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BIM-based Lift Planning Workflow for On-site Assembly in Modular Construction Projects

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Abstract: The assembly of modular construction requires a series of thoroughly-considered decisions for crane lifting including the crane model selection, crane location planning, and lift path planning. Traditionally, this decision-making process is empirical and time-consuming, requiring significant human inputs. Recently, research efforts have been dedicated to improving lift planning practices by leveraging cutting-edge technologies such as automated data acquisition, Building Information Modelling (BIM) and computational algorithms. It has been demonstrated that these technologies have advanced lift planning to some degree. However, the advancements tend to be fragmented and isolated. There are two hurdles prevented a systematic improvement of lift planning practices. First, the lack of formalized lift planning workflow, outlining the procedure and necessary information. Secondly, there is also an absence of a shared information environment, enabling storages, updates and the distribution of information to stakeholders in a timely manner. Thus, this paper aims to overcome the hurdles. The study starts with a literature review in combination with document analysis, enabling the initial workflow and information flow. These were contextualised through a series of interviews with Australian practitioners in the crane-related industry, and systematically analysed and schematically validated through an expert panel. Findings included formalized workflow and corresponding information exchanges in a traditional lift planning practice via a Business Process Model and Notation (BPMN). The traditional practice is thus reviewed to identify opportunities for further enhancements. Finally, a BIM-based lift planning workflow is proposed, which integrates the scattered technologies (e.g. BIM and computational algorithms) with the aim of supporting lift planning automation. The resulting framework is setting out procedures that need to be developed and the potential obstacles towards automated lift planning are identified.

Key words: Modular construction, BIM, Lift Planning, Crane, Construction automation

1. INTRODUCTION

Over the past few decades, modular construction is increasingly prevalent around the globe. This innovative construction method has dramatically enhanced productivity and safety via manufacturing building modules in a controlled plant environment [1] and assembling them on-site. While the modular construction method greatly boosts the efficiency and productivity of the construction process, it increases the complexity in planning and managing on-site assembly processes, which usually involves large cranes lifting prefabricated construction modules. Since these modules to be lifted are typically large and heavy with complex geometries, the lift crew has to take extra care to avoid safety hazards such as collision and crane overturning. Meanwhile, crane-related tasks are critical to prefabrication projects management by significantly impacting the overall schedule and affecting budget implementation [2]. Therefore, meticulous lift planning is essential to mitigate risks and improve efficiency.

Traditional lift planning is a tedious and complex process, depending on planners' evaluations of the site, available crane models, and lifting tasks [23]. In most cases, this information is collected and managed by different stakeholders. For example, a regular crane operation typically involves five participants or participating organizations [12]. Correspondingly, the information from these stakeholders is kept on various physical and digital formats, such as spreadsheets, drawings or text files and exchanged via meetings, emails and handbooks. This exchange process is inefficient and often further prolongs the planning process with possible omissions and delays [17]. As a result, planners have to go through iterative cycles of coordination to retrieve necessary information for decision-making. Hence, the traditional lift planning process usually lasts for months [14]. On the other hand, planners heavily rely on their experience. Thus, the planners may not fully consider all possible scenarios and alternatives, leading to a suboptimal lift plan. These shortages make current lift planning a time-consuming and ineffective process.

Modern technologies have the potential to advance lift planning practices. As a new paradigm in managing construction projects, Building Information Modelling (BIM) is capable of harmonizing information exchanges between different stakeholders in a timely and concise manner [19]. For example, researchers have defined the workflow of design and engineering to coordinate the collaborations among architects and engineers [3,4]. Another widely adopted technology is the planning algorithm. Researchers have proposed numerous algorithms to automate and optimize some lift planning decisions such as crane model selection [5], crane positioning [6], path planning [7], and crane stability design[8]. Thirdly, technologies in acquiring real-time construction data have been evolving in terms of efficiency and accuracy, such as laser scanning and GIS [9,10].

Recognizing the limitations of existing lift planning practices and the opportunities presented by new technologies, this paper presents a new workflow that integrates cutting-edge technologies to acquire, manage and analyse lift-related information. The study is presented as follows: Section 2 presents a thorough literature review on the traditional lift planning process and advanced information technologies employed to assist in current lift planning practices. This is followed by Section 3, describing the research methodology. Section 4 implements the methodology to formulate the innovative workflow. Both traditional and innovative lift planning workflows are illustrated with BPMN models and the necessary information exchanges are identified. Section 5 discusses the benefits and barriers to fulfilling the newly proposed lift planning workflow and concludes the study.

2. LITERATURE REVIEW

As introduced in the previous section, lift planning has a workflow involving multiple stakeholders and comprising several decision-making tasks. Thus, the foremost mission of this study is to clarify the traditional lift planning workflow (section 2.1). The traditional lift planning workflow consists of multiple decisions. In this study, the decision-making processes are abstracted as three modules: information acquisition, information management and decision making. All three modules have been advanced by modern technologies, which is introduced in section 2.2 to 2.4. Since previous research has focused on the application of individual technology, the literature review is expected to enable the formulation of a new workflow utilizing new technologies.

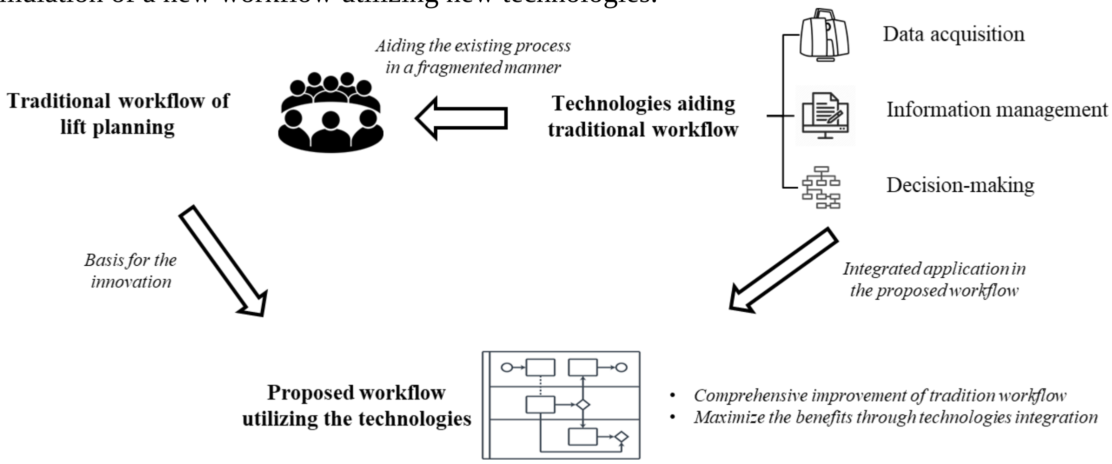

Figure 1. Overview of the relationship between traditional workflow of lift planning, lift planning aiding technologies and the proposed workflow

2.1. Traditional lift planning

Lift planning is a complex task consisting of multiple decisions made through the collaboration of various stakeholders [12]. For example, the site geometric data is collected by the site management team and the crane hire company. Then, the information is exchanged between data collectors and decision-makers so that the decision makers can apply their professional knowledge. In a traditional lift planning process, site geometric data is acquired by manual surveying, managed via 2D drawings, and analysed based on experiences. Therefore, the information is not accurate, comprehensive nor up-to-date.

The traditional lift planning workflow involves many stakeholders and their responsibilities are overlapped in some cases. Thus, many countries formulated standards to specify the stakeholders related to crane operations and their responsibilities. Among the standards, US ASME B30 [12] standards covered most of the roles defined in other standards and further described the respective responsibilities of the crane owner, the crane user, the site supervisor, the lift director, and the crane operator. In this particular paper, the crane owner is specified as the crane hire company and the crane user is specified as the project manager. In the lift planning practice, all stakeholder participates in the decision-making processes, where the major decisions are made by a certain stakeholder while others serve as information sources or reviewers verifying the planning result.

The process of tradition lift planning contains four tasks: (1) determining the type and quantity of cranes, (2) selecting competent crane model, (3) positioning the tower crane on-site and ensuring its stability, and (4) directing paths of individual lifting operations. The sequence has been observed in most lift planning practices, in spite that some tasks are combined in smaller projects. It is also noted that although the sequence exists, tasks are not isolated from each other. For example, in order to select an appropriate crane model, the planners have to know the distances between the supply area and the crane, which is calculated using the location of the supply area and the location of the crane; however, the location of the crane is not determined until the location planning task finishes. In such cases, traditionally lift planning process makes assumptions on unknown information and verify the assumptions in subsequent tasks.

2.2 Data Acquisition

As described in the previous section, information acquisition is the first step to any decision-making in the lift planning process. Traditional information acquisition is accomplished via a hand-operated survey. Recently, cutting edge sensing technology such as 3D laser scanning GIS and photometry technologies have been adopted to aid lift planning. Among the technologies, 3D laser scanning is widely adopted in current surveying practices [9]. Compared with its traditional counterpart, 3D laser scanning outperforms in terms of accuracy, efficiency and ease of communication. Thus, the use of laser scanning technology in construction applications is extensively investigated by researchers. For example, Chen et al. [9] used laser scanning to capture site geometry for tracking mobile assets. Cheng and Teizer [10] utilised laser scanner to measure as-built conditions and site environment. More recently, Goh et al. [11] simulated the lifting operation of critical components in a complex environment based on the authentic information obtained via laser scanning. Although the technology can accelerate tedious manual survey, the scanning results are usually imported as editable models [17]; thus efforts have to be made to convert formats to gain full operability. The reason for this phenomenon is that there lacks a common format accepted by all stakeholders, and each stakeholder has their preferred formats.

2.3 Information Management

Information management is another major interest area of research. Among many information management innovations, Building Information Modelling (BIM) is the most prevailing technologies in the AEC industry. BIM is defined as a digital representation of a facility, which shares knowledge and supports decisions during the entire building life-cycle [29]. The first step of implementing BIM in a certain domain is to specify the workflow of information exchanges, namely Information Delivery Manual (IDM). IDM is a process map denoting the necessary information to be exchanged between two stakeholders [32]. For example, Chuck Eastman et al. [19] generated the IDM for the precast concrete use case and enumerated the information exchanges. Later, efforts were made to consolidate information exchanges to eliminate redundancy and therefore, to enhance efficiency [20, 21]. The application of BIM in prefabrication construction, including modular construction, significantly improved the efficiency of information exchange [30]. However, the studies usually focus on the design and engineering phase, while construction activities such as lift planning are either omitted or oversimplified. For example, in the aforesaid IDM, the general contractor represents all the construction stakeholders [25]. Additionally, construction equipment configurations have not been not clearly defined. One of the obvious reasons is that most lift planning practices are carried out manually and empirically based on drawings and on-site investigations. Thus, construction stakeholders act as end-users, who receive information but provide limited feedback. Therefore, there is no demand to include detailed construction. Nevertheless, the demand grows with the extensive application of modular construction and the increasingly demanding lifting tasks.

2.4 Decision Making

In recent decades, researchers have investigated the potential of algorithms to automate and optimize lift planning. Many algorithms were created and reported for lift planning processes [16]. For the model selection task, some researchers aimed at formalizing the relative importance of selecting criteria and programmed them into an automated scoring system. For example, Han et al. [2] proposed a selection matrix to evaluate each option with scores. Similarly, Marzouk and Abubakr [5] created an analytical hierarchy process (AHP) to score the factors influencing crane type (e.g. Flat Top or Hammerhead tower crane) selection. Meanwhile, other researchers filtered infeasible solutions to narrow down the scope, whereby choose the optimal solution [26]. For example, Sohn et al. [18] adopted a generic algorithm to choose an economical crane model based on crane configurations and soil conditions.

For location planning task, algorithms were adopted to minimize the cost in regards to the crane’s operating time [27]. The location planning problem was therefore simplified as finding the minimum of a function of the cumulative travelling time of loads to be lifted between the supply area and demanding points [28]. Various algorithms have been adopted to seek the minimum of the function. For example, Nadoushani et al. [6] developed a mixed-integer programming algorithm to find the lowest crane rental cost location; Lien and Cheng [16] modified the particle bee algorithm for tower crane layout problems, considering not only budget limit but the capacity of the supply area. It is observed that yielding an optimal result requires cost quotes for many activities and detailed crane configurations from the crane manufacturer; therefore complex information exchanges are inevitable. In this regard, Wang et al. [17] tried to use a BIM model as the source of inputs for algorithms’ mathematical model and a visualisation tool. Although the paper took the advantages of BIM, manual information retrieval from spreadsheets and drawings was not eliminated. In other words, the potential of BIM has not been fully utilized.

For lift path planning, algorithms were adopted to find collision-free and efficient paths for lifting operations. Since path planning is a classic problem in robotics domain, plenty algorithms have been adopted for lift path planning, including Genetic algorithms GA [14], Rapid Random-exploring Tree (RRT) [15], and Probability Roadmaps (PRM) [24]. Compared with the traditional lift path planning process, these algorithms outperformed in finding the shortest collision-free paths and eliminated the worry for exceeding the rated capacity.

2.5 Summary

These data acquisition, information management and decision making technologies have navigated the lift planning towards high efficiency and optimization; however, they arose new problems. One of the problems is poor interoperability. For example, to use planning algorithms, a user may need to translate the schedule information from the traditional Gantt Chart to a matrix or an array in a certain programming language. However, the translation requires a quite specialized yet divergent skillset from the tradition, which is not commonly possessed by AEC practitioners. Therefore, applying new technologies causes extra cost and training time. In addition, new technologies only facilitated part of the activities in the lift planning process. Hence, a limited increase in the efficiency of the entire lift planning process is gained. These two problems reflected a more fundamental issue: there lacks an integrated workflow harmonizing the technology-aided lift planning activities.

According to the previous analysis, lift planning, as one of the increasingly important activities in construction, has the revolutionary potential with emerging information technologies. These technologies are expected to advance lift planning for all types of crane, regardless of tower cranes and mobile cranes. However, in real-world practices, planning activities for tower cranes and mobile cranes are not at this point yet. This difference attributes to their contrasting operating mechanics; for example, mobile cranes can change location during construction while tower cranes cannot. Thus, planning for tower cranes requires a more comprehensive and accurate set of information of all anticipated construction activities at the early project planning stage. This includes the more challenging development of the standardized workflow and information exchange protocol for tower crane lift planning. At a later stage, the workflow can be adapted to mobile crane lift planning.

3. RESEARCH METHOD

The literature review and document analysis of existing manufacture guidelines established an initial BPMN map and helped in identifying subject experts for interviews. Initially, the BPMN map was circulated for comments before a panel discussion with the Australian domain experts of the crane lifting industry established traditional practices as well as validated the set up for the technologically enhanced and integrated workflow.

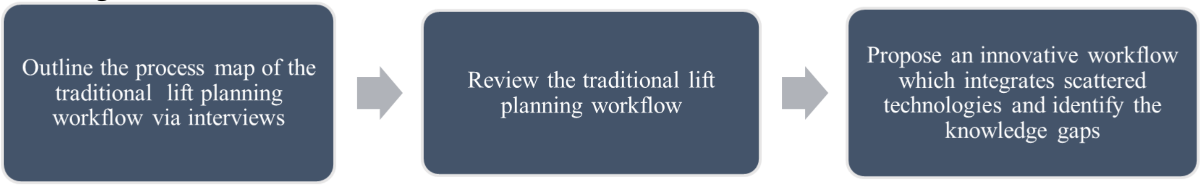

Figure 2. Overview of the method to propose the new lift planning workflow

Focusing on lift planning for tower cranes, the research process followed a three-step method. Firstly, the authors organized a panel of domain experts in the crane lifting industry and based on their discussion, established the traditional lift planning workflow. The result was summarized using a Business Process Modelling Notation (BPMN) map. Secondly, the traditional lift planning BPMN was scrutinized and analyzed. Discussion items included the contents, the level of detail, the formats, the sources, and the exchanges of information. Meanwhile, the traditional workflow was also assessed in terms of efficiency, optimization, and coherence. Thirdly, the authors investigated the potential of aforesaid data acquisition, information management and decision making technologies and systemised them in an integrated workflow. The newly developed workflow was also reviewed and both the benefits and challenges were discussed, for description see Section 4.

4. BIM-BASED LIFT PLANNING WORKFLOW

4.1. Traditional lift planning workflow

Through the consultation with the lift expert panel, a traditional lift planning BPMN model has been developed. BPMN is a graphic representation of a business process, denoting the flow of activities and the corresponding information exchanges [31]. Frequently used symbols and notations of BPMN are illustrated in Figure 3. Afterwards, the traditional lift planning BPMN is demonstrated in Figure 4. This diagram streamlined the lift planning process as 4 phases: (1) crane quantity and type determination; (2) subcontracting; (3) jobsite positioning; and (4) lifting path planning. Concurrently, 7 participants were identified: the engineering firm, the fabricator, the project manager, the site supervisor, the crane hire company, the lift director and the crane operator.

Firstly, the project manager needs to ensure that the number of cranes satisfies the job requirement, time and budget. Then, the crane type is determined based on site spatial constraints such as the jurisdiction boundaries of the site, neighbouring structures and the height of the building. Consequently, each crane has fixed working radius and loads to be lifted. Among all loads to be lifted by a tower crane, the most critical load is determined based on size, weight and the distance between supply and demanding points, revealing the minimum rated capacity. The project manager sends the capacity and coverage requirements to the crane hire companies, who then visit the sites and communicate with the site supervisor for site conditions. After that, the crane hire companies nominate cranes with quotes to the project manager based on the inventory of cranes and lifting accessories. The quotes cover a wide range of costs, including direct costs incurred by hiring and indirect costs as associated with crane erection/dismantling and transportation. Finally, the crane configurations and quotes form a proposal which will be submitted to the project manager for approval. When it is approved, the site supervisor starts to deploy cranes on-site, aiming at determining the most efficient location for each crane and, thereafter, finalizing the detailed stability designs (e.g. crane base and tie-in anchorage). Finally, the lift director implements the decisions of the site supervisor and assigns lifting tasks to the crane operator. For the critical lifting tasks, the lift director and the crane operator convene a meeting to issue a formal lift plan; while for the routine lifting tasks, the crane operator directly determines paths, based on their experience.

In spite of lift planning workflow being described in a linear manner, the planning is actually conducted in a trial-and-error fashion. For example, the project manager has to make some assumptions, which cannot be verified until the site supervisor finishes crane positioning. Therefore, the actual information exchange network is way more complicated than it was described in the BPMN model. Meanwhile, the information exchanges are mainly conducted via untimely methods such as meetings and paperwork. Therefore, it consumes a considerable amount of time for a feasible plan. Due to the time constraints, it is nearly impossible to compare several feasible plans, let alone exhaust all possibilities in pursuit of the optimal plan, in the traditional format. Two main reasons for the over-sophisticated decision-making process are the scattered information storage and overlapping functions. As shown in Figure 4, selecting a capable crane model needs to retrieve information from fabricator, the project manager, the site supervisor and the crane operator, who preserve information in their particular formats; and the decision-making function is shared by the crane hire company and the project manager, who do not always own a shared interest. Therefore, retrieving information and unifying the formats become an inevitable bottleneck of efficiency, along with the negotiations to coordinate the collaborative decision makers.

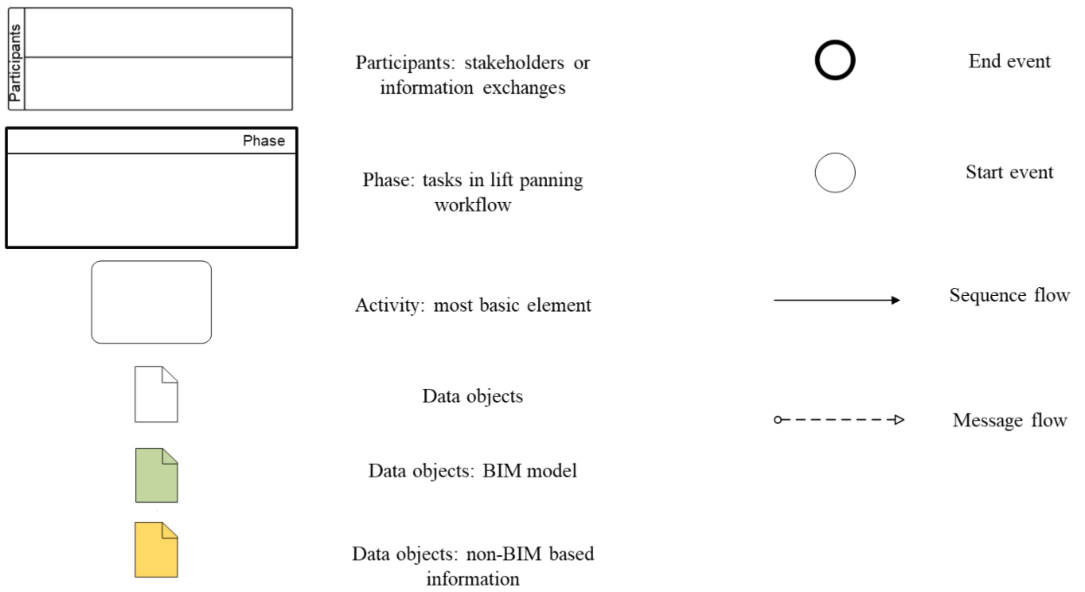

Figure 3 BPMN symbols and notations

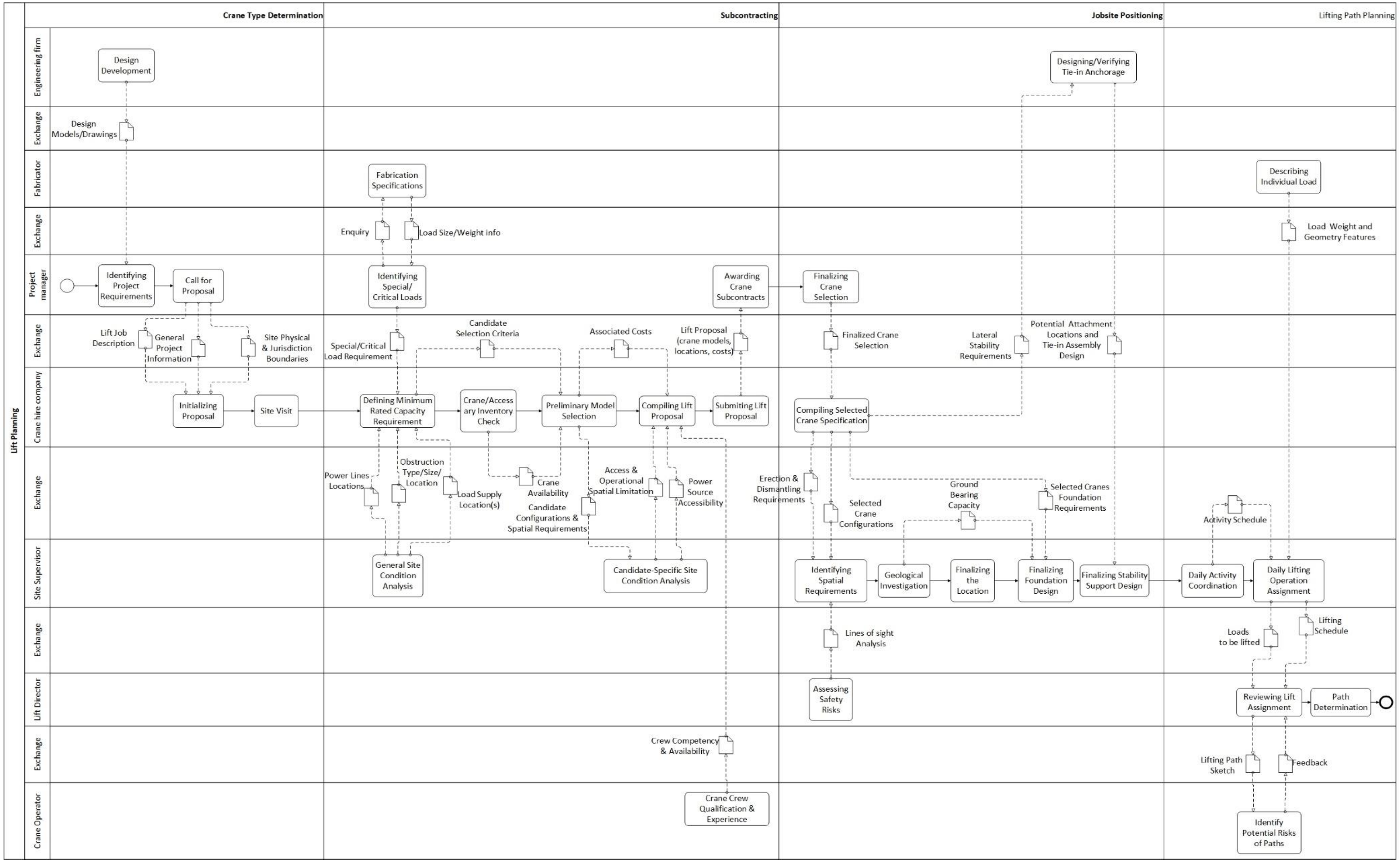

Figure 4 The BPMN model for traditional lift planning workflow

4.2. Reviewing the traditional workflow

Although the traditional crane lift planning workflow is widely adopted, potential improvements are distinctly identifiable. First of all, there is a mismatch between information and knowledge. From the information perspective, there are three clusters: building information, crane configurations, and site conditions. All three clusters of information are held by different stakeholders. For example, building information such as geometry and weight of building components is owned by the engineering firm; crane-related configurations such as jib length, free-standing height, load chart and availability are retained by the crane hire company; and site conditions are kept by site supervisors. In most cases, the decision-maker, who will use their knowledge, is not necessarily familiar with all the information. For example, the crane user determines the crane model but the model configurations are kept by the crane owner. Thus, the information has to be communicated between the information holder and the decision-maker. A decision maker has to request information, wait for information collectors to update their documents (e.g. drawings, paperwork or text files). Such a process occurs repetitively along the traditional workflow, introducing information ambiguity, loss and redundancy.

Additionally, the structure of the whole process is also bottlenecked by manual and experience-based decision-making. For example, the experience-based decision-making process lacks transparency and its result is neither optimal. Since the interests of all stakeholders do not always align, the interest of the project is not prioritized in some cases. For example, crane hire companies are likely to nominate cranes to reduce their inventory. Furthermore, as is discussed previously, the planning result is usually suboptimal due to time constraints.

The problems are partially resolved by applying emerging technologies, which not only enhance the comprehensiveness, timeliness and accuracy of information but advance the decision making. Nevertheless, their application is unsystematic, leading to new problems such as poor interoperability. Furthermore, these technologies have not changed the traditional workflow, which contains complicated and redundant information exchanges. These defects jointly refer to an urgent demand for an innovative lift planning workflow. Since the BIM is the foundation to integrate data acquisition technologies and automated decision-making, the innovative workflow is proposed within the framework of BIM.

4.3. BIM-based lift planning workflow

The BIM-based lift planning workflow synergized laser scanning, BIM and planning algorithms and proposed a novel BIM-based lift planning workflow. The workflow automatically manages information related to building, site, and crane equipment and search for optimal solutions with customized searching criteria. It starts when fabricators pass detailed coordination model to the general coordinator who will review the model and add in duration and budget information. Meanwhile, site condition is obtained via laser scanning, which is combined with the building information. Based on the combined model, planning algorithm estimates the minimum number of cranes needed for the project according to the total lifting demand and the minimum rated capacity for each crane via analysing the spatial relationship between supply area and demanding points. Then the capacity and coverage requirements are sent to the crane hire company for inventory checks. The crane hire company sends back a list of competent cranes specifying their configurations and quotations for candidate-specific investigation. Due to the variation of boom length and capacity chart, the feasible locations vary for each crane model. The planning algorithms can identify the feasible locations and enumerate the crane model and deployment location combinations. For each combination, the efficiency and safety indices are analysed to find the optimal combination of crane model and location. The planning algorithms further assist the stability designs such as base and tie-ins. When the above decisions are made, BIM visualizes the decisions for manual reviews. Finally, the results are elaborated in proposal awaiting approval from the project manager. Once approved, lift schedule and specific component information such as size, weight and hook locations take part in the determination of lift paths of each component, which is visualized and reviewed by the lift director and the crane operator before implementation.

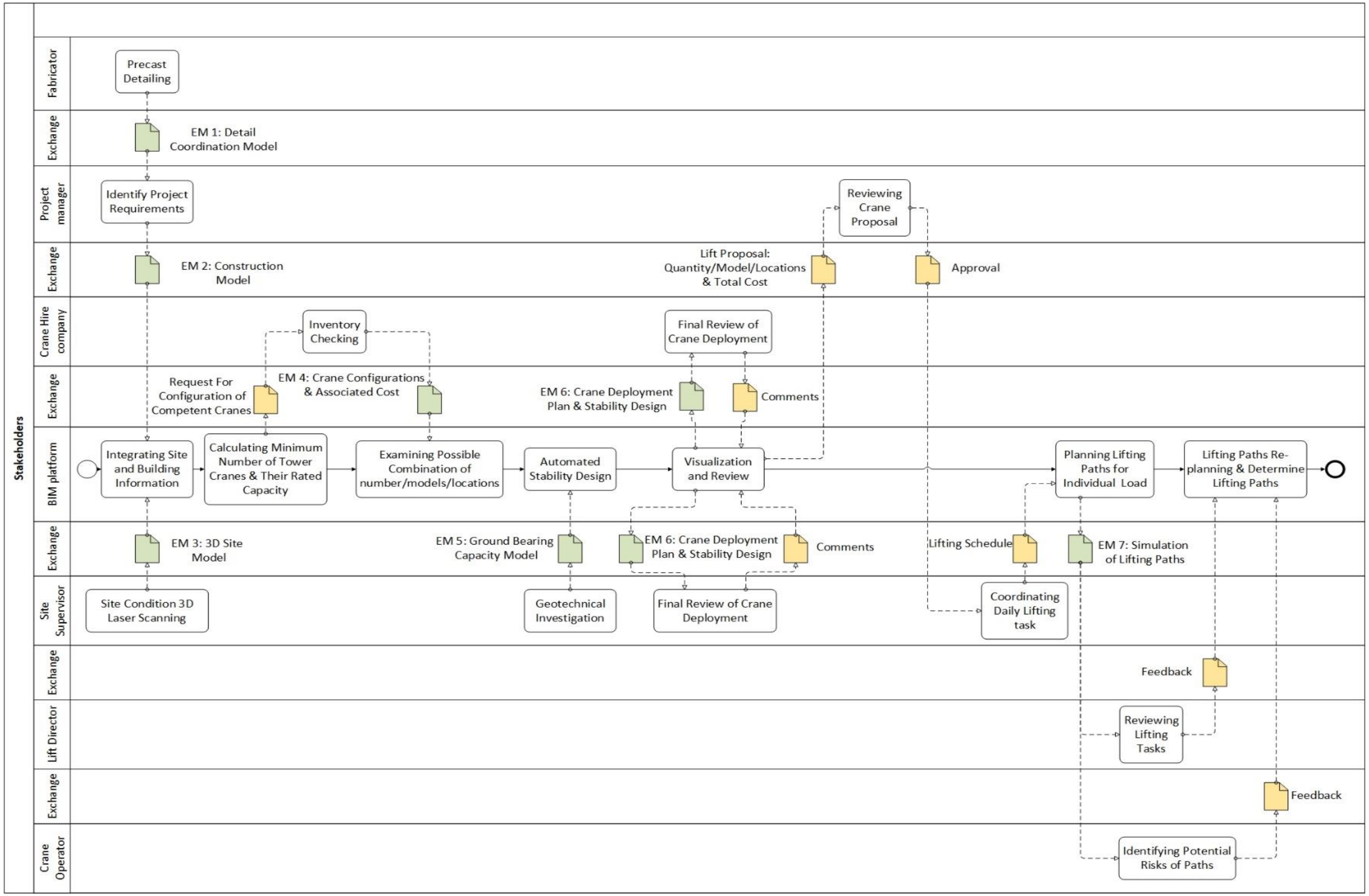

Figure 5 The BPMN model for the proposed lift planning workflow

5. DISCUSSION & CONCLUSION

Information technologies are reshaping AEC industry and creating more possibilities. However, previous efforts have mainly focused on the application of individual technology and neglected their impact on the workflow of lift planning. Thus, there is a demand to explore an innovative workflow organizing scattered technologies. This paper proposed such a workflow based on a thorough review of a validated traditional lift planning workflow. Both workflows are illustrated in BPMN process maps. It is expected that the newly proposed lift planning workflow is able to solve the limitations of the traditional workflow, such as redundant communications, information inaccuracy and decision-making opaqueness. By adopting the proposed workflow, site conditions, building information and crane configurations are synchronized to an integrated BIM-based information management environment. Therefore, the paper-based information exchanges are avoided together with the inherent ambiguity. Additionally, the automated decision-making for multiple tasks can be achieved simultaneously and there is no need to differentiate the tasks and their responsible stakeholders, reducing the complexity of information exchanges. Furthermore, the system is expected to enhance the transparency of decision-making. For example, the project management team retains the privilege of finding the most economical tower crane without interfering in other considerations.

Despite the foreseeable advantages, the limitation of this study is its application scope. Since the interviews targeted at the crane industry practitioners in Australia, the traditional workflow only reflects the practices in Australia. Additionally, several barriers and topics for further research still exist.

- Firstly, existing BIM platforms cannot satisfactorily support all the necessary information for the planning algorithms. For example, the current information model such as IFC does not have sufficient items for crane configurations and costs. Hence, there is a demand for expansion of the BIM data schema for lift planning;
- Secondly, most research on planning algorithms has hitherto focused on individual tasks. Thus, the same information has to be repeatedly retrieved, weakening the efficiency of the new workflow. Therefore, an integrated lift planning algorithm is needed;
- Thirdly, the interoperability of technologies can be challenging when implementing the innovative workflow. Typically, it takes a team of professional personnel to ensure that every stakeholder can understand the information generated by different types of technologies. However, the extra costs are anticipated to discourage contractors. Thus, there is a lack of unified information schema or a common protocol, enhancing their interoperability.

In conclusion, the study investigated the impacts of cutting-edge technologies on the lift planning workflow and underlined the missing pieces to support a federated, integrated lift planning system. Furthermore, this paper also identified the existing challenges for implementing the new workflow, which exhibits the initial steps to achieve the proposed workflow.

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