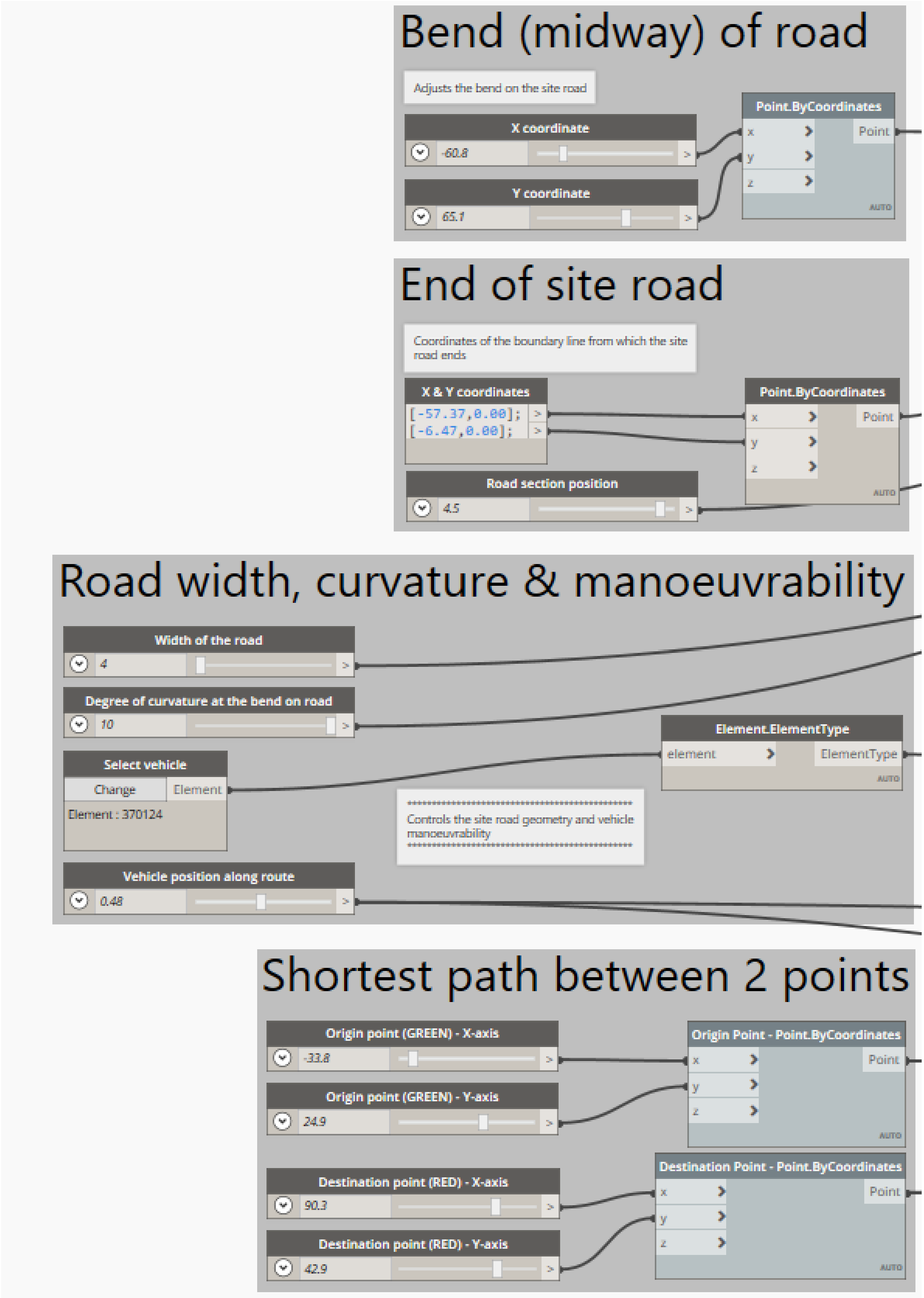

Figure 5.10: Input graphs for the case study site mode – 2

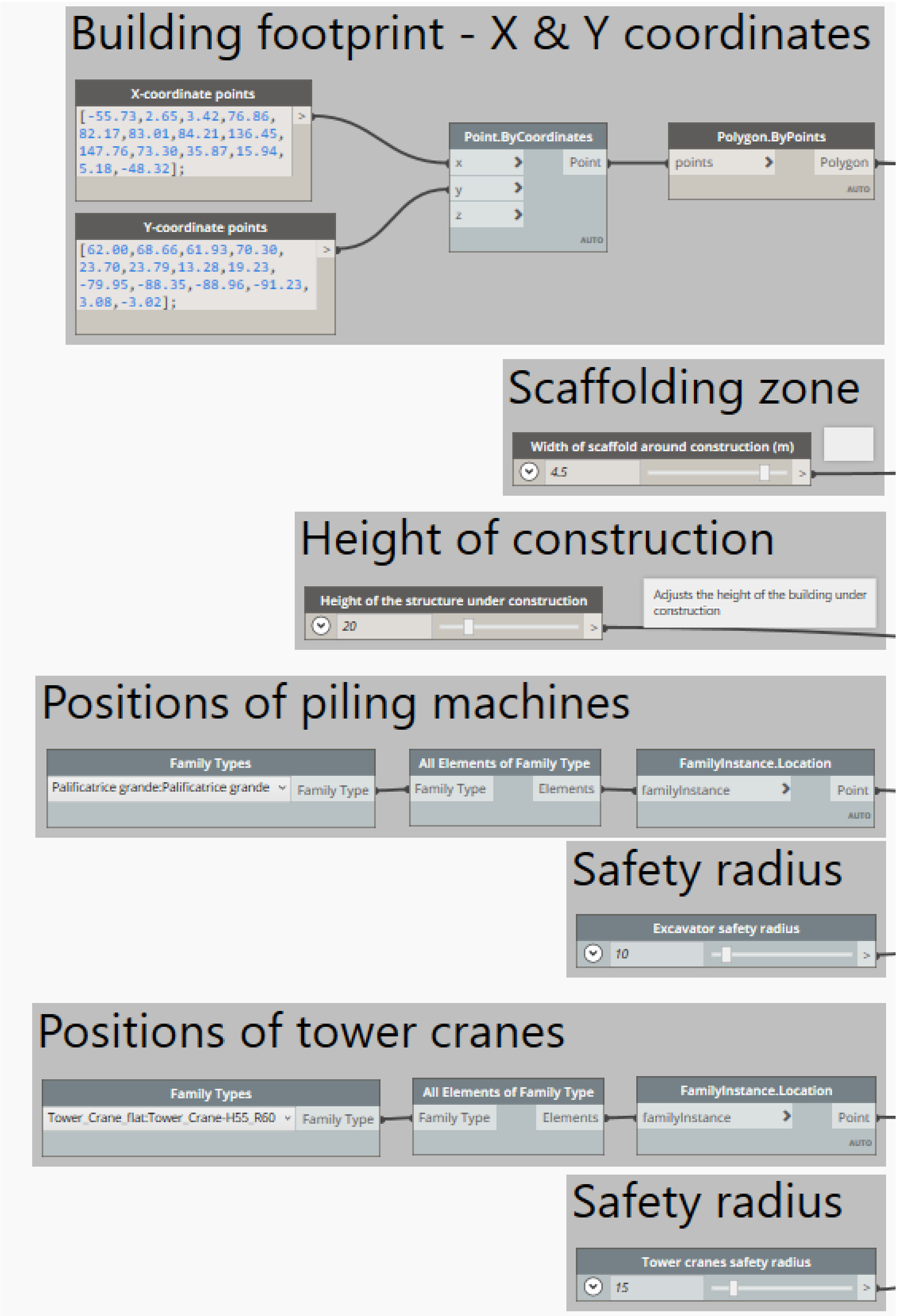

Figure 5.11: Input graphs for the case study site model – 3

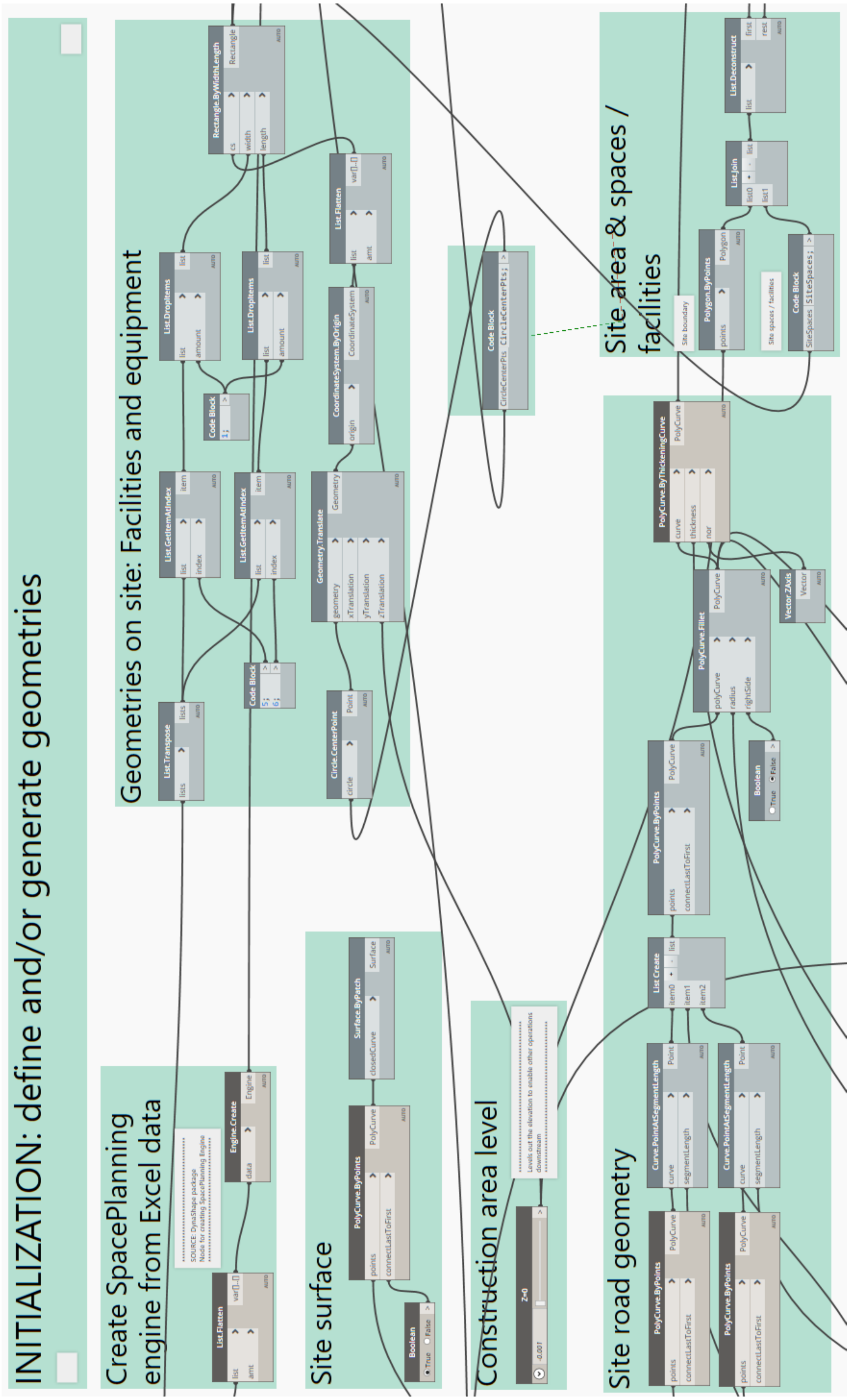

Figure 5.12: Initialization graphs for the case study site model – 1

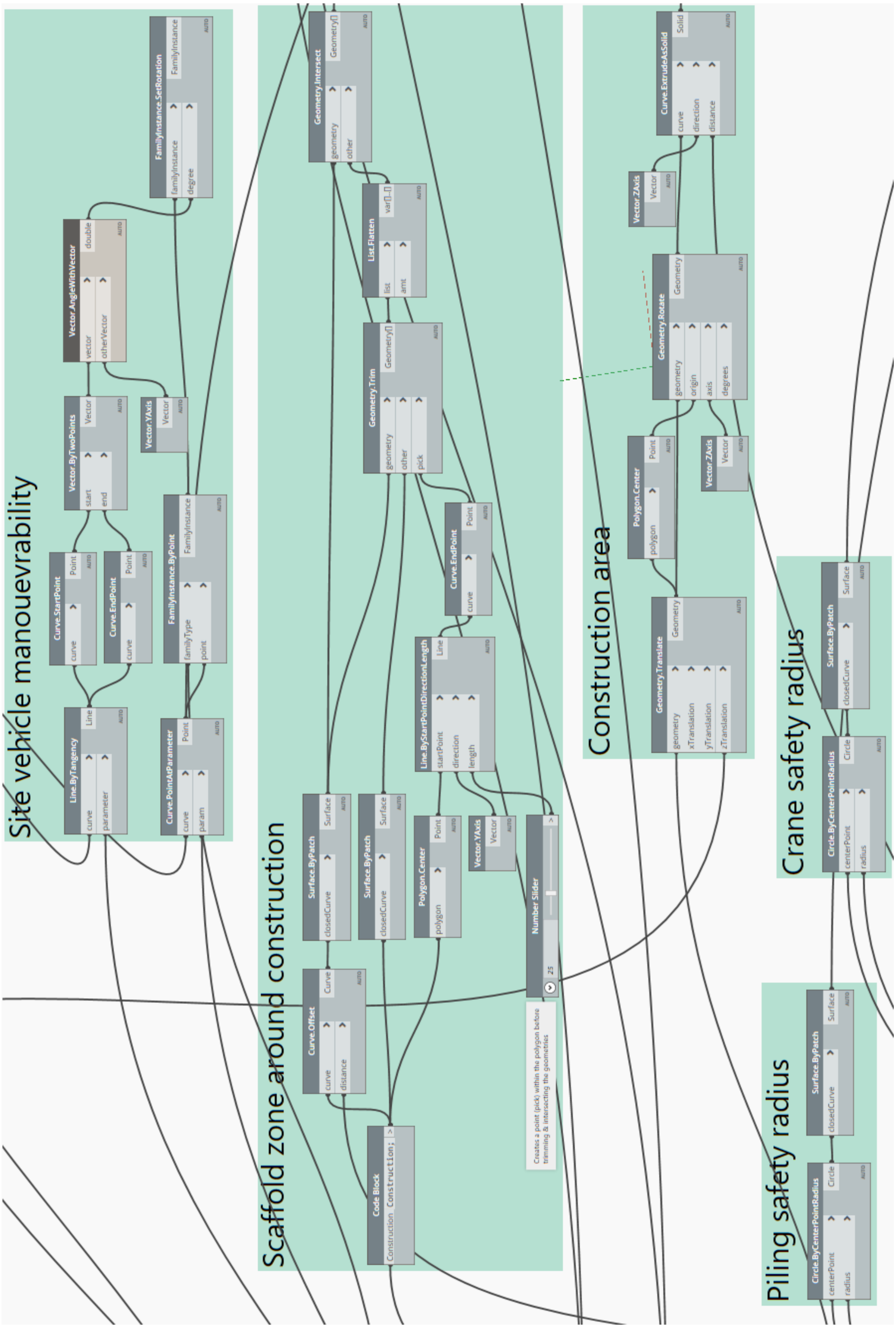

Figure 5.13: Initialization graphs for the case study site model – 2

A3: SCRIPT FOR THE OPTIMIZATION OF CRANE POSITIONS

The Dynamo script shown in this section was used to optimize the positions of the tower cranes in both the abstract site model and the case study model.

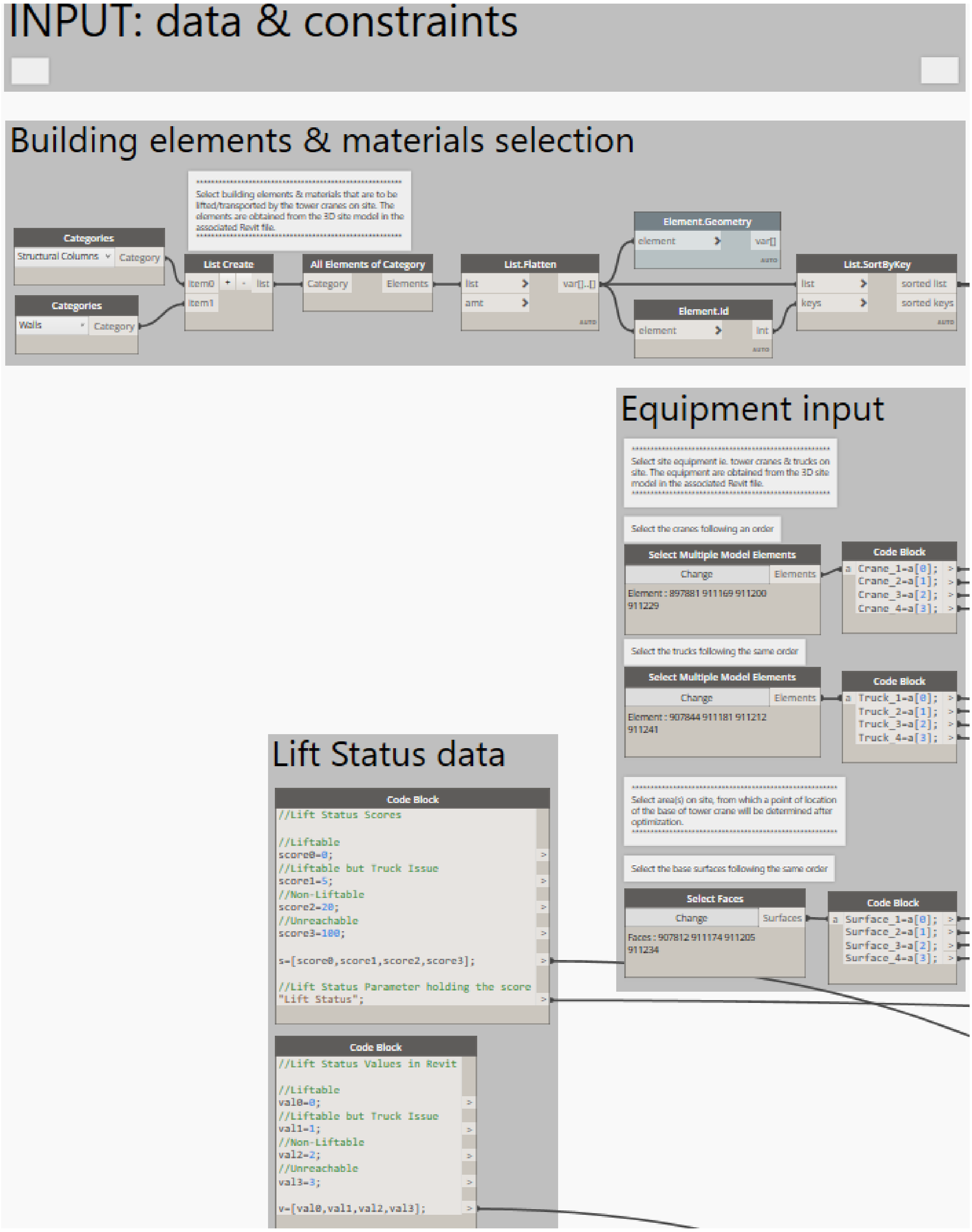

Figure 5.14: Input graphs for crane positions optimization – 1

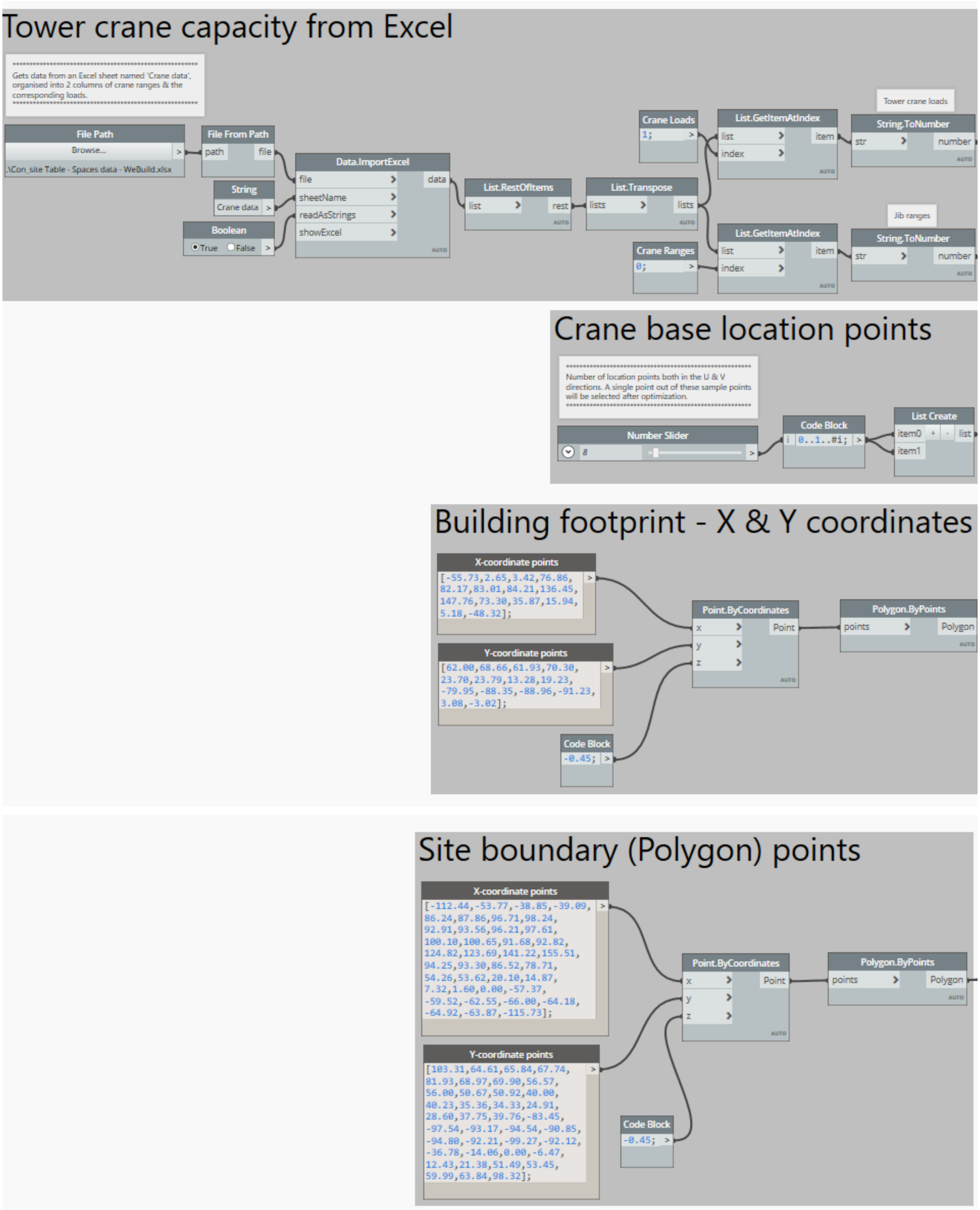

Figure 5.15: Input graphs for crane positions optimization – 2

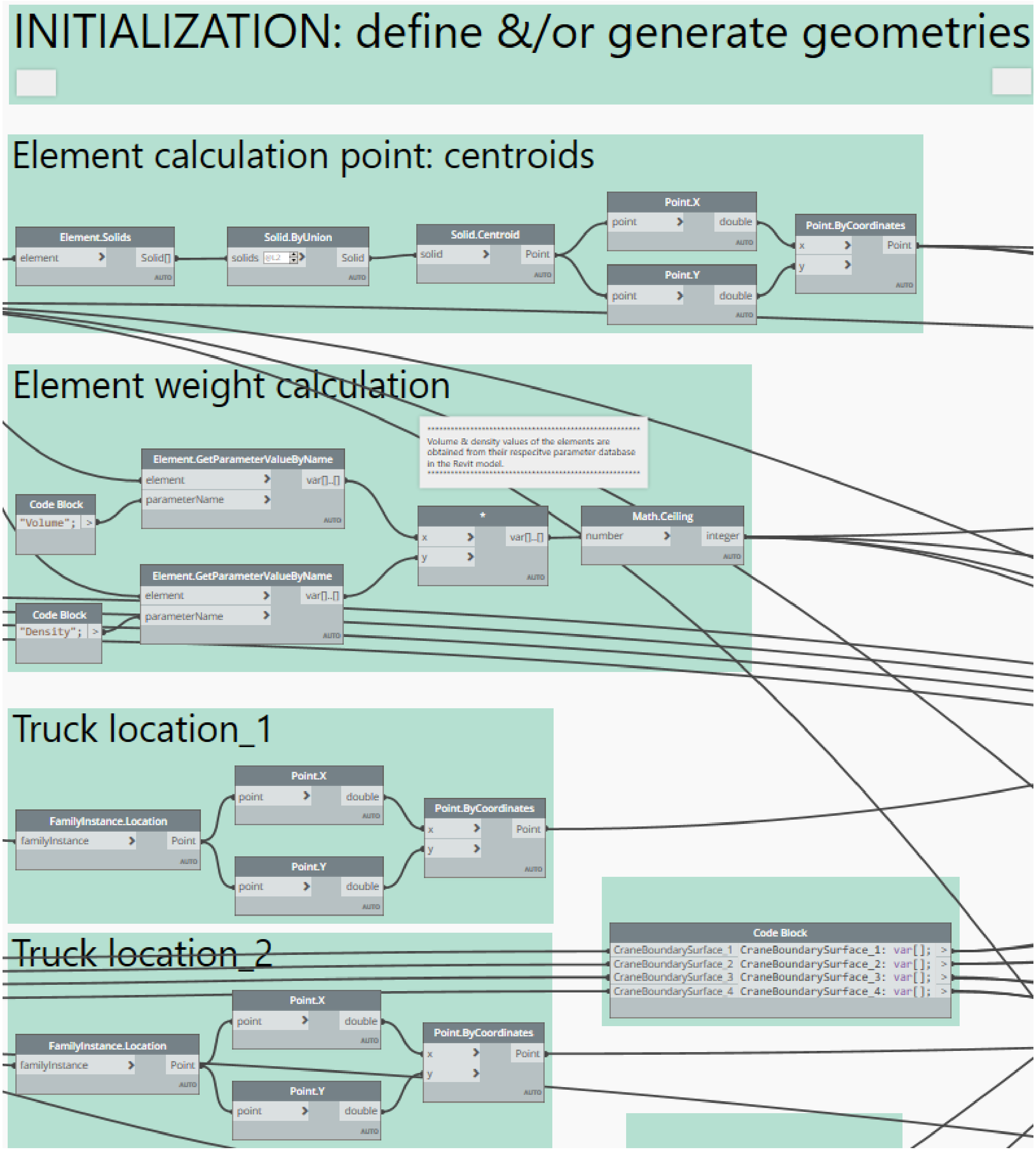

Figure 5.16: Initialization graphs for crane positions optimization – 1

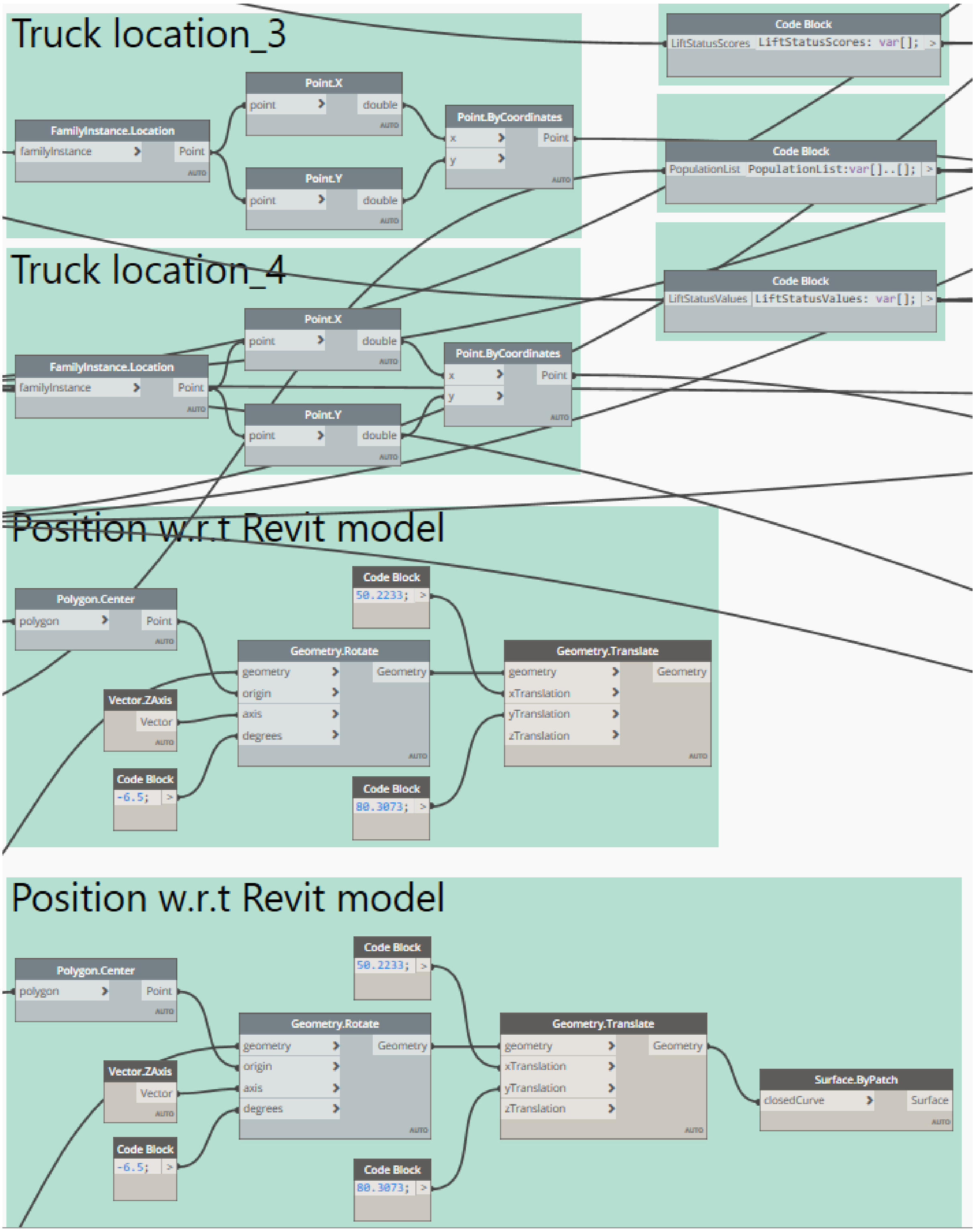

Figure 5.17: Initialization graphs for crane positions optimization – 2

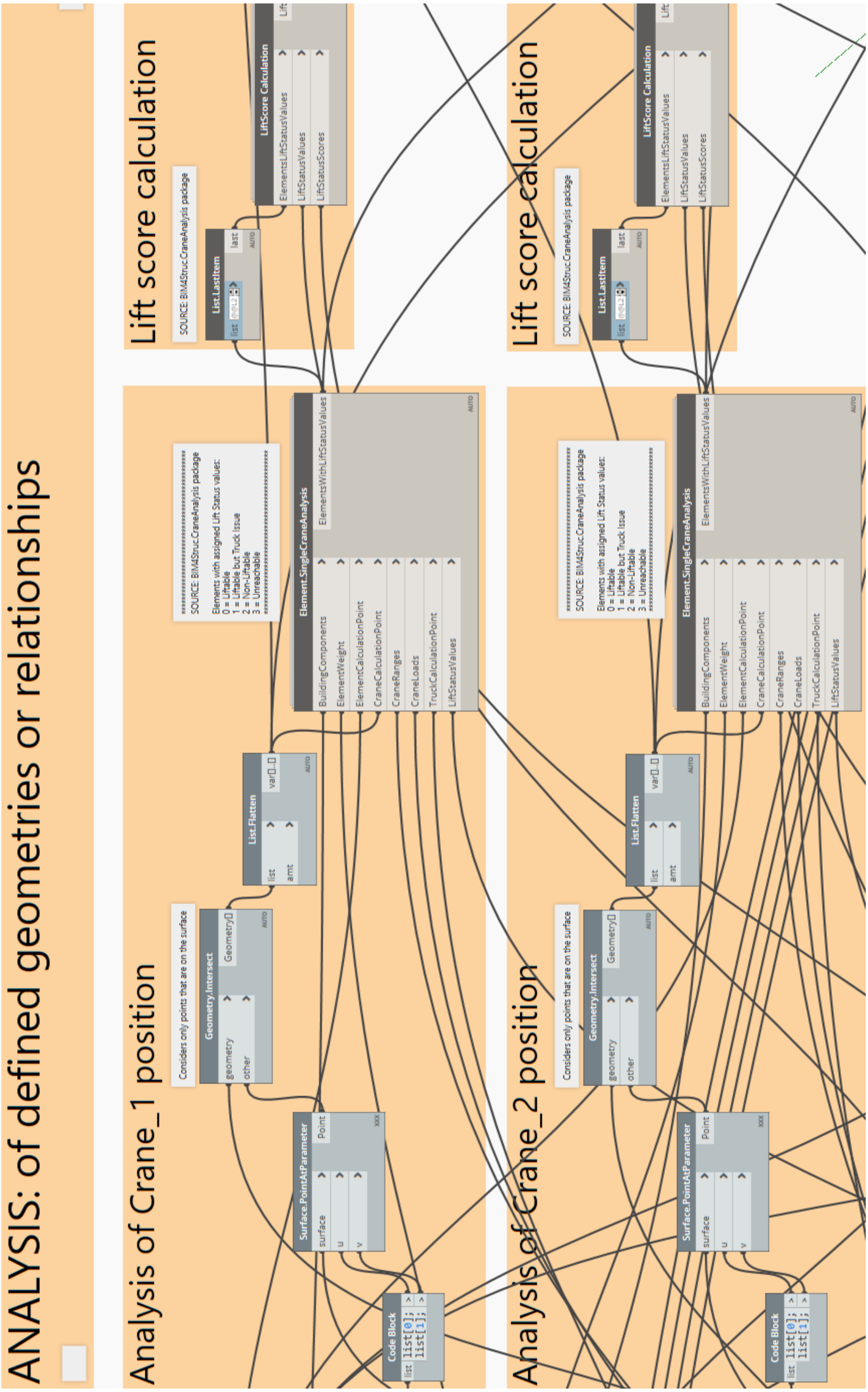

Figure 5.18: Analysis graphs for crane positions optimization for two of the four tower cranes

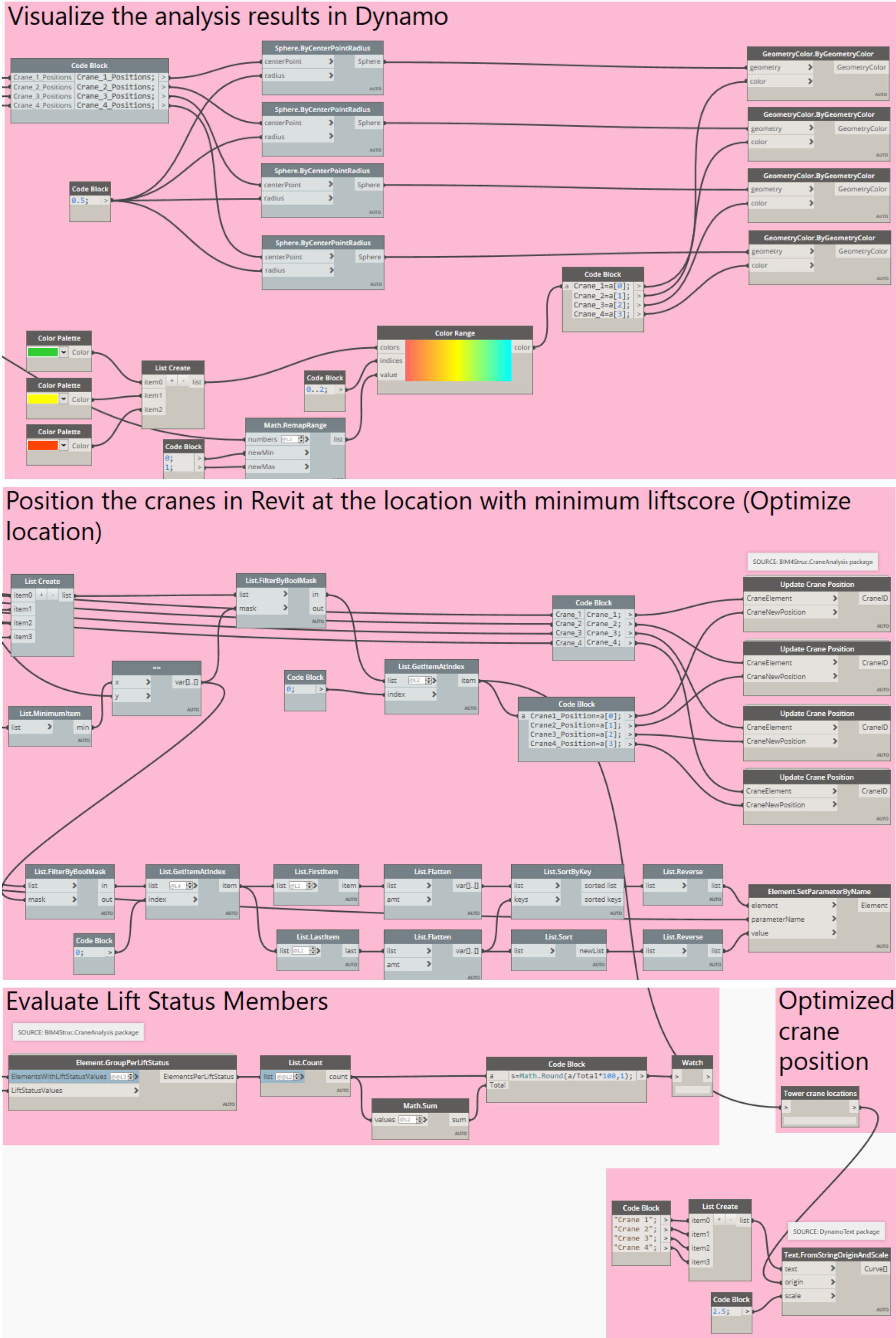

Figure 5.19: Results and visualization graphs for optimized crane positions

APPENDIX B: INSTRUCTIONS FOR RUNNING THE SCRIPTS

This section contains summarized instructions for an effective running of the generated Dynamo scripts.

B1: BRIEF INSTRUCTIONS FOR SPATIAL PLANNING SCRIPT

1. With the central site BIM model in active session, open the Dynamo script in Manual mode. Select the path for the Excel spatial data, then set the 'Execute' and 'Manipulate' nodes to 'True' as shown below.

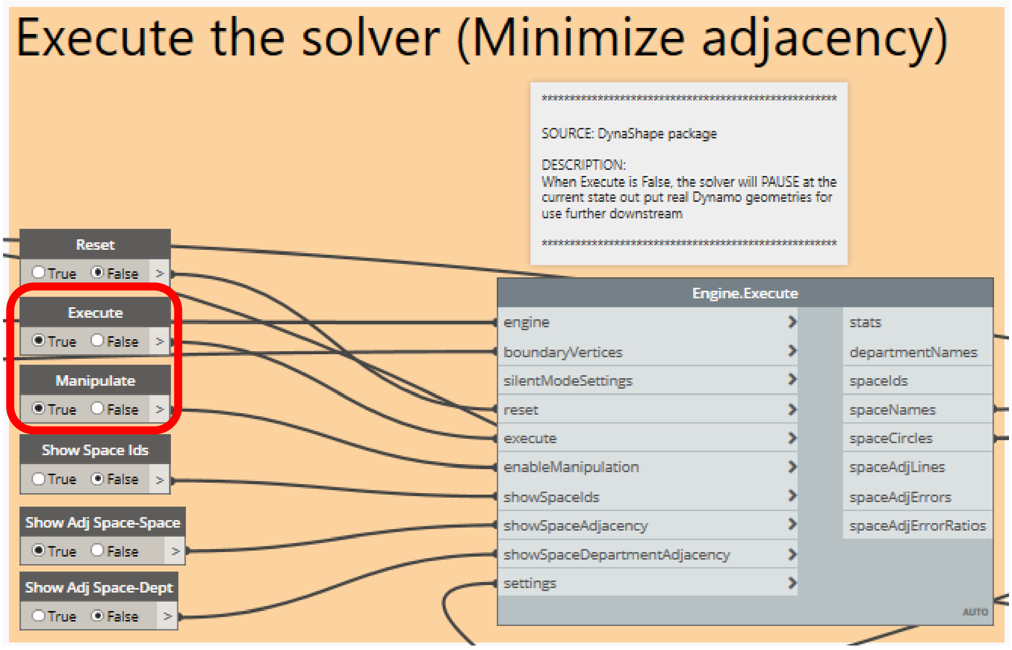

Figure 5.20: Initializing the solver

2. Run the script, then adjust the spaces (circles) in the background 3D preview navigation as required by dragging at their center points.
3. If need be, minimize the parameters shown below to reduce the 'bouncing' of circles to make the adjusting process easier.

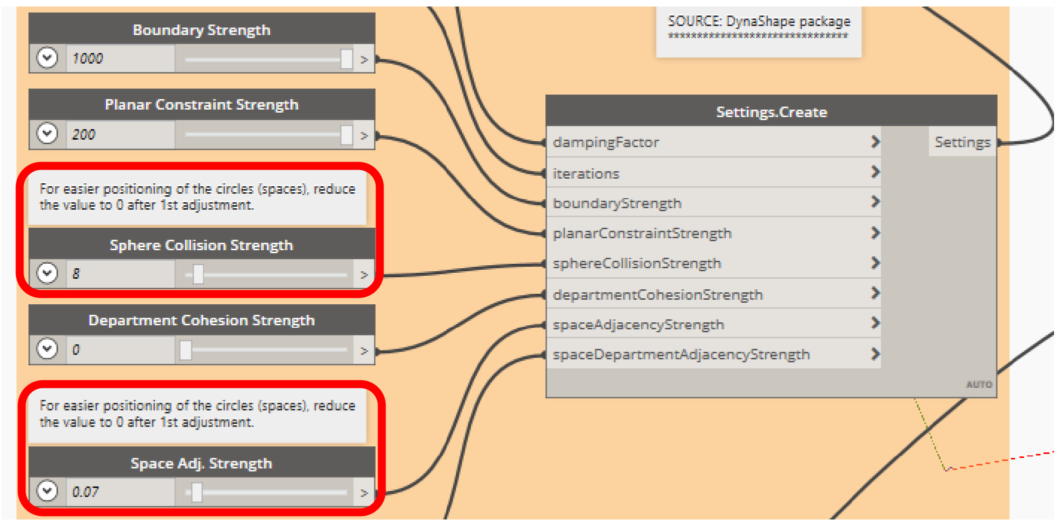

Figure 5.21: Advanced settings

4. After the adjustment of positions, set the 'Execute' and 'Manipulate' to 'False' then Run to generate the site geometries downstream.
5. The site geometries can be adjusted from the Input section of the Dynamo graphs.

B2: BRIEF INSTRUCTIONS FOR CRANE POSITIONING SCRIPT

1. With the federated model in active session, open the Dynamo script in Manual mode.
2. In the Input section of the Dynamo graph, select the file path for crane data in Excel, and the building elements to be lifted. The tower cranes, trucks and crane base host area should also be selected in the same order as described by the commentaries in the script.

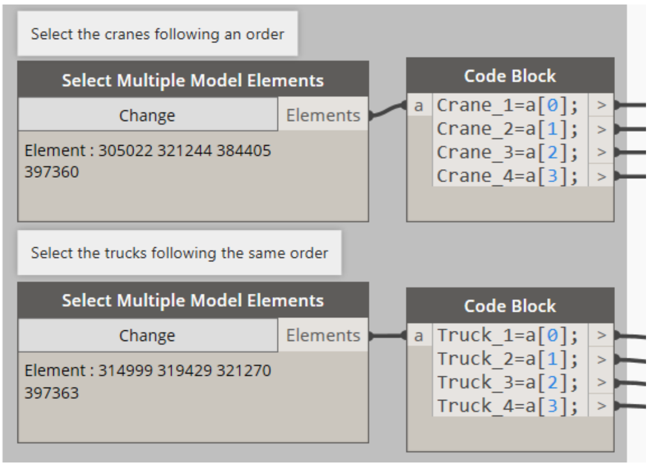

Figure 5.22: Selection of the cranes, trucks and host areas from the Revit BIM model

3. Run the script to optimize the positions of the tower cranes and update in the Revit BIM model.
4. The analysed points of crane base locations on the crane base hoist areas can be viewed in the background 3D preview navigation as shown below. The crane reachability decreases as the colours transition from green through yellow to red.

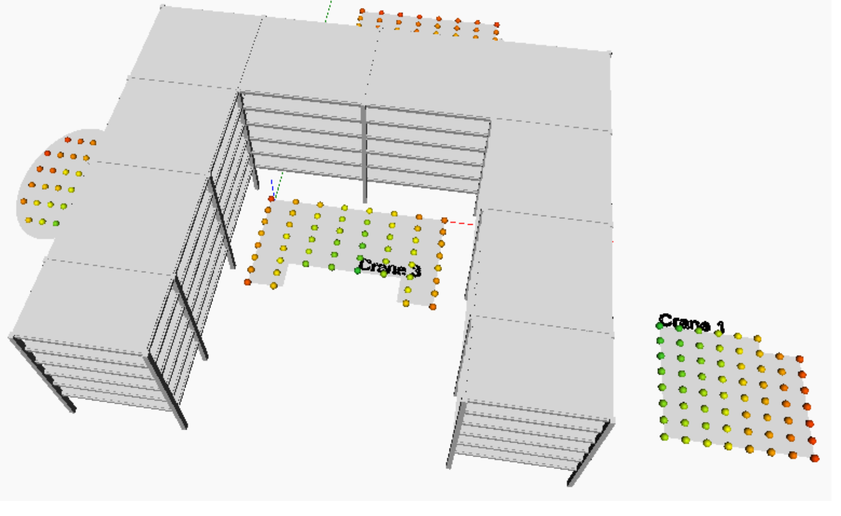

Figure 5.23: Analysed points of tower crane base locations on the host areas

APPENDIX C: LOAD CHART FOR TOWER CRANES

Table 5.2: Load chart for tower cranes (Source of data: ALL Tower Crane)

LOAD CHART (metric tons/meters) 4-PART LINE
WB 66-100/4F ~108 HP (79KW) Hoist Winch

"A"	2.5	3.5	4.6	5.8	7.1	8.6	10.2	12.1	14.4
"B"	74	69	64	59	54	49	44	39	34
"C"	17.6	19.4	21.2	22.7	24	25.1	25.6	26	26.1
Hook Radius [ft.] ▼	AVAILABLE JIB LENGTHS								
	L9 74(m)	L8 69(m)	L7 64(m)	L6 59(m)	L5 54(m)	L4 49(m)	L3 44(m)	L2 39(m)	L1 34(m)
4.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
17.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
18.00	19.34	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
19.00	18.11	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
20.00	17.00	19.23	20.00	20.00	20.00	20.00	20.00	20.00	20.00
21.00	16.01	18.13	20.00	20.00	20.00	20.00	20.00	20.00	20.00
22.00	15.11	17.13	18.97	20.00	20.00	20.00	20.00	20.00	20.00
23.00	14.30	16.22	17.98	19.50	20.00	20.00	20.00	20.00	20.00
24.00	13.55	15.39	17.07	18.53	20.00	20.00	20.00	20.00	20.00
25.00	12.88	14.64	16.25	17.64	18.76	20.00	20.00	20.00	20.00
26.00	12.26	13.95	15.50	16.84	17.91	18.85	19.36	20.00	20.00
27.00	11.69	13.32	14.80	16.09	17.12	18.03	18.52	18.85	18.95
28.00	11.17	12.73	14.16	15.40	16.40	17.27	17.75	18.06	18.16
29.00	10.68	12.19	13.57	14.76	15.72	16.56	17.02	17.32	17.42
30.00	10.22	11.68	13.01	14.17	15.09	15.91	16.35	16.64	16.73
31.00	9.79	11.21	12.49	13.61	14.51	15.29	15.72	16.00	16.09
32.00	9.40	10.76	12.01	13.09	13.96	14.72	15.13	15.40	15.49
33.00	9.02	10.35	11.56	12.60	13.44	14.18	14.58	14.84	14.93
34.00	8.67	9.96	11.13	12.14	12.96	13.67	14.06	14.32	**14.40**
35.00	8.34	9.59	10.73	11.71	12.50	13.20	13.58	13.82	
36.00	8.03	9.24	10.35	11.30	12.07	12.75	13.12	13.36	
37.00	7.74	8.91	9.99	10.92	11.67	12.32	12.68	12.91	
38.00	7.46	8.60	9.65	10.56	11.28	11.92	12.27	12.50	
39.00	7.19	8.31	9.33	10.21	10.92	11.54	11.88	**12.10**	
40.00	6.94	8.03	9.02	9.88	10.57	11.18	11.51		
41.00	6.71	7.76	8.73	9.57	10.24	10.83	11.16		

42.00	6.48	7.51	8.46	9.28	9.93	10.51	10.82		
43.00	6.26	7.27	8.19	8.99	9.63	10.20	10.50		
44.00	6.06	7.04	7.94	8.72	9.35	9.90	**10.20**		
45.00	5.86	6.82	7.71	8.47	9.08	9.62			
46.00	5.67	6.62	7.48	8.22	8.82	9.35			
47.00	5.49	6.42	7.26	7.99	8.57	9.09			
48.00	5.32	6.22	7.05	7.76	8.34	8.84			
49.00	5.16	6.04	6.85	7.55	8.11	**8.60**			
50.00	5.00	5.86	6.66	7.34	7.89				
51.00	4.85	5.70	6.47	7.14	7.68				
52.00	4.70	5.53	6.29	6.95	7.48				
53.00	4.56	5.38	6.12	6.77	7.29				
54.00	4.43	5.23	5.96	6.59	**7.10**				
55.00	4.30	5.08	5.80	6.42					
56.00	4.17	4.94	5.65	6.26					
57.00	4.05	4.81	5.50	6.10					
58.00	3.93	4.68	5.36	5.95					
59.00	3.82	4.55	5.22	**5.80**					
60.00	3.71	4.43	5.09						
61.00	3.61	4.31	4.96						
62.00	3.50	4.20	4.84						
63.00	3.41	4.09	4.72						
64.00	3.31	3.98	**4.60**						
65.00	3.22	3.88							
66.00	3.13	3.78							
67.00	3.04	3.68							
68.00	2.96	3.59							
69.00	2.88	**3.50**							
70.00	2.80								
71.00	2.72								
72.00	2.64								
73.00	2.57								
74.00	**2.50**								

"A" = Load at maximum radius (tons)

"B" = Maximum radius (m)

"C" = Radius with maximum load (m)