ON MODELING AND SIMULATION SITE MATERIAL FLOWS AND LOGISTICS THROUGH BIM

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ON MODELING AND SIMULATION SITE MATERIAL FLOWS AND LOGISTICS THROUGH BIM

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To My Family,

ABSTRACT

Material flows and logistics are essential for proper material management within construction sites. Its effective implementation can improve efficiency of construction activities, handling and distribution of the materials. Many construction projects lack detailed analysis regarding flow of construction materials and logistics in early phases and during construction. Most analysis and evaluations for material flows and logistics are simplistic and not fully integrated with Building Information Modeling (BIM), relying on previous experiences of managers, heuristic planning and previous project data. A realistic analysis for material flows and logistics with consideration of spatial configuration, equipment handling, crews, construction and delivery schedule, and other dynamic site aspects can support better material processes with more efficient use of available resources and improved work sequencing.

This thesis aims to develop multiple techniques to support detailed simulations of material flows and logistics at construction sites on BIM for evaluation and analysis. These material flows are based on common site material processes and include all material steps from site entry to installation points with respect to temporary storages areas, crews and handling by equipment. To simulate material related processes occurring at site, BIM and construction schedule are used and requirements are identified. Information related to materials, logistic procedures, site operations and resources have been determined. Afterwards, this information was managed through developed database to make it compatible with simulation framework. All necessary information for site material processes have been integrated for detailed simulation of material flows and logistics using an existing a BIM based resource-integrated simulation tool called GSimX

for analysis. Results show that the developed techniques for material flows can realistically support complex material processes integrated with construction schedule, crews and equipment, site status and other construction constraints.

ÖZETÇE

İnşaat sahalarında saha içi malzeme döngüleri ve iş sahasında gerçekleşen lojistik işlemler büyük önem taşımaktadır. Uygun teknikler ve yaklaşımlar kullanıldığında, saha içi materyal döngüleri inşaat aktiviteleri üzerinde etkin bir fayda sağlayabilir. Günümüzde çoğu inşaat projelerinde malzeme akışı ve saha içi lojistikleri, inşaat başlamadan önce ve inşaat sırasında kapsamlı bir şekilde analiz edilmemektedir. Çoğu analiz ve değerlendirme yöntemi yetersiz kalmakta, yapı bilgi modellemesi (BIM) analizlerde etkin bir şekilde kullanılmamakta ve yapılan planlamalarının çoğu daha önce edinilmiş deneyimlere bağlı kalmaktadır. Gerçekçi bir şekilde saha içi materyal akışını analiz edebilmek için inşaatın uzaysal yapısı, inşaat operasyonları sırasınca kullanılan ekipman, işçi ve gerekli diğer kaynakların inşaat programı üzerinden ilişkilendirilmesi, inşaat operasyonlarının ve diğer karmaşık aktivitelerin değerlendirilmesi büyük önem taşımaktadır.

Bu tez, saha içi malzeme döngüleri ve lojistik prosedürleri için BIM üzerinde simülasyon oluşturulması için gerekli çeşitli teknikleri geliştirmektedir. Malzeme akışları, malzemelerin sahaya tesliminden inşaat aktiviteleri için kullanılışlarına kadar değerlendirilmiş, gerekli depolama alanları, gerekli ekipmanlar, gerekli malzeme çeşitleri ve işçi birimleri de dahil edilmiştir. Bütün bu bilgilerin BIM ve simülasyon arasında bağlantısı geliştirilen veri tabanı ile oluşturulmuştur. Tezde sunulan yaklaşımı gerçekleştirebilmek için gerekli olan bütün bilgiler BIM tabanlı inşaat simülasyon programı olan GSimX üzerinde uygulanıp analiz edilmiştir. Sonuçlar, geliştirilmiş tekniklerin saha içi malzeme döngülerini ve saha içinde gerçekleşen aktiviteleri iş

programı, ekipman, işçi ve diğer kaynaklarla ilişkili bir şekilde gerçekçi olarak yansıtılabildiğini göstermektedir.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

4D CAD	: Four-Dimensional Computer Aided Design
ABM	: Agent Based Modelling
ACO	: Ant Colony Optimization
BIM	: Building Information Modelling
BOQ	: Bill of Quantities
CPM	: Critical Path Method
DES	: Discrete Event Simulation
ERD	: Entity Relationship Diagram
FAR	: Floor Area Ratios
GA	: Geometric Algorithm
ICT	: Information and Communication Technologies
JIT	: Just-in-Time Approach
LAS	: Look- ahead Scheduling
RFID	: Radio Frequency Identification
SA	: Simulated annealing
TS	: Tabu Search

CHAPTER I

INTRODUCTION

In construction sites, ineffective material management strategies usually result in poor construction operations. Materials represent an important part of cost component in construction projects, therefore proper material management practices for both on-site and off-site the construction is essential (Thomas, Sanvido et al. 1989, Ibn-Homaid 2002). Materials and installed equipment can count for up to 50% of total cost of a project (Kini 1999) and might have significant impact on productivity (Ibn-Homaid 2002). Construction sites are highly dynamic, there are numerous activities involved and production can be influenced adversely by many external factors such as resource allocation, productivity of the labors, supply of required materials to installation locations and eventually financial status of the shareholders. Although many studies show the adverse effects of poor materials management on construction productivity (Thomas, Riley et al. 2005), construction industry barely invests in material management and control (Formoso and Revelo 1999).

The planning of construction activities and processes involved during the materials handling and distribution is challenging since there are various interactions between involved parties during the construction operations. Due to ineffective material management techniques, many problems may occur throughout the construction processes including decreased work quality, time delays, ineffective use of resources, waste material generation and even incomplete parts of the project. On the other hand, effective material management techniques within a construction site together with effective planning approaches can lead to more systematic construction processes, on-time material delivery, better resource allocation, improved construction quality and decreased construction cost.

Material management in a construction site requires detailed planning of on-site and off-site aspects. Temporary on-site and off-site storage areas, location of the heavy equipment (e.g. tower crane), on-site material distribution paths are all specified in the project layout schematics. However, to provide construction materials with the right quantities at a right time at construction projects, planning and decisions are not only limited to storage areas, handling of the materials and delivery schedule but also related to general construction processes. There are high-level material related decisions at the project site in early construction stages and such decisions are highly related to construction schedule and resource usage. Furthermore, during the construction, all steps from delivery to installation such as storage of the materials, material handling with equipment and labor and material transportation to installation locations are not considered comprehensively in analyses and planning. Eventually this results in poor material management approaches. Thus, site processes need to be analyzed in a holistic manner in order to prevent delays, waste of materials and provide proper resource allocation, efficient inventory control, decrease cost and time.

To improve material related processes such as handling of the materials, loading, unloading, transportation of materials between specific points (e.g. storage areas to installation points), it is beneficial to analyze construction processes in detail. The flow of materials in the job site from site entry to installation locations potentially can be evaluated and analyzed by recent computer aided technologies. Site processes can especially benefit from modeling using recent construction and control technologies such as Building

Information Modelling (BIM) and simulation. Gathering all the information and documentation necessary for required amount of materials for specific construction activities, required material quantities, resources, storage information and other aspects regarding to construction can allow ability to directly manipulate complex material processes and offer great benefits.

This thesis work presents several important elements for supporting material flows and logistics implementations within a BIM based resource-integrated simulation environment. These elements include a developed database that helps to capture planning and material related information for simulation, conversions necessary for site material flow simulations, material flow diagrams that show materials' on-site routes during the simulation, relevant properties for material handling equipment and storage areas, and a building test case to demonstrate site material flow simulation. The presented work aims to represent detailed process models for typical material flows and logistics at site for analysis and provide ability to evaluate different alternatives of material flows.

1.1. Management of Construction Materials

Material management includes all processes involved for planning, executing and controlling activities such as manufacturing, procurement, logistics, delivery, handling of the materials, storage and eventually installation and waste control. The purpose of a proper material management is to ensure that the right quantities of construction materials are available when needed for activities to be performed (Gulghane and Khandve 2015). Material management is a system that governs all the efforts necessary to make sure that materials required are properly specified in a timely manner, are obtained with feasible costs and are delivered, stored, handled and eventually transported to be installed in necessary locations at a point of use (Patel and Vyas 2011). It involves identification of the materials to be used for different purposes, storage of building materials, inventory control, handling, transportation and other construction methods that seeks same purpose for proper material management. Each of these are collaborated with productivity and schedule. An adequately implemented material management strategies can lead to proper and timely flow of materials and resources to operation areas and therefore, improve project productivity (Caldas, Menches et al. 2014). Successful completion of a project necessitates resources to be effectively managed. On the other hand, poor planning and control of the materials, lack of required construction materials, inadequate use of storage areas, re-handling and improper transportation techniques results in decrease of the labor productivity, overall time delays and direct increase in total cost.

Since materials used in construction represent major cost component within the projects, timely flow of materials must be well established (Gulghane and Khandve 2015). In this sense, preventing delays occurred by poor material management is crucial for avoiding large costs. For instance, if the purchase of materials is made early, expenses due to excessive storages of materials can increase. Some of the materials could be damaged, deteriorate or even worst; materials become dysfunctional during storage or such materials could be stolen if precautions are not taken. For example, many of the materials that are fragile and sensitive to certain conditions must be kept in closed, secured and waterproofed locations. Otherwise required materials will not be available for activities, delays and extra expenses will occur.

Construction has highly dynamic nature; it involves activities mostly characterized by complex coordination systems that governs interaction of many functions from production of the materials to installation at job site. Aside from these, problems that arise from material quality and quantity, availability of materials and resources, handling and movement, general quality of the work, safety, design and all the processes involved are all related to construction environment. Thus, such complex and highly problematic system requires well organized, detailed and systematics flow of materials.

Currently, in many construction projects supply of the necessary materials and handling are managed just to satisfy construction schedule and plans. The management approaches are mostly relying on experience and previously obtained project data. The decisions related to material supply and handling are not fully satisfying the general construction needs and methods, and there is limited consideration of requirements for other tasks and trades. In the project sites, the personnel are mostly effective on tracking the required materials and procurement of necessary materials to activity points. However, such actions are mostly time consuming and their approaches are not productive; important early material decisions are not provided considering multiple factors for whole project. There is lack of integration between different activities, tasks and their needs in terms of material, labor and equipment. Decisions and planning for on-site material management approaches should also include on-site material flows and logistics, size and locations of temporary storage areas, handling equipment, procurement of long-lead items, off-site and on-site inventories and site layout. On the other hand, the current analysis approaches are simplistic; alternatives for site material flows, logistics and workflows are not provided comprehensively considering site aspects and resources at once. As a result, unnecessary delays or costs might occur due to factors such as missing materials, limited space and insufficient equipment use. Therefore, efficiency of material management during construction phases relies on these early decisions and strategies made early on in the project.

1.2. Need for a Material Planning System

As construction processes are highly complex, development of a project usually comprises of varying phases, requires specialized services, labors and participation of several parties. Consequently, managing construction projects is difficult. Computerized tools or software for the construction projects are required and would be beneficial in complying with project costs and schedule. However, many of the construction management tools or platforms lack representation of spatial aspects of construction environment and activities involved. Most of these tools do not allow managers to generate schedule alternatives to construct a specific design or find the best way to execute construction operations. Traditional way of material management techniques usually relies on previous construction project experiences and collected data. Decisions and planning made for site operations depends on historical data and heuristic adjustments, preventing collaboration between high-level processes and dynamics of productivity, causing costs overruns and time extensions. Other traditional tools such as bar charts and network diagrams are not capable of representing spatial aspects of construction activities. Due to the characteristics of the construction sites and related projects, systems or tools that are highly capable of representing complex workflows and ability to make analysis on materials management and evaluating different scenarios with respect to resources available are recently getting the attention of construction industry.

The characteristics of construction projects prevent traditional construction planning and materials management approaches to establish effective workflows and to develop workable plans. Such traditional way of management strategies push managers to analyze on-site construction processes using data and information from previous projects. But different projects have different settings and site conditions, requiring individual planning and unique strategies. Apart from these, scheduling also depends on previously collected data, the duration of the activities and projects is being calculated by quantity of materials and resources available. Since construction operations are based on outdoor, project-based production processes, circumstances are different for each project. In this context, minimizing wastes, preventing time delays early in construction phase and in production phases, optimizing operation costs and eventually evaluating different alternatives to achieve better productivity is primary objective of material management systems.

Contemporary approaches for planning and controlling of site related processes can help represent workflows and analyze material related operations. Most important of these approaches include Building Information Modelling (BIM) and simulation techniques. When integrated, the BIM and simulation can allow for analysis on construction operations including resources, materials, logistics and others. This will also provide early evaluations of processes and improve decision making and planning before the project starts. Therefore, this thesis study presents an approach that models site material flows and logistics using BIM and resource-integrated simulation framework to evaluate construction processes including site handling by resources and storage capacities and allows analysis and evaluation on different alternatives of material flows.

1.3. Automation in Construction

Site material related processes such as delivery of the goods, handling of the materials to different locations, inventory control, distribution of the required materials to activity locations with available resources are essential for construction production and therefore vital to be analyzed and evaluated accordingly. These mentioned material processes and flow of the construction materials within the operation sites can benefit greatly from modeling and evaluation using recent computer technologies to avoid errors and obtain reasonable material related decisions before or during the construction phases. In this sense, BIM and simulation are two promising technologies to automate on-site material flows and logistics. BIM provides detailed information for building including geometry, shape, quantity, location stored within building model. It is a data rich representation of a building. On the other hand, simulation approach can be used to both for production and logistics (Rabe, Spieckermann et al. 2008). It offers realistic representation of involved elements and integration between them. Simulation enables analysis and evaluation for operations by running scenarios before realizing them at site (Fu 2012).

BIM has potential to support material process models. Because of the dynamic structure of construction sites, material logistics and site layout must be carefully coordinated and organized to ensure that workflow is smooth. Improper deliveries and inadequate inventory control of the materials should be avoided to prevent ineffective processes. Logistic paths between material storage areas and installation points, insufficient transportation methods, re-handling of materials, congestion at site due to untimely deliveries can increase operational wastes generated. BIM can reduce occurrence of these problems by controlling construction processes, properly coordinating delivery of materials and optimizing material storage. Combining the information coming from BIM, construction schedule, and other resources, important material related calculations can be automated. For instance, using BIM, material information such as material quantities and material properties can be extracted to be linked with construction schedule for utilizing required materials in order to form a basis for logistics and storage model at site. Furthermore, information regarding storage capacities, labors and available equipment to be used for handling and transportation of the materials can be also included to examine construction processes in detail. With BIM, information required for representing site material process models could be extracted and engineers could be able to make decisions on site related aspects; determining storage capacities and resource needs with respect to material quantities for activities before construction starts.

Like BIM, simulation techniques can help automation of construction processes. In a practical manner, simulation can offer better implementation for site process analysis and evaluations. Simulation helps decision-making processes and comparing different alternatives related to construction activities during early phases and construction phases. Simulation offers improvements for design or planning of construction processes, allows representation of equipment used, labors, environmental aspects and impact of such factors to the whole project in a formal structure. Simulation allows project participants to evaluate different scenarios and its effects with low costs and less time. Apart from these, simulation models can be used to emulate construction activities, resources and other aspects before they happen to improve on planning. Simulation may also allow for integration with BIM which includes information necessary for the development of desired model. Such simulation models can provide basis of logic for varying activities required in construction projects, utilization of resources involved and analysis regarding to environment that the project is built in. Other than that, simulation can be applied for analyzing site logistics, planning of construction processes, tasks, evaluating material storages, construction costs and estimating total duration as well. However, existing simulation tools are either simplistic or require too much manual work. They allow analysis for basic construction operations such as duration of loading tasks, time spent for unloading a material, number of installed materials etc. with predefined programming codes to manipulate whole structure of the simulation model more accurately. In addition, links between construction schedule and simulation model are usually limited; defining and maintaining equipment, labors, and material assignments to corresponding tasks while maintaining a construction schedule is time consuming and prone to errors and this eventually results in myopic way of analysis for construction operations.

In this thesis, process models of site material flows and logistics are presented to work with a multi-method 3D construction simulation platform called GSimX. GSimX is a resource-integrated simulation platform developed for analyzing the construction processes as a whole on BIM. GSimX uses both discrete-event simulation and agent-based modelling techniques together to represent construction processes naturally. Here, discrete-event simulation controls overall construction simulation while crews and used equipment are being managed by agent-based modelling techniques with respect to spatial interactions in 3D and recourse availabilities. GSimX simulates activities and resources on BIM and calculates statuses of activities, locations and resources. Within this platform, users can generate different alternatives by changing the parameters regarding to crews and equipment, resource allocation, work sequences to evaluate cost and time changes. The results can be seen by 3D visualization, charts and graphs for each individual alternative scenario as well. Ability to perform detailed analysis regarding site materials flows and logistics implemented by providing necessary inputs within this platform will help to make site material related decisions in an integrated way.

1.4. Research Questions

Many materials are delivered to site and handled throughout construction operations, during which they go through many processes including handling, storage, procurement, installation and waste control. Possible problems related to material delivery issues, on-site material distribution, material quantities, number of material containers, capacities of storages and resources during early stages of the construction phases should be predicted and evaluated to take necessary precautions. Ensuring an effective flow of the materials is key to reduce occurrence of on-site material flow and logistic problems. To achieve this, logistic processes and material flows should be planned in detail and analyzed for site production including all information regarding resources, storage areas and other site aspects. Using BIM and simulation technology, it is possible to perform a detailed site process analysis. However, current systems and techniques lack integration with BIM and simulation as a whole. BIM and simulation can provide a wide range of analysis during early stages of construction for material processes and logistics occurring at site.

To support simulation of site material flows and logistics on BIM, this thesis describes the information flow through BIM management to simulation processes to have material process models and effectively perform detailed analysis on material flows and logistics processes using GSimX. Various information coming from BIM model, site layout, site progresses, resources and construction schedule must be managed. Then this set of information should be used to build a simulation model and be analyzed to consider various scenarios. Here, the role of BIM is providing necessary information for construction components and materials so that proper flows are generated for them to ensure that right amount of materials are handled to the installation point at a right time when needed. Also, simulation provides better automation system for analysis on crews, site equipment and construction activities. This thesis has two main research questions:

1- **What are the information and modelling requirements for material flows and logistics to be simulated in a BIM and resource integrated simulation setting?**

All the necessary information related to site materials for simulation must be created according to project specifications and requirements. However, since detailed analysis for on-site material processes requires project-based information, many of the site aspects including temporary storage areas, on-site logistic paths, heavy equipment locations such as crane, equipment needed for transferring necessary materials to the installation points, materials containers and their capacities and properties of available resources must be also included. Thus, relation between BIM entities and material related aspects should be defined using a structured database. Once the database is constructed and required information related to BIM entities including attributes, components codes, locations, types, resource requirements and any other constraints for specific BIM objects are extracted; it can be automatically linked to belonging BIM object within the used framework. For material processes and site related operations, information related to BIM group of entities must be extracted, extra material related information must be determined, capacities of storage areas, construction methods, equipment must be defined and crews for specific works must be assigned. Within the site layout, the location of the temporary storage areas, logistic paths, heavy equipment locations must be specified. Furthermore, using documentation techniques; the links between BIM entities and tasks must be formed properly as well. All the site properties, site updates and any other required information for simulation of material flows should be transferred properly to the simulation framework.

2- **How can on-site material flows and logistic processes involved be analyzed through BIM and simulation?**

The information coming from varying sources should be integrated properly to create aimed process models within the simulation framework. All of this information must be periodically updated and rechecked. During construction phase, necessary materials and required resources must be updated for further analysis as well since on-site progresses form basis for material flows and logistics

Simulation analyzes activities with respect to required resources and materials in relation with construction schedule and obtains status information for crews and equipment used. Simulation includes all the steps and processes involved from delivery of the materials to installation. Users should be able to estimate basic properties for material related decisions with respect to project circumstances. In the case of providing the necessary resources or materials for activities is impossible due to any reason, an alternative new estimated construction schedule should be generated based on capacity of site aspects and resources. These changes must be reflected to simulation processes to meet planned project dates and defining the revised schedule.

1.5. Aim and Objectives

This thesis aims to demonstrate BIM and resource-integrated simulation to support site material flows and logistics. With this approach, users and planners will be able to evaluate alternative flows and logistics for materials at construction sites with consideration of material availability, temporary storage area locations, transportation methods, equipment, crews, and labor. Additionally, with the presented approach, it will be possible to estimate and detect material related conflicts during construction phases early in the project. Therefore, some material related issues during construction will be automatically detected, idle times will be reduced, and necessary precautions will be taken accordingly.

To achieve the general aim discussed above, the objectives are determined as follows:

(1) Identifying requirements for on-site material flows and logistics in order to support construction schedule and represent whole material processes within a BIM and resource-integrated simulation context.
(2) Managing information extracted from BIM and establishing a database to support on-site material flow simulation model.
(3) Developing integration processes into BIM and resource integrated simulation tool to enable detailed analysis of site material flows and logistics processes.

Using BIM and simulation can provide stable construction material flows and decrease time consumed during construction processes, where users will be able to consider required resources and allocate them on site as necessary.

The thesis work presented here enables BIM-resource integrated simulation approach for representing detailed material flows and logistics processes within a construction site. The approach presented describes a methodology for integration into material flows logistic processes at site. From delivery to installation, intermediate processes including their requirements are specified. For various material types, storage areas are located within the construction site layout and different equipment for providing such materials transportation are assigned. Conversion of material quantities to materials containers and pallets is provided by defining capacities for containers and pallets. Properties and capacities of equipment and storages areas are all specified and related with construction schedule.

1.6. Scope of Work

This thesis focuses on site material flows and logistics for medium-scale residential and commercial buildings to demonstrate modeling and simulation of common site material management approaches using BIM and simulation. The presented approach requires BIM model of the project, construction Critical Path Method (CPM) schedule and site layout so that site flows can be simulated in a 3D environment. The simulation approach allows for analysis of construction operations including equipment and crews that are assigned to activities in schedule. Material related extensions to the existing simulation approach include material containers and capacities, storage area and equipment capacities for different material types, steps from delivery to installation and a database that supports material related processes.

This research specifically focuses on on-site material flows and logistics; off-site material related processes such as production, transportation, delivery etc. are not included. The approach assumes that the required materials are delivered to the site when needed for use, although they may not be ready for installation and can be stored for later use.

1.7. Research Methods

In order to achieve objectives discussed above, the presented thesis work follows several steps, namely: (1) literature review and identification of current practical problems, (2) developing material related information regarding site material process simulation on

BIM, (3) developing a database to help transfer information from BIM to simulation modeling of site material processes, (4) development of an approach to represent pallet capacities, material containers, conversion of quantities and amount of containers in pallets for the simulation model, (5) implementing an experimental test case including site layout, flow diagrams, storages, hoisting equipment, and (6) analysis for site material flow alternatives and evaluation on results using BIM and resource-integrated simulation platform. Figure 1.1 summarizes methods used for this research. Background information on practical problems related to site material processes from delivery points to installation is presented. A comprehensive literature research has been made to identify current practices for tracking site resources and materials and current approaches to analyze site operations. Previous studies conducted on site operations and material related processes are evaluated. Relevant automation technologies such as BIM, simulation, 4D CAD etc. are discussed, including current uses and limitations of such technologies. To demonstrate site material flows within the simulation environment properly, market research has been made on packaging methods of material suppliers; material quantities in different packages and properties of standard pallets identified. Through the developed test case scenario, the presented approach is tested and evaluated as per obtained results and necessary updates has been made accordingly.

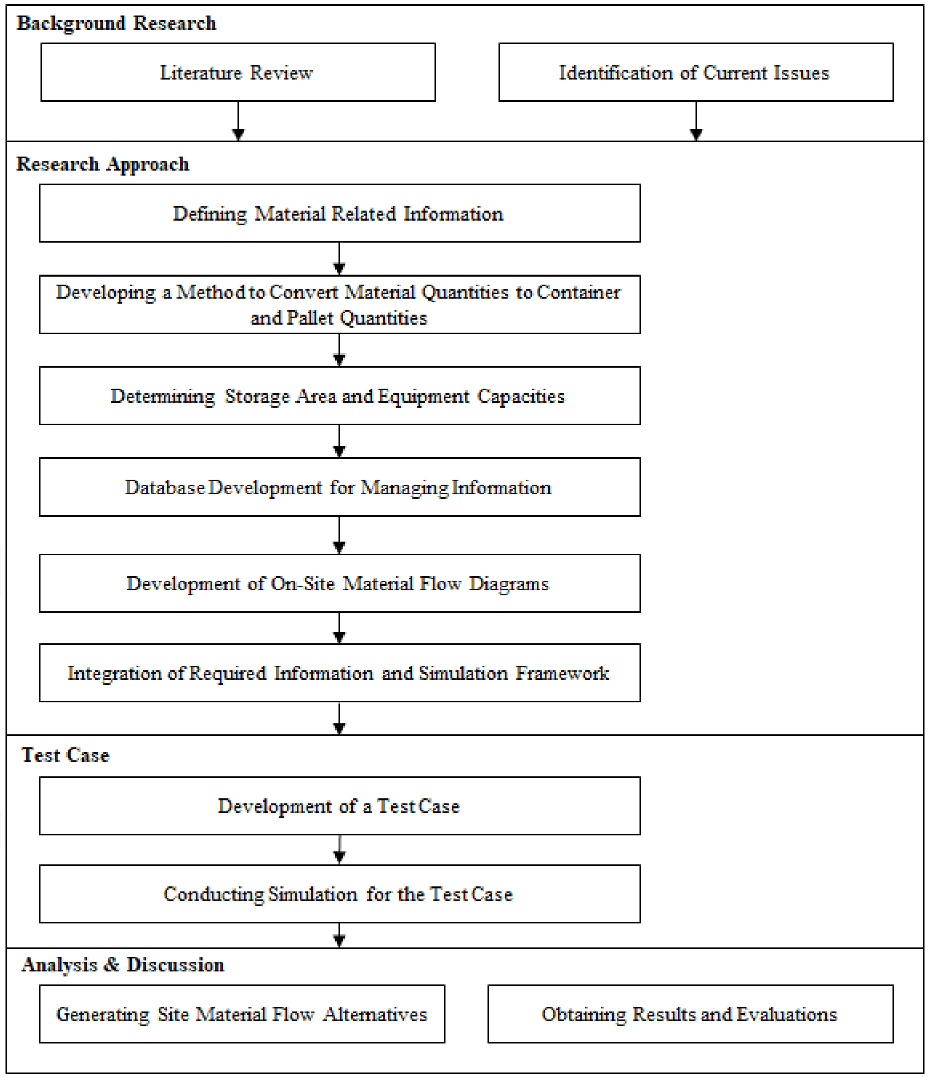

Figure 1.1 Research methods for this thesis

The literature survey part identifies current analysis methods and approaches for site material flows and logistics processes. Current construction planning standards and approaches to manage flow of the materials and logistics processes within the construction sites are discussed. In addition, gaps in current approaches for analyzing site material flows and logistics processes, information needed for conducting detailed site material flows are discussed. Gaps between planned and actual processes on site as it relates to site materials management are discussed and identified. Since current practices do not fully combining

BIM and simulation to manage site material processes, the presented approach discussed current problems and possible threats during the planning phases and construction phases and presents integrated approach to solve them. Furthermore, current site material processes, logistics management approaches, BIM, current simulation techniques to analyze workflows are discussed and reviewed; the requirements of conducting detailed site material flows analysis, its advantages and limitations are presented in Chapter 2.

For the analysis of detailed material processes at site, integration of information coming from different sources for simulation approach is described. In this presented research work, the information management method for analyzing detailed material processes at site using BIM and simulation technology has been provided. The design of information for material flows and the integration of multiple information elements are developed. Later, the managed information database becomes the part of material flow simulation approach through the integration between BIM data flow and GSimX.

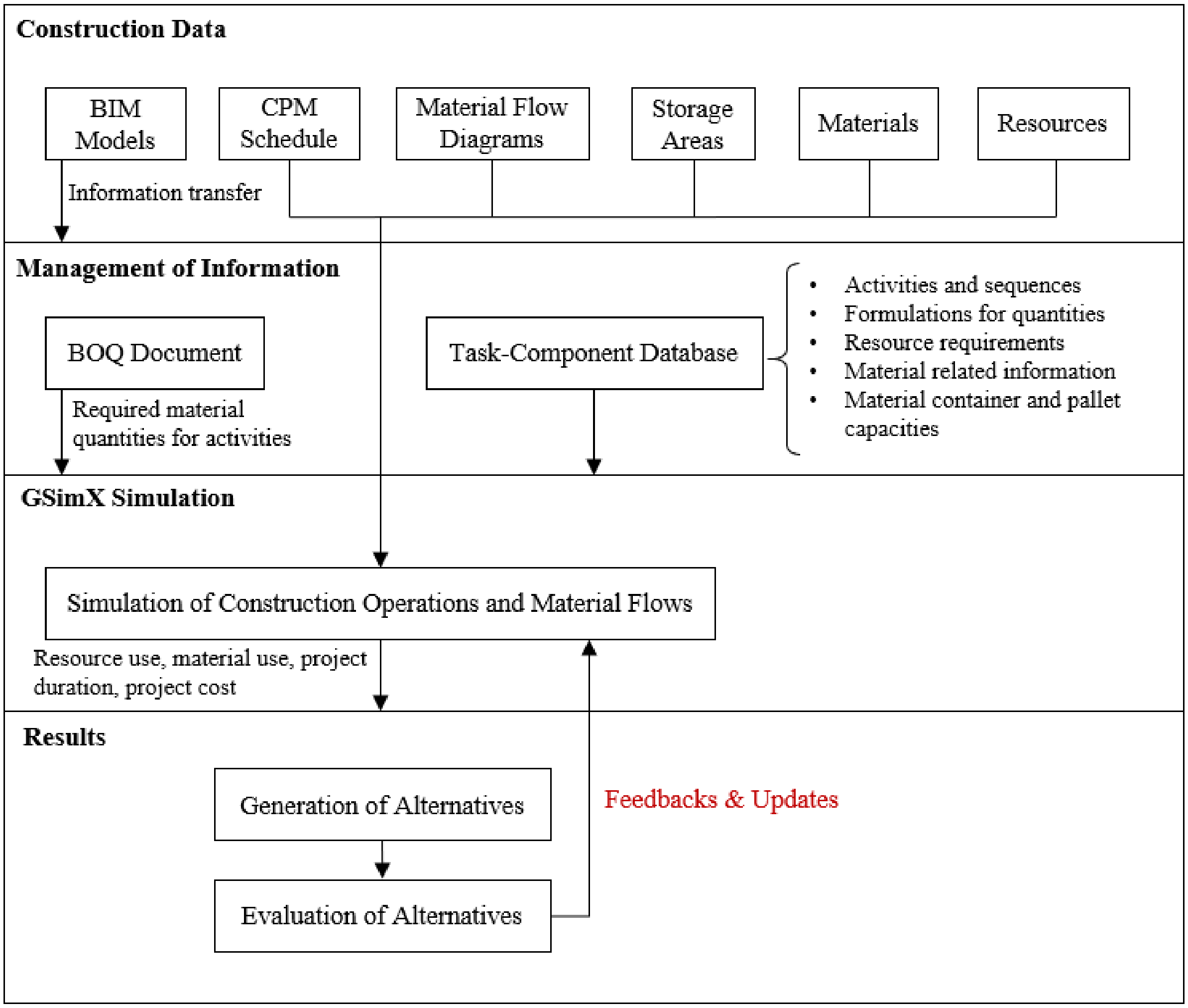

Figure 1.2 Simulation requirements for the test case

As illustrated in Figure 1.2, a test case for demonstrating and evaluating the presented approach for site material processes has been developed. A simulation for demonstrating site material processes on a residential reinforced concrete building, which consist of structural and architectural components is conducted. The test case describes how simulation of process models have been conducted with respect to developed database, BIM models and GSimX environment. For the test case, an existing 3D BIM model based on design drawings and specifications has been used. Then, CPM schedule including attributes that specify activity locations and other simulation requirements has been imported in GSimX. The properties of the site layout are also considered for simulation processes. In addition, information regarding to materials used, storage areas and resources are other inputs to simulate site material flows. The created material flow diagrams have been tested and evaluated, the parameters regarding to simulation have been changed, and more alternative were obtained by repeating simulation processes. As a results, charts and lists are obtained from the simulation experiments regarding to use of resources and duration according to specified material flows. The test case is discussed in Chapter 4.

Finally, site material flow simulation has been evaluated and discussed from many perspectives. To examine material flows and its effects on site processes, the existing simulation approach and developed extensions are compared. Site progresses, material status, resource availability and others have been integrated into simulation process which will allow for customization of site material processes for simulation approach, better consideration of resources within the simulation processes and therefore will allow better updates for resources and construction schedule.

1.8. Organization of Thesis

For the remainder of the thesis, Chapter 2 discusses the background, including site material flow and logistics practices, current approaches of site material management, used techniques and their evaluation. Moreover, this chapter covers the BIM and simulation technology, current practices and their benefits, implementations as well as their limitations. Additionally, this chapter is also introducing geometry-based planning approach and GSimX as a tool for BIM and resource-integrated simulation approach for detailed analysis of site material processes. Chapter 3 discusses the research methodology for conducting detailed site material flow analysis and evaluating logistics processes and how these are integrated with BIM based resource-integrated simulation framework of GSimX. Chapter 4 includes the test case, technical information regarding to test case development, simulation processes and finally result discussion. Finally, in Chapter 5 concluding remarks, summary of findings, thesis contribution and further research are discussed.

CHAPTER II

BACKGROUND

The focus of this thesis is to present process models of material flows and logistics in construction site using BIM data and simulation. The goal is to evaluate different alternatives of complex material and logistic processes occurring at job site. For this goal, BIM and simulation techniques are used and analyzed accordingly.

This chapter presents background information on the techniques used for the thesis. This chapter discusses current methods used for material management, site material processes and logistics. This chapter also discusses BIM and simulation techniques which are related to automated approaches for planning and controlling construction processes. Current use of BIM for on-site material management, material processes and logistics, benefits and deficiencies of BIM for analyzing material processes and logistics discussed. In addition, current simulation approaches; simulation techniques for analyzing on-site construction material flows and its pros and cons on site material processes are discussed. Furthermore, integration of BIM and simulation techniques, its potential and limitations are covered. Moreover, literature review presents GSimX platform as a tool used for generating material process alternatives, their evaluations and analysis.

2.1. Material Management Processes

Material management in the construction industry is vital; proper implementation of material management strategies can lead to effective project execution and increased quality of the work. However, it is still performed fragmentally with minimum communication and no clearly assigned responsibilities to involved parties (Bell and Stukhart 1986). Many research and reports showed that the industry suffers due to lack of efficiency in material management strategies; in contrast, a properly implemented material management strategies can lead to timely flow of the materials and resources to the project site and therefore promotes for increased productivity, feasible costs and better planning of site activities (Caldas, Menches et al. 2014). Material management practices applied in project sites are further complicated by temporary storage areas, storage spaces, material supply delays, resource use, logistics related to distribution of required materials, ordering and delivery of the necessary materials to the construction site. Previously conducted researches have also pointed out material management problems related to material delivery (Aibinu and Odeyinka 2006), difficulties regarding to transportation of the materials (Zakeri, Olomolaiye et al. 1996) and storage capacity (Agapiou, Clausen et al. 1998). To ensure that the material flow is smooth at sites, many aspects such as delivery, handling, storage keeping, and logistics should be analyzed and evaluated properly. Different from these, there are varying approaches to address current issues such as material logistics planning, Just-In-Time (JIT) concept to solve problems regarding to space constraints and use of tracking technologies namely bar-coding and RFID.

Material management processes includes the planning, procurement, waste control and storage and logistics of the materials within the construction projects. Implementation of effective material management strategies enables proper handling of the materials and results in good material flows at project sites. To have a better understating of material management in construction projects, the following sections discuss different stages of material management processes.

2.1.1. Material Planning

The planning of the construction processes is understanding what has to be constructed or built and determining right methods in most feasible way to meet project requirements for achieving certain level of work tasks. Material planning is the most essential part of the overall material management processes. Efficient planning of materials not only increases productivity and profit to the company, but also facilitates the completion of construction projects (Wong and Norman 1997). For materials to be used in construction sites, appropriate planning should be made with construction methods used, engineering approaches and other project plans (Stukhart 1995). It is also mentioned that material planning guides subsequent activities and effects project planning positively (Stukhart 1995). The planning processes of the materials cover scheduling and gathering information or data required for determining inventory levels, delivery times and resource use. Typically, planning of the materials based on project plans, design, bill of quantities (BOQ), procurement plans, and resource plans which are later integrated to the construction schedule (Ren, Anumba et al. 2011). As a result, recorded information regarding to site aspects, delivery times and available resources can enable proper material flows at project sites. Problems considering out of stock materials and late delivery of the materials can be eliminated and activity times can be reduced.

2.1.2. Procurement and Storage of Materials

Procurement governs varying activities at project sites and material supply chain including purchasing of necessary equipment, materials, coordinating crews or labors necessary for construction and execution of projects. The aim of the procurement in material management is providing right materials with right quantities and quality at right time and place when needed with feasible costs. It is about organization of the material purchasing and extracting delivery schedule for manufacturers or suppliers to provide deliveries on time since the cost of materials used in a construction is between 30-80% of the total project cost depending on the project (Kasim, Anumba et al. 2005). Procurement of the materials are influenced by inadequate handling of the materials during the construction processes (Patel and Vyas 2011). Therefore, defining the requirements of the projects and establishing a control strategy are key factors to achieve aimed objectives.

Material storage is closely related to procurement. Material procurement and storage on construction site should be planned to avoid excessive amount of materials on the job sites or negative impacts (Said and El-Rayes 2010). Therefore, proper procurement plan and consideration of site spaces and storages are vital. Usually, storage capacities are determined by project managers excluding procurement of materials and site layout. This mostly causes to improper storage, poor and unsafe site layout and decrease in productivity (Jang, Lee et al. 2007). Therefore, decisions on storage areas and capacities should be made including total material quantities required for activities and storage properties by material types. If the materials are fragile, sensitive to weather changes and expensive, then storage areas can be located within the site layout to ensure that transportation of materials are smooth. This also allows choosing right equipment to handle materials to required locations effectively.

2.1.3. Logistics Management

The concept of logistics focuses on planning, implementing and controlling material flow and storage of all goods from production to the finished product (Stukhart 1995). It is management of material and information flow during the project execution. Material needed during construction phases varies. Some of the materials may be delivered as bulk, others might be supplied as bagged, palleted or packaged. Therefore, construction professionals need to move necessary materials to and within construction site from suppliers to where production is taking place and from temporary storage areas to installation points (Sui Pheng and Joo Chuan 2001). The focus of site logistics in material management is to enhance coordination and communication between the project participants both in design and construction stages, especially for material flow processes. Site managers can improve project metrics by focusing on optimization of material movement from starting point to a destination point and planning of logistics paths, routes and access points within the project sites.

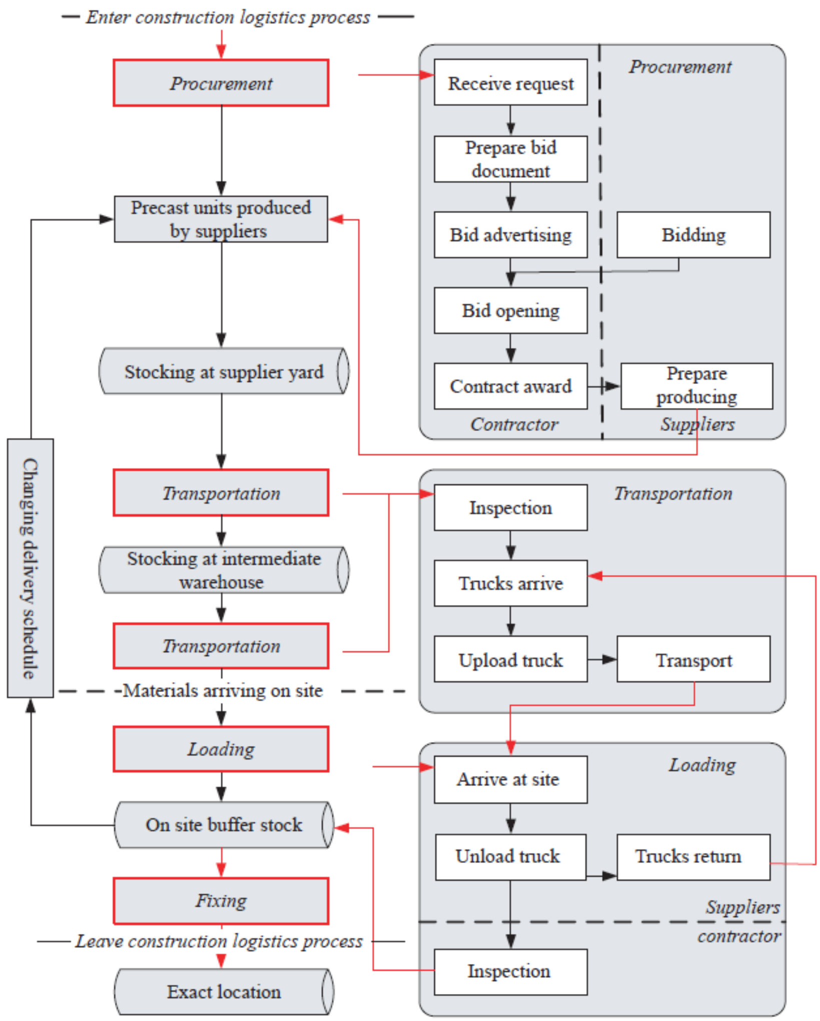

Figure 2.1 Overall logistic processes of precast concrete units (Fang and Ng 2008)

Logistic procedures in a construction can be separated into two basic functions: supply logistics and site logistics. Supply logistics are based on activities related to production processes. These activities include determination of required materials, resources and manpower. In addition to these, planning of supply, acquisition of raw materials, transportation of requested materials to site, delivery and storage are other processes occurring in the field of supply logistics. On the other hand, site logistics are more related to planning, organizing and controlling on-site related processes. This includes managing the handling equipment, planning site layout, defining sequences and resolving conflict among the involved parties (Fred and Francisco 1999). An example of typical logistic procedures involved for precast units is shown in Figure 2.1 (Fang and Ng 2008). This shows how logistic processes are occurring for precast units in site and out of the site. The required materials are passes through several processes. These include providing raw materials to manufacturer, storing produced goods in warehouses and delivering required materials to the construction site. At site, these materials are delivered, transferred to temporary storage areas and handled with equipment for installation. The flow of materials from obtaining raw materials to installation is summarized in Figure 2.2. At the same time, there is also information flow backwards to the supplier. The planning made on construction projects requires several decisions on logistics to properly obtain required materials in a right time with feasible costs. This includes documentation, data processing, communication between different parties, analysis and planning of logistics processes. Therefore, this flow of information provides knowledge that relates to physical services within the supply chain.

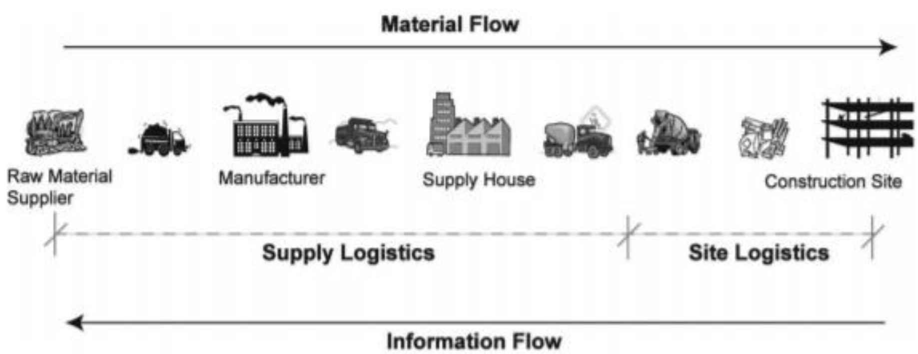

Figure 2.2 Summary of material logistics (Jang, Russell et al. 2003)

2.1.4. Handling

Handling of materials is a key component for material flow processes and provides transportation and placement of the materials through necessary locations at site. Due to the high frequency of material handling processes at project sites, selection of equipment to be used is important since it can improve production processes, utilization of labor force and flexibility in construction processes (Chen, Li et al. 2002). Common problems that arise with supply of the materials is improper loading and unloading that increases portion of wastage. Selection of right equipment is essential. As such, material storage locations at site needs close attention to reduce waste, loss or damage that can influence construction operations adversely. Problems may arise during the supply of materials due to improper storage and protection facilities as well (Canter 1993). Thus, safety precautions and choosing right equipment during the material handling operations within the sites is essential.

2.1.5. Waste Control

Generation of material waste is one of the major issues in construction industry (Formoso, Soibelman et al. 2002). In order to reduce waste, on site material storage should be managed properly. Waste can arise during construction operations if storage areas are not secured and waterproofed or the transportation of bulked materials are not planned properly. During the flow of the materials, materials stored must be classified and routes for supplying required materials to the installation point from storages should be planned as well. Stored materials should be permitted to easy access and retrieval.

2.2. Existing Technologies and Methods to Manage Materials

In construction industry, there are many technologies and approaches that are capable of tracking site materials which are required for certain tasks and activities. RFID tags, bar-codes and just-in-time strategies are commonly used to manage site materials properly to improve on traditional way of managing materials.

On the other hand, use of information and communication technologies (ICT) can help implement management of materials at site more effectively and it provides efficient control of construction materials at project sites. Such technologies can transfer information necessary for management strategies faster than traditional way of management practices. Traditional construction processes usually depend on paper documents including drawings and specifications. This way of management is mostly resulted in excessive paperwork and increased possibility of poor site material management. It also causes problems during the exchanging and recording of the information regarding to the materials within site construction processes. Following parts discusses currently used information and communication technologies used for better management of site materials.

2.2.1. Bar-Code Labels

Bar-code is a self-contained message with the information encoded within the bars and spaces in the printed pattern (Harmon and Adams 1989). Bar-codes allow for quick and errorless data entry in to a computer system (Bell and McCullouch 1988). In the construction sites, integrity of site related aspects is achieved by using bar-code labels in different phases of construction (Cheng and Chen 2002). By programming on-site material management systems, the scanned bar-code can provide information for delivery of the materials, storage areas of the corresponding materials and status of the materials to be used for specific activities. Basically, the implementation of bar-code identification systems consists of three phases; designing, manufacturing and erecting of required components for the project respectively. For example, during the design phase of a prefabricated parts of a building, detailed designs drawings are obtained, and necessary structural analysis are made. Later on, an individual code is being assigned to same component to specify information regarding to site delivery dates, storage and installation time. Again, same code is being used in the manufacturing stages in order to create production schedule, inventory and storage management at plant yards. When the erection phase starts, site managers are able to track required materials that are transported to project sites and initiate erection phases by construction schedule which is correlated and updated with production and delivery schedules of required building components. Therefore, bar-code labels help to make required materials available, ensures delivered materials, fulfil the activity requirements and provides flow of necessary materials through the construction processes.

2.2.2. Radio Frequency Identification (RFID) Systems

The timely and accurate provided information regarding materials availability for high-level material related decisions can lead to increased performance in construction processes. Therefore, tracking, location and distributing necessary materials to right places with a timely manner is essential. Materials found at yard before should be issued to an equipment or crews for the installation. However, field engineers spend most of their time on tracking required materials and equipment (McCulloch 1997), but lack of information management regarding to the building materials and resources limits effectiveness of the production at site (Kiziltas and Akinci 2005). As an alternative, different from human observation; many of the researchers have focused on investigating the feasibility of: (a) tracking the location of equipment and labors automatically, (b) determining activity status including assigned resource to that specific task and (c) finding out the performance indicators (Sacks, Navon et al. 2003, Ren, Anumba et al. 2011). In this sense, use of radio frequency identification (RFID) system are offering storage of data required to properly manage on-site materials, tracking of necessary resources and materials and identification of building materials at site. RFID provides wireless communication between the tagged products or goods and users, eliminates collection of data manually and provides automated identification. In addition, many of the researchers have improved RFID technology to adopt it in construction industry for material and equipment tracking. For instance, Song, Haas et al. (2006) presented an approach that automatically tracks and identifies the tagged materials and material handling equipment. They have created a mathematical model that can calculate the location of the materials or equipment needed for construction processes at site by 2D grids. Results show that the model is capable of accurately locate materials and equipment at experimented field. The studies on locating building components and materials using RFID technology have also conducted by other researchers using different approaches (Dziadak, Kumar et al. 2009, Torrent and Caldas 2009). Chin, Yoon et al. (2008) worked on an information system that can manage the logistics and control the processes of steel structured works with the integration of RFID and four dimensional and computer aided design (4D CAD). They have developed strategies using two state of art technologies for manufacturing and erection processes of steel structure works and created a framework that supports management of the processes and logistics based on RFID and 4D CAD. By this approach, researches have realized the potential of RFID and 4D CAD on minimizing the risks of loss of materials, schedule overruns and delivery issues. RFID has proven that it is a promising technology in the construction industry by many of the application in the construction sites. Significantly, it increases construction productivity, provides feasible costs, saves time, decreases errors and maintains efficient process management.

2.2.3. Just-In-Time Concept

The Just-in-time (JIT) concept is applicable for logistics management on job sites to increase productivity. Just-in-time concept originated in the manufacturing industry. But both manufacturing and construction industries are highly dynamic, require movement or transportation of the materials to the right places at work areas. It is firstly developed in Japan, and also known as Toyota Production System. Toyota used this approach to smoothen the production line with less inventory levels. Application of just-in-time concept helped to increase performance of production processes by handling of materials, providing right materials in a right time with right quantities (Pheng and Meng 2018), therefore minimizes material quantities in inventories. JIT enables timely on-site delivery of the necessary materials when the materials are required for production or before installation happens. Therefore, JIT can increase efficiency of the construction productions, smoothen the workflow and facilitate good material flow process at site.

2.2.4. Site Layout Planning

A good site layout for construction operations is important to ensure that the transportation of the materials and equipment are properly performed and smooth flow between site facilities such as storages areas can be maintained. Safe working environment can provide for effective and efficient material related processes. In addition, this can lead to minimized travel distances within the operation site, decreased material handling and also avoids obstruction of materials and plant movements (Lam, Ning et al. 2007). However, the arrangement of site facilities is complicated by many constraints including area limitations at site, adjacent buildings, site access and the location or orientation of the building to be constructed. Additionally, dynamic and complex nature of construction operations increase difficulty of layout planning. That is why traditional construction sites often found to be more messy, disorderly and lack adequate planning.

In designing a site layout, key facilities that influence method and sequence of construction are positioned and remaining facilities are assigned in remaining spaces accordingly. This process is mostly managed by several algorithms categorized as ; (1) exact algorithms, (2) heuristic algorithm and (3) population-based algorisms. Exact algorithms (Christofides and Benavent 1989) are for solving site layout problems but mostly used for small scaled projects . Heuristic algorithms are including tabu search (TS), simulated annealing (SA) and genetic algorithm (GA). The common objective of these algorithms is optimization of on-site facilities, cost of resources' transportation between facilities, frequency of tips made by construction personal and so on. Ant colony optimization (ACO) algorithm is a population-based algorithm and used to find solution for difficult combinatorial problems. This approach was inspired by foraging behavior of the ant colonies (Stützle and Dorigo 1999). In the process of searching food, ants are coordinating their activities using a chemical named pheromones. During the search for food, ants are always choosing shortest branch to reach the food source return to the nest. As such, during site operations, routing problems are solved using the same principle as ants follow. Therefore, ACO algorithm is a promising approach to solve assignment problems, scheduling problems, delivery problems, handling and procurement problems for the materials to be used in construction.

2.2.5. Resource Levelling and Smoothing

On project sites, resources are needed to carry out specific activities, but the availability of the resources is limited. During construction scheduling, engineers may schedule some tasks in parallel with same type of resource with limited availability. Resource levelling aims is to solve over-allocation of resources for the given project. Traditional project scheduling methods do not take resource usage into consideration and often results in improper resource use that increases project cost. In most of the cases, problems related to resource leveling are resolved by modern scheduling software such as MS Project and Oracle Primavera P6.

A resource is over-allocated in the case of when resource is scheduled to complete more work than possible. While performing the certain tasks in the site, resource levelling can be solved easily by simply delaying tasks until the required resource is available or it would be very complex to solve if the resource is assigned to multiple projects throughout the company. In this case resource levelling should be done at the company level rather than the individual project. If the levelling is done on a task which is not present on the critical path, the project will not be delayed however, if the task is present on the critical path; then the project can be delayed. Resource levelling is a critical issue which should be solved accordingly to avoid delays at project. A proper resource levelling can reduce project cost and provides a realistic schedule. For instance, there is a task which involves excavation. To perform this task, one excavator is needed, and it takes 4 days to perform the task. In the case of two excavations as shown in Figure 2.3, the job cannot be completed as planned when there is a single resource. In this case lengthening the schedule (trade off) would solve the problem.

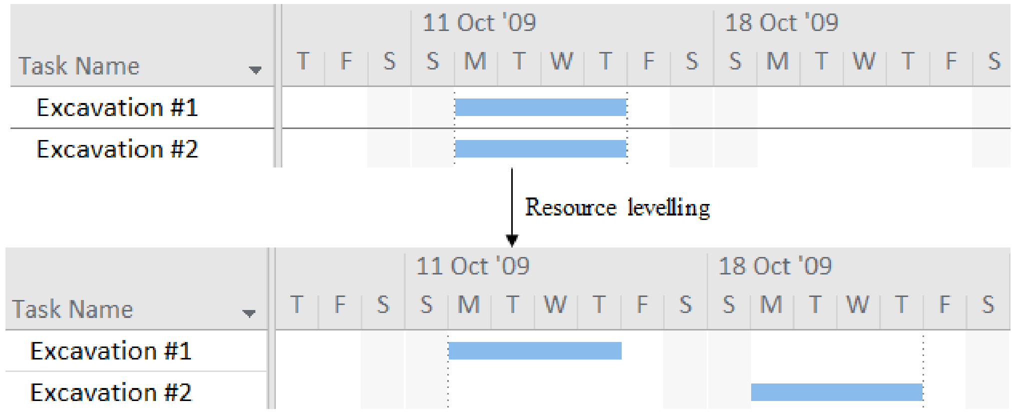

Figure 2.3 Example of resource levelling

Resource smoothing is used when the time constraint takes the priority in the planning of the project. The goal of resource smoothing is to complete a task within the required date or time. The smooth profile for the resources can be achieved by delaying some tasks in the schedule. It is a cost-effective way for managing resource use. The difference between resource levelling and resource smoothing is resource availability and time constraints.

Resource levelling and smoothing is important for site material flows as they use limited amount of handling equipment. The simulation platform used in this thesis can perform resource levelling by allowing limited number of resources and delaying activities when there is no available resource.

2.3. Automation in Construction Material Management

Construction operations can be affected by many factors such as resource allocation, labor productivity, delivery schedule, storage of materials, supply of necessary materials and eventually financial status of shareholder. Planning of construction activities and involved processes are challenging, there are numerous interactions between involved disciplinaries; causing unpredictable outcomes and problems. Due to the increase in complexity and changing environment as the construction projects continue, traditional way of construction planning is no longer effective for creating effective work plans and providing good material flows at sites. Traditional material management approaches have limited management of material related information. Lots of the analysis regarding to site material related processes such as handling, storage and resource use remain manual and dependent on engineers' previous project experiences. Traditional methods push project managers to utilize previously obtained project data and make heuristic judgments for plans and decisions related to on-site processes. However, each construction project has its own requirements and each project is planned within different conditions. Each project is being operated under different constraints, environment and require coordination of different site resources (AbouRizk 2010). Construction plan prepared for a different construction project cannot provide sufficient data to predict productivity and resources needed during construction processes (Jeong, Chang et al. 2016). Usually, on-site workflow suffers from changes and updates, which cause delays, cost overruns and operation problems. Additionally, such changes lead to ineffective material supply, excessive or lack of necessary materials may not coincide with actual material demand. All these leads to more complicated planning of site processes.

In order to manage and automate material related operations at site, two potential technologies are promising: Building Information Modeling (BIM) and simulation. BIM can utilize information needed to accurately manage construction processes and simulation approach can be used to analyze construction operations more logically. This part of literature review discusses BIM and simulation approaches. The definition of BIM, the potential use of BIM in material management context and its current use are discussed. In addition to BIM, simulation technique used for site related operations, its current use and potentials, opportunities and limitations are discussed.

2.3.1. Building Information Modelling for Site Management

BIM as it relates to a construction project provides detailed information and relevant data of design, planning procurement, logistics, fabrication and activities involved during the different construction stages. It provides geometry information related to building components or materials, spatial relationships, quantities regarding to materials, components or elements, properties of materials to be used, information for construction schedule, cost and site progress. Even after the project completion, BIM model can be used for operational purposes as well. It is not just a revolutionary tool to simulate construction projects visually but also a visual process that governs different disciplines, systems and aspects within a single virtual model, integrates varying parties including; engineers, suppliers, contractors to collaborate under same platform more accurately and efficiently than using traditional techniques (Azhar 2011). It can be used to demonstrate whole building life cycle. It provides accurate information to manage materials required for each activity, it improves planning and scheduling, and ensures just-in-time arrival of necessary resources and materials (Eastman, Teicholz et al. 2011).

Planning and scheduling for construction operations requires sequencing of activities, material procurement, use of resources, evaluation of construction methods and arrangements for different trades. In the past, bar charts were used; however, it was not able to show how different activities were linked in an order. Currently, Critical Path Method (CPM) is the standard for scheduling, supported by computer software such as Microsoft Project and Primavera P6. However, using Critical Path Method with BIM is mostly limited to utilization of the spatial components of the related activities and linking of such spatial elements to construction model (Choi, Lee et al. 2014). Scheduling remains mostly manual and not synced with the actual building model, therefore it is prone to errors. Gantt Charts are useful to manage various tasks and relationships between them such as sequences, dependencies, priorities, completion of task in terms of time and duration of activities. However, Gantt Charts exemplify how hard it is to evaluate construction operations; they need to be frequently updated and become very hard to maintain. Gantt Charts can be difficult to understand and do not identify spatial aspects of construction activities, as they are not linked to design or building model (Raut, Valunjkar et al. 2017). 4D CAD promises solutions to these problems; allows engineers for scheduling plans visually and manipulating activities in the context of space and time by linking 3D model and construction schedule of a project (Eastman, Teicholz et al. 2011). Previously conducted studies have shown that 4D models can be very effective for supporting project management. 4D models were used to compare alternative task sequences, predict problems regarding to construction logistics, resolve spatial problems between activities, monitor construction progresses, plan site layout and utilize resources (Akinci, Fischer et al. 2002, Chau, Anson et al. 2004, Ma, Shen et al. 2005, Hartmann, Gao et al. 2008, Golparvar-Fard, Peña-Mora et al. 2009, Li, Chan et al. 2009). But none of these studies have included logistics and material flows at site. 4D models can be used to determine quantities required for construction activities by obtaining BOQ information for each building component and defining required materials. As construction progresses, plans change and there are lots of materials that are delivered to be used in required location on site. Therefore, 4D can be also help manage material logistics. It is possible to create an overall view of site processes and site operations using 4D models so that site conflicts can be identified in early phases. For instance, Wang, Zhang et al. (2004)

developed 4D dynamic model of a construction project that manages planning of the construction and resource utilization. They have generated a 4D model and defined requirements for each activity including materials, labor, workspace and cost. By doing so they were able to analyze resource requirements and assign materials accordingly. However, detailed analysis regarding to temporary objects such as storage areas capacities, on-site logistic paths, resources and flow of materials including required material quantities for activities are not considered. Most of the 4D modelling approaches are lack of generation of site usage, estimation of quantities for construction materials and evaluation of cost.

2.3.2. Simulation of Site Processes

In many industries, simulation is used to solve problems and make decisions. One use has been analysis of production and logistics. Simulation of construction was developed due to the needs for designing and analyzing processes involved (Sawhney, AbouRizk et al. 1998). Simulation offers improvements for planning and design of the construction processes, allows representation of resources used, environmental aspects and impact of such factors to the whole project more logically. Using simulation tools, activities required to construct a building, resources involved to complete the work (equipment, labor etc.) and environment that the project is built under can be represented (AbouRizk 2010). It allows engineers to compare different scenarios of construction processes with less time and low costs. Problems occurring during the construction phases can be identified and necessary actions can be taken.

There are simulation methods used to represent set of different operations in different industries especially in the field of construction. These methods are known as discrete-event simulation (DES) and agent-based modelling (ABM). In DES, processes are modeled as a series of discrete-events (Maidstone 2012). Events occurring in particular times mark a change in the system and between the events no change is assumed to occur (MacDougall 1987). On the other hand, ABM is used to simulate actions and interactions of autonomous agents such as equipment used in a construction, labors or other resources and mimics complex system behaviors and responds to conditions in system (Sanchez and Lucas 2002). By doing so, the effect of agents can be seen thought the simulation to whole system.

There are many simulation tools used in the construction sector to analyze specific site operations such as on-site material logistics. The CYCLONE (Halpin 1973) is an approach to model and analyze typical construction operations and it relies on flow diagrams of repetitive processes (AbouRizk, Halpin et al. 2011). Likewise, STROBOSCOPE (Martinez and Ioannou 1994) is a simulation tool that can evaluate construction processes dynamically, properties of equipment and labors involved in operations and can develop complex construction simulations (Halpin, Jen et al. 2003). It allows user to represent complex site operations by flow diagrams and users can analyze duration of loading tasks, time spend for loading and unloading of materials, number of installed materials, etc. by defined programming codes to get more accurate results. Other multi-method simulation tools such as AnyLogic and Simulia. These are available software that are used as general purpose simulation tools for analysis of manufacturing processes of any goods or other events happing in hospitals, warehouses, supply chains etc. These simulation tools use multi-method modeling techniques; integrate different methods of modelling and simulation namely system dynamic, agent based modelling and discrete event modelling. Such simulation frameworks are highly beneficial as decision making tools however, these approaches are rarely adopted by the construction sector. One reason is that defining and maintaining equipment, labors and material assignments to corresponding activities, while keeping synced with the general schedule is time consuming and prone to errors. Building simulation models mostly remains manual. For instance, if there is a change or update in processes, resource allocation or any other constraints; the operations must be reupdated and formalized properly again. BIM can address these problems since it provides detailed information for building components. BIM is not integrated with simulation, however when used with simulation technique; potentially develop building simulation models and promises detailed analysis on whole construction phases.

Computer simulation techniques have been used to analyze construction operations such as tunneling, bridge construction, earthmoving, pipeline construction and so on (Touran and Asai 1987, Vanegas, Bravo et al. 1993, Huang, Grigoriadis et al. 1994, Shi and AbouRizk 1998). Others have simulated manufacturing processes of precast concrete members to improve performance of the production (Balbontín-Bravo 1998). Processes involved in these construction projects requires several unique activities and these activities cannot proceed until necessary resources are provided. In a real case scenario, resources can be busy; involved to an activity or idle. As such, during the simulation, this resource requirements are logically depended on activities executed and the dynamic behavior of construction process are portrayed over time accordingly (Ng, Shi et al. 2009). It is proven that simulation of construction operations is possible by defining random nature, resource-driven characteristics of processes and dynamic interaction between activities during the operations (Shi 1999). By the previous attempts and researches on simulation of construction operation, it has proven to be one of the most effective approach on improving performance of construction processes (Halpin 1977). Since then, simulation is used widely by academicians and civil engineers for analysis purposes.

2.3.3. Integration of BIM and Simulation Approaches

As discussed, BIM offers data-rich parametric representation of construction projects and simulation approaches promise detailed analysis on planning, design and construction of the projects. BIM and simulation approaches within the same platform can provide parametric studies on 3D building models. Recent researches have attempted to integrate BIM with simulation technique. König, Koch et al. (2012) presented an approach for automatically assigning process patterns. They defined activity interdependencies for construction operations. BIM-based multi-method approach is used to acquire necessary input data both for the construction simulation and the schedule. Wang, Weng et al. (2014) utilized 4D BIM to support simulation of site level-operations for generating construction simulation. The proposed approach was able to calculate the duration of the activities and tasks, resource needs among the tasks and evaluate resource allocation strategies to generate proper construction plan. It used BIM and discrete event simulation (DES) to propose a framework that can integrates DES in planning of construction activities. BIM is used to provide process and product information for the DES model and DES model used to evaluated performance of the project. Resulting integration was promising to provide reasonable information, feedbacks. It used as a decision-making tool to support BIM processes as well. Liu, Al-Hussein et al. (2015) presented BIM-based scheduling approach that enables automatic generation of activity level construction schedules for building projects under resource constraints. They were able to generate schedules for the construction projects using BIM, WBS information in MS Access, process simulation model Simphony

(Hajjar and AbouRizk 1999) and optimization algorithm. However, proposed work have limitations including estimation of project duration and productivity, factors affecting construction schedule such as weather changes, delivery of the goods, work space limitations and other risks are not considered and simulation part of the presented study remains manual. Jeong, Chang et al. (2016) integrated BIM with simulation to predict productivity for steel construction project. A structural steel BIM model was imported into an external simulation software to develop construction plans which were capable of adapting project changes. By doing so, they were able to estimate productivity dynamic, manage resources, control time and cost. Other than these studies, BIM and simulation has been used to analyze cost estimations and energy usage (Welle, Haymaker et al. 2011, Cheung, Rihan et al. 2012, Kota, Haberl et al. 2014). With the use of BIM, cost for each building components including all the resource used for construction can be simulated for forecasting total cost of a project. As such, building or architectural models can be used to convert thermal analytical models to examine heating or cooling energies within simulation methods parametrically.

2.4. GSimX Simulation Framework

As discussed, for construction planning, BIM is mostly used for visualization of construction processes, and the most common approach is 4D visualization to validate construction sequencing. It is used to coordinate ordering, manufacturing and delivering of the materials needed for the production. As a project progresses, extra information added to 3D visualization of the project shows time or schedule related information for a specific component of a building. On the other hand, simulation technology promises detailed analysis for resource use, on-site related aspects and effect of change in such parameters to whole project with improved time and costs. But again, simulation is not widely adopted by the construction industry because it remains manual and hard to maintain. Although recent studies relate BIM with simulation, potentially for planning and analysis of processes in different construction phases, use of this approach is very limited, BIM and simulation techniques are not fully integrated.

In this thesis, for material simulation using BIM, GSimX is used. GSimX is a prototype BIM-based resource-integrated simulation framework that can model and simulate construction production directly on BIM as a whole. GSimX (Akbaş 2016) is a BIM-based simulation platform that can model and simulate construction production directly on BIM elements considering labor and equipment, while keeping in sync with project schedule. It uses both discrete-event simulation and agent-based modeling approaches to analyze construction processes. Simulation generates detailed flow sequence of all installation work by enacting each crew and equipment performing work as an agent and respecting relationships from the schedule. BIM elements directly become a part of discrete-event simulation and all process entities are simulated as queueing networks. It uses quantities for tasks during simulation, matches site resources with activities, and identifies resource assignments to satisfy project schedule. During simulation, each activity can begin if the prerequisite tasks are complete, necessary resources are ready at installation location and there are no other construction constraints. Different from other analysis tools, GSimX also analyzes crew and equipment behavior on site based on construction schedule. It allows users to realize impact of a change in a parameter to whole construction site and evaluate different scenarios.

2.4.1. Simulation Approach in GSimX

To be able to perform a simulation in GSimX, first 3D BIM model of the project and master schedule are imported to GSimX. After that simulation units called location flows are formed, either manually or automatically, by linking activities with 3D BIM elements. Project resources (crews, labor, equipment used for construction processes) are defined by the users. Properties of crews and equipment used are specified within GSimX such as equipment capacities, number of labors in each crew, productivity rates etc. The identified resources, crews and equipment are all linked to corresponding site activities and any other resources can be defined if necessary. After the modeling is complete, simulation can be performed. The simulation processes can be seen on 3D BIM in the workspace of GSimX. During the simulation, all BIM elements become a part of discrete-event simulation and all process entities are simulated as queueing networks. Again, during the simulation; each activity can begin if the prerequisite tasks are complete, necessary resources are ready at installation location and there are no other construction constraints. At the end of the simulation, GSimX provides an analysis results of the activities, resource use, project time and cost in graphs and reports. Users can easily change project parameters and inputs to simulate processes differently. For instance, users can add new crews and equipment or specify how a crew or equipment should proceed can be easily determined through the simulation. Additionally, parameters and inputs can be changed to compare different process alternatives and evaluate analysis results of different simulations.

GSimX is capable of analyzing site operations with respect to available resources however, it cannot simulate material related processes at site. In order to analyze site material flows and logistics using GSimX, many definitions and developments have to be made including; defining information related to construction materials, defining resource requirements such as equipment, labor and storage space, defining material flow patterns, developing a database to manage information required for simulation and integrating this database with GSimX simulation framework. After all of these done, process models will be ready to simulate material flows and logistics. But again, there are still much to include to detailly analyze all the material related process not just in the site, but also out of the site. Still, processes involved for supply logistics; obtaining raw materials, production, manufacturing, procurement and delivery of the materials are not included neither in the model nor construction schedule.

GSimX offers great advantages for construction processes and planning. Since it integrates BIM, simulation technique and resources use within the same environment, a change in project component can be monitored and analysis of construction works can be made more comprehensively.

2.5. Literature Review Conclusion

Traditional way of material management methods is limited for managing on-site and off-site related aspects. Traditionally, planning and decisioning on construction processes are based on engineers' experience and previously collected data. Multiple factors around the project are not fully considered. Supply, handling and logistics of necessary materials are managed in an ad-hoc fashion.

Existing technologies such as RFID and barcoding along with different logistic planning strategies such as just-in-time approach promising for tracking required materials for specific activities. Integration 4D CAD with RFID technology allows planning of site operations more effectively, however it only visualizes operations, spatial analysis of the construction productions remain limited.

Implementation of BIM can support management of processes and materials. BIM can be integrated into planning of the construction. It can be used for controlling system for effective management of site material delivery and logistics. Since the construction projects are getting more complicated as the operations are keep going, controlling activities and sequencing of tasks manually getting harder. BIM can automate operation of such processes and can provide more reliable information. BIM for planning promises for better management of resources and therefore, logistics and flow of materials become more workable.

With the integration of BIM with simulation, planners can be able to manage all resources and construction logistics more detailly, since integration of these approaches provides compressive analysis of site activities with detailed information and data provided by BIM use. Simulation promises for stabile workflows and works as effective decision-making tool. Site operations and material logistics can be structured through BIM and resource integrated simulation approach. Therefore, planners will be able to generate effective workflows and process plans for better material flows and logistics of required building components.

CHAPTER III

METHODOLOGY

The methodology chapter of this thesis identifies the requirements, information management and integration of different sources with simulation framework to conduct on-site material flow and logistics simulation using BIM.

3.1. General Methodology

The presented approach for this thesis builds on an BIM and resource-integrated simulation framework (GSimX) that can analyze site related operations and obtain requirements for the resources. This simulation platform can simulate site operations including resource use with imported BIM and a construction schedule. When BIM and the construction schedule are imported and links between BIM entities and activities in the schedule are formed, necessary resources are defined. Construction operations are simulated accordingly and GSimX provides detailed results with graphs and documents regarding to equipment and crew use, project cost, project time, etc. However, GSimX cannot simulate material related processes at site with handling equipment, storage use and materials, as it lacks information and techniques to simulate on-site material flows. To simulates on-site material related processes, material processes need to be represented, information regarding to resources, storages, site layout and required materials along with material quantities needs to be transferred correctly from BIM, and this information should be integrated with simulation platform properly to perform the analysis. On the other hand, off-site logistics (supply logistics); processes involved from manufacturing to delivering of the materials to the construction site (production, manufacturing, procurement, transportation, delivery etc.) are not considered for simulation, not reflected to construction operations. Required materials are assumed to be delivered to the site as necessary, ready for use at a time or stored for later use.

The developed approach for demonstrating on-site material process simulation includes the following:

(1) Identifying information needed for representing site material flows and logistics. This includes (a) creating on-site material flow diagrams to represent for simulation steps from delivery of materials at site to installation of required materials and calculate duration of each process step, (b) supporting storage area properties to represent storage area capacities in terms of pallet quantities and defining hoisting equipment capacities for transporting palleted materials between different locations during simulation, and (c) supporting conversion of material quantities into container quantities, then into pallet quantities given predefined container capacities and pallet dimensions.

(2) Managing information extracted from BIM of the project using the developed Task-Component Database. A new database model is prepared based on the existing Task-Component document that contains formulations for obtaining material quantities, production rates for crews, required resources and material types for each task is established. All properties such as material types, container types, container quantities and pallet quantities of required materials are included within the

developed database. This developed database provides information for material flow simulation in the simulation framework.

(3) Defining an approach to integrate the identified material information and the developed database with BIM and resource-integrated simulation tool (GSimX) to enable on-site material flow and logistics simulation. This will allow for generating alternatives for evaluation of on-site material processes and resource use. As a result of that, early important decisions on site related aspects such as storage space required, material quantities delivered, equipment and labor use will be taken in early stages of the construction processes.

(4) Demonstrating the approach on an experimental test case.

The following sections describe each of these steps for this research. The last item is described in Chapter 4.

3.2. Information Required for Material Flow Simulation

The existing simulation approach can support crew, equipment and high-level material requirements however, analysis of material flows will require extra materials related information: (a) steps required with site material flows and calculation of duration for material flow processes, (b) storage area and equipment capacities for simulation, and (c) container and pallet capacities for converting material quantities suitable for into container and pallet quantities.

This section describes the developed material process flow diagrams for different type of materials, calculating the durations of material processes, storage area and equipment capacities for and material conversion to containers and pallets. Once these inputs are received, detailed location flows considering material logistics will be generated automatically within the BIM environment for simulation. Simulation will generate possible alternatives for material flow processes and on-site material logistics. This can be used to analyze on-site material flows and logistics in the early phases of the construction to determine resource use and storage capacities per material quantities.

3.2.1. Material Process Flows

To demonstrate on-site material flows and logistics, a generic process model has been developed following multiple steps from site delivery to installation. This generic material flow will be used for two types of materials classified as ‘Type 1’ and ‘Type 2’. Type 1 materials have long storage duration and these materials are generally inexpensive such as ceramic tiles, structural metal profiles, plywood and membrane. Type 2 materials on the other hand, are sensitive to weather changes, more fragile, have short storage duration and are more expensive. This type of materials is usually used for architectural works.

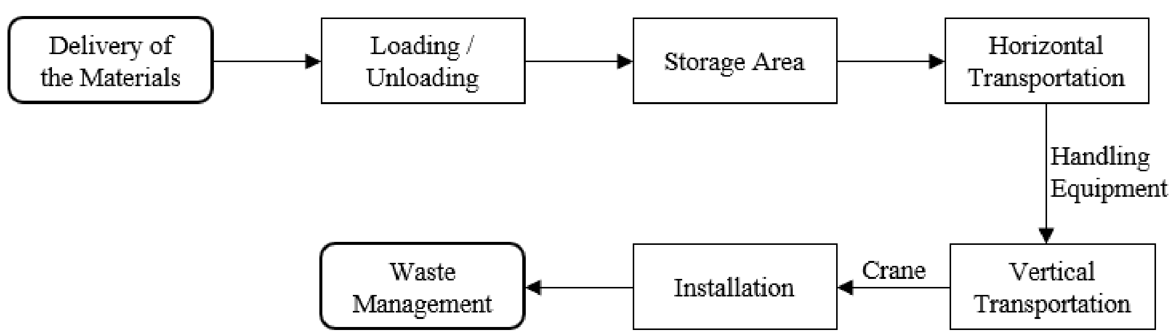

Figure 3.1 Generic Material Flow diagram for site materials

Figure 3.1 shows developed generic material flow diagram for considered types of materials. Once materials are delivered and classified, materials are loaded and unloaded to storage area locations. When materials are needed for a specific activity, materials are transported horizontally and vertically by specific equipment to installation locations. When an activity is completed, waste management takes in place. Site activities cannot proceed until all necessary materials are ready. This generic material flow forms cycles that are repeated many times during the project.

Delivery of goods, storages area and hoisting equipment capacities, transportation of the materials and eventually installation of required materials are key aspects for this material flow diagram. For Type 1 and Type 2 materials, two different material flow diagrams are formed. For Type 1 materials, materials carried by powered machinery since these materials are heavy and big in size; requires heavy equipment. On the other hand, Type 2 materials can be carried by powered and unpowered machinery. These materials are mostly sensitive, fragile and can be a lot in amount depending on requirement, therefore can be transported by powered machinery and also can be carried by manpower using pallet jack additionally.

For conducting material flow simulation; storage areas, resources and materials quantities are included within the created flow diagrams. During simulation, transported material quantities, resource use and storage usage are calculated using the steps specified in flow diagram and alternatives can be generated for evaluation of site material processes.

3.2.2. Storage Areas and Handling Equipment

For different material types, there are different storage areas in and out of the project site. For instance, since Type 2 materials are fragile, sensitive to weather changes and expensive; these materials are kept in secured and safe storage areas. Since Type 1 materials are large in size, they are mostly stored in larger storage areas. Storage area capacities are defined based on dimensions of the storages and pallet size. Due to space needed for travel paths for loading and unloading of the materials within the storage areas, total volume of storage areas is reduced by a coefficient called Floor Area Ratio (FAR).

When materials are required, they are received from storage locations and transported for installation. If required materials are not available at on-site storage areas, these materials are transferred from off-site storage areas and production continues. Again, if the materials are not available at off-site storage area then production stops and waits for material deliveries. Figure 3.2 depicts how this process is working during the simulation.

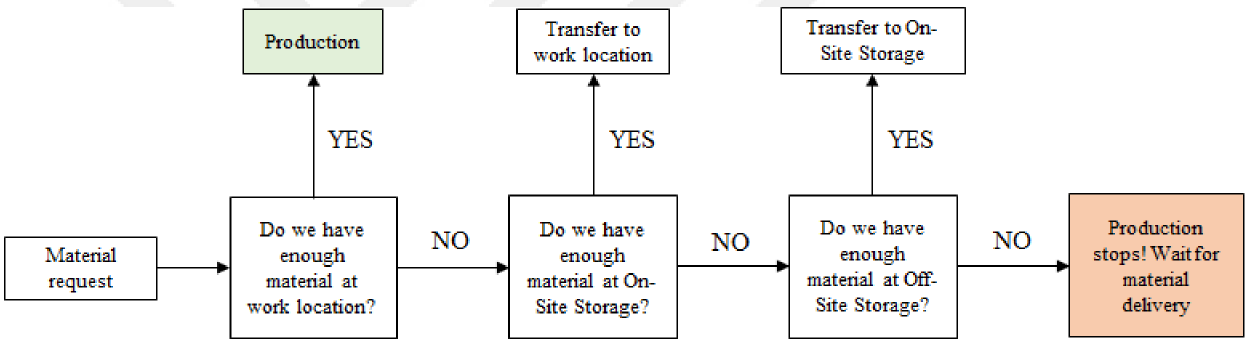

Figure 3.2 Decision processes during simulation

Hoisting equipment capacities are defined in terms of pallets; assuming all the materials delivered are carried as pallets. Possible equipment for transporting materials include backhoe, mobile crane, tower crane and loader crane. Each has its own loading capacities and different behavior. For instance, there are equipment for vertical transportation, horizontal transportation and even some of them are able to do both types of transportations. If necessary, new equipment can be added to the simulation as well. Equipment such as backhoe can carry materials from one storage area to another and it can load, and unload required materials from storage area to different points for installation horizontally. Other than backhoe, forklifts can be used to move materials within the storages only and it can deliver materials to another equipment to be transfer necessary quantities for installation. Crane can be used for vertical transportation; they can only transfer materials from on-site storage areas to installation points directly. Other than these, truck cranes which are mobile can be used to pull necessary materials from storages for transferring materials to installation points. Different from this aforementioned equipment, materials that don't need storage keeping such as concrete, sand, mortar etc. are supplied directly to required places using concrete mixers, truck or pumps.

Material transportation occurring during construction is represented in 3D space. During simulation, materials can be moved by specific equipment in x and y axes horizontally and can be transported through z axis vertically. For instance, tower crane transports materials vertically to the required locations. On the other hand, backhoe can carry materials horizontally within x and y axes.

3.2.3. Container and Pallet Quantities

To support on-site material flow simulation, material quantities need to be converted into container and pallet quantities using predefined container and pallet capacities for each material. There are different container types for materials such as buckets and packages. Not all the materials require containers for site transportation; they might be rolled, bundled or itemized to be carried by pallets.

For this thesis, capacities for different container types are defined using supplier's websites, catalogs and packaging methods. Pallet capacities are defined using dimensions of a standard pallet. Each pallet used has fixed width of 1.2 meters, length of 0.8 meters and allowable height with materials on pallet is 1-meter. Using these dimensions, total volume is found as 0.96 m^3. Using this information, pallet capacity is fixed to $1m^3$ when loaded.

To transfer right pallet quantities to installation locations from storage areas, material quantities are converted into container quantities and then, these container quantities are converted to pallet quantities. The conversion method developed for the material flow analysis is illustrated in Figure 3.3. The conversion is as follows; (1) total quantities are obtained for each task using BOQ file, (2) for each task, necessary material quantities are determined using quantities in each work location, (3) required materials in different units converted into different container types suitable for different material types, (4) container quantities on pallets are determined and finally (5) total number of pallets are found.

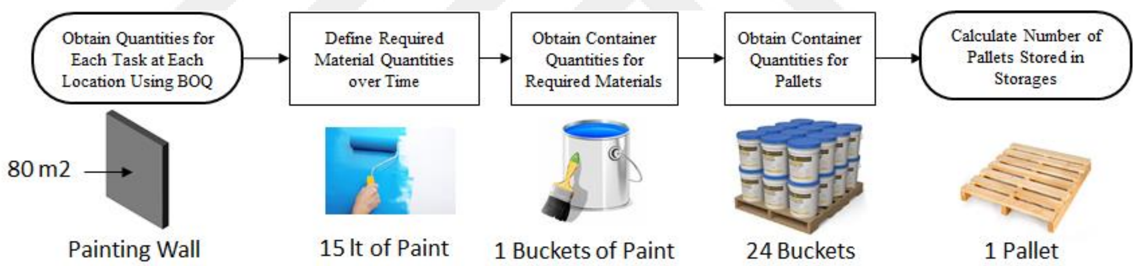

Figure 3.3 Conversion of Material Quantities

As an example, assume that one bucket of paint that is 15 liters can cover 80 m^2 work area. Using pallet capacity found as 0.96 m^3 and converting 15 liters to volume (1 liter = 0.001 cubic meters), it is approximated that each pallet can carry 60 buckets of paint. Therefore, each pallet filled with 60 buckets of paint can cover 4800 m^2 area (60*80=4800 m^2). Total pallet weight when loaded with 60 buckets of paint is found to be 0.9 tons by the weight of one bucket of paint (each bucket of paint is 15 kg). As other examples, capacity of one pallet to be 20 packages of plaster or 45 buckets of 20-liter insulation mixes. More examples are shown in Table 3.1. These materials on pallets are stored in storage area locations within the range of defined storage area capacities in volumes and transported to required location with hoisting equipment.

The converted material quantities are following predefined routes as illustrated in Figure 3.4. The flow of materials on pallets during the simulation as follows; (1) material quantities on pallets are obtained, (2) required material quantities are ordered from the suppliers as pallets that contains different types of material containers, (3) delivered pallets are stored in classified storage areas by material types, (4) during the production, required materials on pallets are located in site. If found, containers are pulled from storage areas by handling equipment horizontally to transfer necessary materials for vertical transportation. If materials are not found, production stops and waits for new materials to be delivered at site (5) materials are transported vertically by crane to installation points, and finally (6) materials are used for the task. As seen below, pallets are following these steps to reach their final destination. As the quantities in BOQ document are obtained for each task, necessary material quantities are determined, and materials on pallets are obtained, delivered and transferred to installation locations during the flow illustrated as in Figure 3.4.

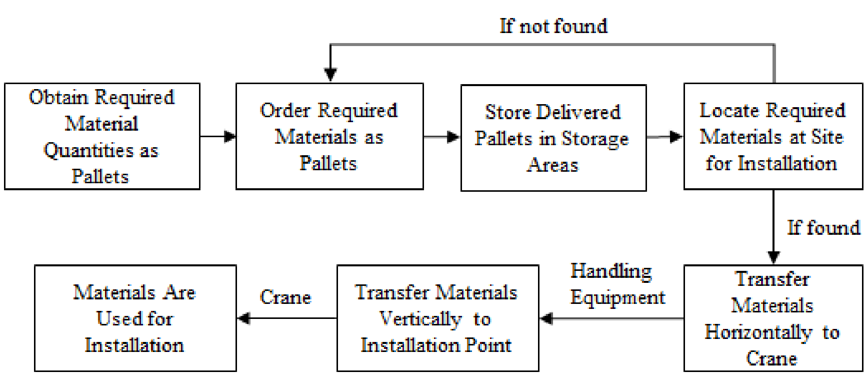

Figure 3.4 Flow of pallets during the simulation

For different types of materials, there are different container types with different capacities in terms of lengths, areas, volumes or liters while pallet capacities in terms of volumes which is 0.96 m3 for each pallet remains same as aforementioned. However, not all materials are delivered as pallets but containers. Therefore, these materials are not included within this approximation, such materials are directly transported to installation locations without the conversion mentioned.

Table 3.1 Example for container and pallet capacities for Type 1 materials

Material Name	Unit of Material	Container Type	Install Quantity per Container	Container Quantity per Pallet	Pallet Weight (kg)
Paint	m^2	bucket	80 m^2	24	900
Cement Screed Powder	m^2	package	80 m^2	20	1000
Ceramic Floor Tile	m^2	package	1.5 m^2	48	998.4
Ceramic Wall Tile	m^2	package	1.5 m^2	48	993.6
Cladding Adhesive	m^2	bucket	80 m^2	20	400

For this approach to work, all types of materials should be provided with total quantities in containers and pallets, number of containers in each pallet and total pallet weights with materials. Information regarding quantities are approximated from suppliers' websites and catalogs and material quantities are converted into pallet and container amounts. All this information regarding types, material quantities in containers and pallets will be included within the Task-Component Database. Users can change these conversion factors as needed using the created database. Using the quantity of work location to be installed for a task, the necessary numbers of packages, buckets, rolls, items and pallets are obtained. This creates association between site production and material flow simulation. Whenever a location is ready to be installed, simulation calculates material quantities required daily in appropriate unit and pulls the materials from storage locations and calculates resource use based on defined equipment properties, material quantities and pallet weights.

3.2.4. Calculation of Durations

As materials are requested during production, each material spends a specific amount of time for loading, unloading and transportation to the required locations. Duration for material flow activities are calculated during the simulation based on location of each storage area and heavy equipment used. Duration for transportation of the materials is calculated by the distance between the point of transportation equipment and installation location divided by the transportation speed of the equipment used. As such, loading and unloading durations are also calculated using loading/unloading durations and transportation speed provided for each equipment.

3.3. Management of Material Related Information

The material related information coming from different sources to the simulation platform should be managed to accurately represent material conversions as described in previous section and relating material information to production. Information regarding properties of tasks; production rates, disciplines, formulations for obtaining material quantities, necessary equipment for transportation and necessary materials types in containers and pallets are stored within the Task-Component Database. This information is used to obtain necessary material quantities, number of containers and pallets during simulation. This section discusses information flow between different sources and how the information is used by the developed database to calculate necessary quantities in simulation.

3.3.1. Information Flow Between Different Sources

To be able to demonstrate detailed analysis of on-site material flows and logistics integrated with BIM, construction schedule and resource use; various information coming from different sources should be integrated with simulation platform. Figure 3.5 describes general information flow between different sources to support analysis of material logistics at site within simulation platform.

To conduct the material flow simulation, BIM models, construction schedule, BOQ document and Task-Component Database are imported to simulation framework. Each BIM element is assigned with a code named as Object Code and each task in Task-Component Database is assigned with code called Component Code. Quantities in BOQ document is obtained by the formulations defined in the Task-Component Database. Within the BOQ document, Object Codes and Component Codes match and form Task Codes.

Task-Component Database defines production rates, master categories, disciplines and sequences for the BIM entities. In addition to that, material container types, material quantities in containers and pallets, total pallet weights for each material and material container amounts in pallets are all specified within the Task-Component Database. These BOQ and Task-Component Database are imported to simulation environment to provide right quantities at locations corresponding to BIM entities. During the simulation, quantities for tasks at locations are calculated, site resources are matched with activities, and resource assignments are identified to fulfil requirements of master schedule.

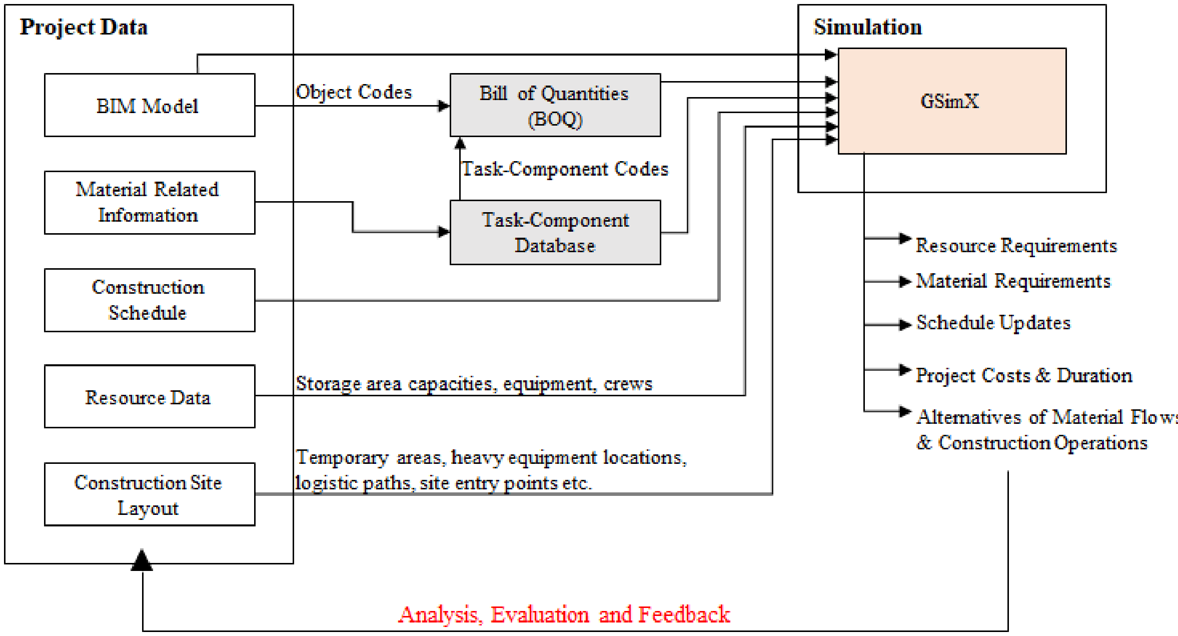

Figure 3.5 General Information Flow Between Different Sources

Along with BIM, construction schedule, BOQ and Task-Component Database; resource data and site layout are imported into the simulation environment. Storage area capacities, equipment and crews are defined and location of the temporary areas, heavy equipment (e.g., tower crane), logistic paths, site access locations and others are specified within the workspace of simulation framework.

The integration of the project data, BOQ and database with simulation framework for material flow analysis will enable users to analyze and evaluate different alternatives of site logistic processes by simply manipulating available resources and sequences of processes.

3.3.2. Task-Component Database

Task-Component file has an important role on providing required information to perform simulation in GSimX. It helps define links between BIM model and BOQ while relating to activities and detailed tasks (Hasan and Akbas 2017). It contains detailed construction operations and their sequencing for construction activities. It also specifies calculation for obtaining quantities for each BIM entity in different units, production rate per day for a crew corresponding to the task, required resources (equipment and labor) for task and required material types and quantities. Each entry in the existing Task-Component file is codified to be shared among each BIM entity, bill of quantities and GSimX framework (Hasan and Akbas 2017). Each code in Task-Component database has five levels, representing discipline, category, task and sequence. For instance, STR-100_05_LAS-BOQ refers to formwork task for structural column and is the second in the sequence of column formwork task. If the task requires more than one activity to be completed, then these tasks have the code 'LAS', means it will need resource and time to be finished; if the task has 'BOQ' code, means the BIM component is not a direct task in LAS level. Each task type in Task-Component Database is unique and called as Component Code. One Component Code can be assigned to many BIM entities and in contrast, each BIM entity can be assigned to many Component Codes.

This thesis improves on the Task-Component database in multiple ways. First, the existing Task-Component uses Microsoft Excel sheets, which is not normalized and lacks logical relationships between different attributes. This necessitates manual adjustments in case of any updates or changes. Secondly, it does not include material related information to support material flow simulation.

To support material flow simulation, a new Task-Component database has been designed and created using Microsoft Access. This database contains compatible information with the previous database, improving on it and adding material related information. Since the purpose of this thesis work is to demonstrate site material flows, many information regarding to materials, equipment, and other components should be organized within this database. The data tables are normalized and dependencies between the attributes are defined accordingly. For instance, discipline column was depending on main code column as material column was depending on component code. In addition, relationships between these columns are also defined.

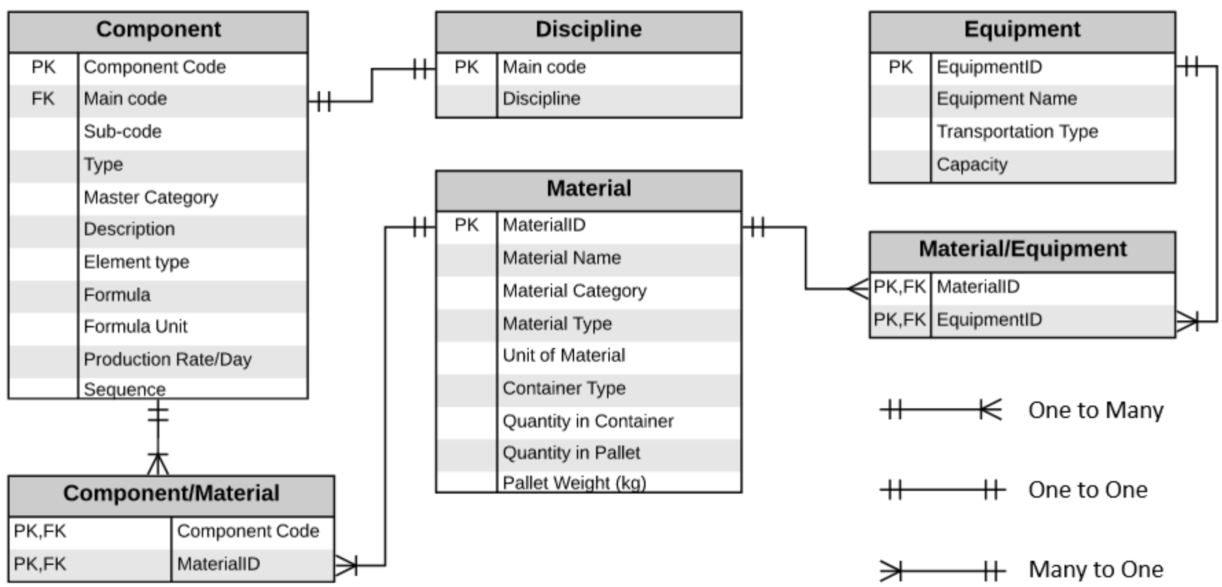

Figure 3.6 Developed Task-Component Database ERD for site material flows

Figure 3.6 illustrates the developed Entity-Relationship Diagram (ERD) for the new Task-Component Database. ERDs are used as a basis for unification of different views of data; the network model, the relational model, and entity set model (Chen 1976). ERDs are graphical representation of different entities and their relationships between them. These entities can have attributes that define its properties. Each Component Code is related to one-to-many materials and one material can be required by one-to-many Component Codes. Similarly, many equipment can be used for each task and one task in Task-Component Database requires many equipment for delivering necessary material to installation location.

Each Component Code has discipline referring to main trades at site and each discipline item contains master category, such as wall lining, wall tiling, painting for wall finish discipline. As an extension to the existing Task-Component file, material properties and used equipment are included within the created database. This Task-Component Database is imported into the simulation platform separately. This database helps define sequence of tasks for locations and forms a basis for simulating how materials are matched with available resources and how quantities transfer during site flows.

Material quantities for each task are specified within the BOQ document that is imported into the simulation platform. This BOQ document is extracted using the formulations defined in Task-Component file through BIM. Each code in BOQ document is combination of Object Code and Component Code. Object Code is composed of seven levels of work break down structure which represents information of location, category (structural, architectural etc.), name and ID of the corresponding BIM element. As illustrated below, the combination of these codes is under the column named Task Code. During the simulation, these quantities in BOQ file are used to calculate required material quantities, number of material containers and amount of material pallets.

ID	Sequence	TaskCode	TaskCategory	Component	Description	Unit	Total
20813	1	OZU_BE_FON_STR-CON_FBED_14303/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20813	2	OZU_BE_FON_STR-CON_FBED_14303/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
20873	1	OZU_BE_FON_STR-CON_FBED_14315/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20873	2	OZU_BE_FON_STR-CON_FBED_14315/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
20969	1	OZU_BE_FON_STR-CON_FBED_14327/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20969	2	OZU_BE_FON_STR-CON_FBED_14327/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
20981	1	OZU_BE_FON_STR-CON_FBED_14339/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20981	2	OZU_BE_FON_STR-CON_FBED_14339/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
20993	1	OZU_BE_FON_STR-CON_FBED_14351/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20993	2	OZU_BE_FON_STR-CON_FBED_14351/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21029	1	OZU_BE_FON_STR-CON_FBED_14363/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21029	2	OZU_BE_FON_STR-CON_FBED_14363/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21423	1	OZU_BE_FON_STR-CON_FBED_14387/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21423	2	OZU_BE_FON_STR-CON_FBED_14387/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21267	1	OZU_BE_FON_STR-CON_FBED_14399/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21267	2	OZU_BE_FON_STR-CON_FBED_14399/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21279	1	OZU_BE_FON_STR-CON_FBED_14411/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21279	2	OZU_BE_FON_STR-CON_FBED_14411/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21291	1	OZU_BE_FON_STR-CON_FBED_14435/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21291	2	OZU_BE_FON_STR-CON_FBED_14435/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21303	1	OZU_BE_FON_STR-CON_FBED_14459/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21303	2	OZU_BE_FON_STR-CON_FBED_14459/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21315	1	OZU_BE_FON_STR-CON_FBED_14471/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21315	2	OZU_BE_FON_STR-CON_FBED_14471/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21327	1	OZU_BE_FON_STR-CON_FBED_14483/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21327	2	OZU_BE_FON_STR-CON_FBED_14483/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21339	1	OZU_BE_FON_STR-CON_FBED_14495/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21339	2	OZU_BE_FON_STR-CON_FBED_14495/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
21351	1	OZU_BE_FON_STR-CON_FBED_14507/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
21351	2	OZU_BE_FON_STR-CON_FBED_14507/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
20825	1	OZU_BE_FON_STR-CON_FBED_14519/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20825	2	OZU_BE_FON_STR-CON_FBED_14519/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324
20837	1	OZU_BE_FON_STR-CON_FBED_14531/STR-100_03_LAS-BOQ	Formwork	STR-100_03_LAS-BOQ	Slab edges formwork	m2	7.2
20837	2	OZU_BE_FON_STR-CON_FBED_14531/STR-102_02_LAS-BOQ	Concrete	STR-102_02_LAS-BOQ	Concrete B200 for foot bed	m3	0.324

Figure 3.7 Sample of BOQ document obtained from BIM model

3.4. GSimX Implementation

To support analysis of site material flows by simulation, several features needed to be added to GSimX. The required information for material flow simulation comes from various sources. BIM models are providing required information such as geometries, shapes and locations of the building components. BOQ document and developed Task-Component Database are imported to GSimX to obtain necessary material quantities and resource use. CPM master schedule and resources are other inputs to GSimX. Once all the inputs are ready, GSimX can simulate alternatives of site operations and material flows.

The existing simulation approach in GSimX assumes that required materials are ready for use when needed. Within the existing approach, use of equipment for material activities such as handling, loading and unloading are not considered in simulation. GSimX does not calculate material requirements for specific tasks, storage capacities and resource use involved in on-site material logistics. The existing simulation approach only provides resource requirements. To model site processes along with the material related processes, typical GSimX modelling procedures were followed (Baltasi and Akbas 2017). Figure 3.8 summarizes proposed material flow simulation steps:

(1) BIM models are imported CPM master schedule, BOQ document and developed Task-Component Database are inputs which are imported to GSimX. As an extension to existing database, material related information, conversion of material quantities to container and pallets quantities, pallet weights and volumes are included.

(2) Location flows are defined. To form the location flows; BIM entities, activities and sequences in Task-Component Database are used. The role of BOQ on the other hand is to provide right quantities for each BIM entity for a task.

(3) Resources are assigned. For each activity in construction schedule; crews, equipment and other available resources are assigned. As such, these resources can be also defined and assigned for each activity in schedule using GSimX. However, they are imported using Microsoft Project Scheduling.

(4) In order to represent material process flows, a graph has been formed according to predetermined material flow diagrams for each material type with each node one of a storage area, site access location, or installation point. Storage areas are assigned with height, width and a 3D location within the BIM environment as located in site layout plan. Material containers will move from node to node to reach their final installation point.

(5) Simulation of material flows are conducted in GSimX. During the simulation; delivered pallet quantities are stored with respect to storage capacities, the number of pallets necessary for each work location is calculated and required equipment

are assigned accordingly to each pallet to send necessary pallet quantities from the storages to installation locations. If required quantities of materials are lacking at installation location or at the storage area, production waits until necessary materials are received. If required equipment and crews are not ready or available when needed, activities stop and wait for the required resources.

(6) Resource parameters can be updated. If needed new equipment and crews can be also included in the simulation. Storage capacities can be changed

(7) Necessary material quantities for different tasks are obtained. Quantities in containers and pallets can be updated or new materials can be added to the database.

(8) At the end of the simulation, results are obtained as charts or reports. These outputs provide information regarding to equipment and crew use. Activity performances can be seen by the charts. Cost performance of the project can be obtained. In addition to that, material requirements for tasks and storage space use can be obtained as a daily basis. According to analysis results and evaluations, master schedule is updated, and simulation processes is repeated once again to fit project cost and duration.

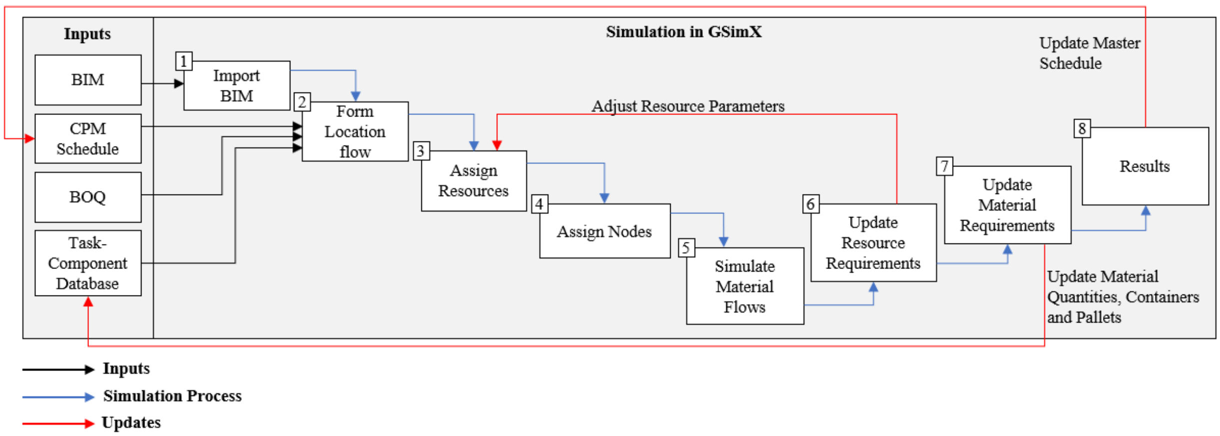

Figure 3.8 Developed GSimX approach for material flow simulation

3.5. Summary

This chapter discusses the required information for demonstrating material flow simulation in GSimX, namely BIM model, Task-Component Database, construction schedule, site and material related information. It also describes requirements to represent material flow processes, describes managing information for generating alternative material flows and logistics at site and discusses integration of information with simulation platform GSimX. The upcoming chapter describes the test case and the GSimX implementation for material flow simulation and discusses about obtained results.

CHAPTER IV

TEST CASE

The aim of this work is to demonstrate on-site material flows and logistics by using the simulation approach on BIM. To validate the developed approach, a test case has been prepared. The main objective of developing a test case scenario is demonstrating how it enables site material related decision-making processes during preconstruction through the simulation approach. By doing so, project managers will be able to design site environment by available resources and obtain best sequences for activities and material processes. Once the alternative scenarios are generated, users will be able to locate required materials for activities with right quantities within the lookahead level and assign resources accordingly. The following sections discuss the implementation for the test case.

4.1. Test Case Inputs

The experimental test case developed for this thesis will demonstrate the simulation of on-site material processes on BIM. This will help determine necessary material quantities for each particular task and assign resources accordingly. Through this, construction professionals will be able to determine capacities, sizes and locations for storage areas before the construction starts as well. Project managers will be able to manipulate the construction schedule; assign equipment and crews for specific activities and simulate whole site processes to make decisions on project cost, duration and performance. To conduct the test case simulation, several inputs are provided to the simulation framework. This includes BIM, schedule and other developments. This section discusses the requirements and developments made to demonstrate site material related processes. First, BIM models need to be imported into the GSimX workspace for conducting the simulation of construction operations and on-site material flows. To be able to create location flows as described in Chapter 3, a master schedule of the project should be also imported to GSimX for attaching construction activities to BIM entities. The specifics for the BIM models and building the construction schedule and importing them into GSimX for simulation are described below.

4.1.1. BIM

For the test case of this research, two existing BIM models have been used. The first model is a part of an existing residential project from Istanbul, consisting of two residential buildings and one commercial building identified as M1-A, M1-B and T1 within the project layout. This model is mainly used for creating site layout plan. In addition to that, this model is used to represent site material flows and durations between each process specified within the material flow diagrams, storage area locations and dimensions, equipment and crew properties, the location of heavy equipment and on-site logistic paths.

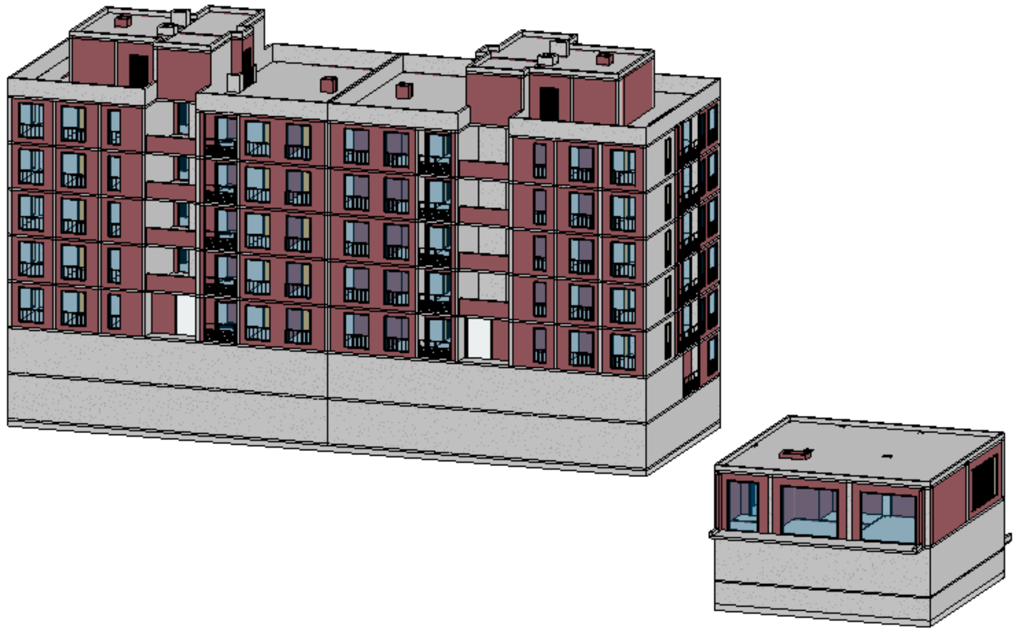

Figure 4.1 Revit Models of M1-A, M1-B and T1

The second model is a sample residential 10 floors reinforced concrete building that is medium project scale, which was created by Hasan and Akbas (2017), named as OZU_BE_01 and labeled as L1 in site layout. This model contains detailed quantities extracted from the BOQ document of this model and developed Task-Component Database. This will help determine construction material requirements and represent detailed on-site material flows including the storage space and hoisting equipment usage for material transportation to installation points with accordance to project requirements. Necessary construction materials for this model have been identified and using material suppliers' delivery information and methods; container and pallet quantities for each material have been extracted with samples shown in Table 3.1.

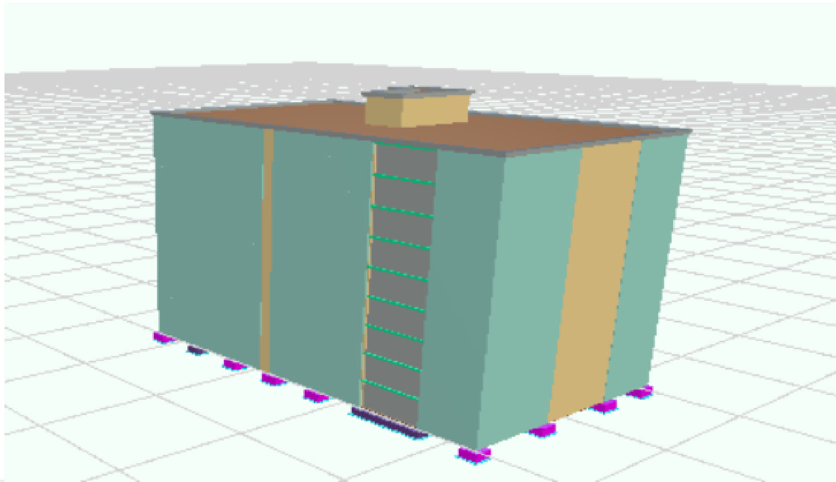

Figure 4.2 The 3D model of OZU_BE_01

The BIM models used for this test case have structural and architectural components. The structural components contain superstructure and substructure, including columns, structural walls, slabs, footings and architectural components including interior partitions, ceilings, floor and wall finishes, doors, windows, claddings, and accessories. The used BIM models have scoped to LOD350 (level of detail); all the BIM elements are graphically represented in the created model and detailed information regarding to shape, size, orientation and location have been specified during the creation of BIM models.

4.1.2. Construction Master Schedule

For the test case of this research a master schedule has been developed for the BIM model that represents structural and architectural activities and milestones. Figure 4.3 shows the developed master schedule for this test case. Microsoft Project scheduling software has been used as per steps specified below to make it compatible with simulation environment:

(1) Main activities and their sub-activities are specified. Sequences of activities formed logically. For example, concrete work activity has three consecutive sub-activities;

rebar works, form works and pouring the concrete respectively or columns works begin after the slabs are completed.

(2) Durations, necessary work forces and equipment are determined realistically. For instance, time required for concrete to get its strength included in concrete tasks.

(3) In order to automatically match activities with BIM entities and tasks in schedule in GSimX, three different attributes; namely the building name, building level and master category of the tasks have been also included within the master schedule. Building Name specifies the building the BIM entity belong to (M1-A, M1-B etc.). Building Level describes the location of the BIM entity within its corresponding building (ground floor, first floor, etc.), and Master Category shows activity work type such as shaft opening, floors, concrete walls etc. These attributes are shown within the red lines as depicted in Figure 4.3.

Task Name	Duration	Start	Finish	Resource Names	Building	BuildingLevel	MasterCategory
Project	**319 days**	**Mon 13/02/17**	**Mon 19/02/18**				
Mobilization	30 days	Mon 13/02/17	Sat 18/03/17				
M1a	**187.75 days**	**Mon 13/02/17**	**Tue 19/09/17**				
Excavation	4 days	Mon 13/02/17	Thu 16/02/17	Excavator	M1a		
Foundation	**7 days**	**Fri 17/02/17**	**Fri 24/02/17**		**M1a**	**Foundation**	
Concrete Work	**7 days**	**Fri 17/02/17**	**Fri 24/02/17**		**M1a**	**Foundation**	
Rebar Foundation	4 days	Fri 17/02/17	Tue 21/02/17	Rebar,TowerCrane	M1a	Foundation	Shaft Openings
Form Foundation	2 days	Wed 22/02/17	Thu 23/02/17	Carpenter,TowerCrane	M1a	Foundation	Shaft Openings
Pour Concrete	1 day	Fri 24/02/17	Fri 24/02/17	Concrete,ConcretePump	M1a	Foundation	Shaft Openings
-2nd Floor	**43 days**	**Mon 13/02/17**	**Mon 03/04/17**		**M1a**	**-2nd Floor**	
Structural Foundation	**6 days**	**Mon 13/02/17**	**Sat 18/02/17**		**M1a**	**-2nd Floor**	
Rebar Foundation	3 days	Mon 13/02/17	Wed 15/02/17	Rebar,TowerCrane	M1a	-2nd Floor	Structural Foundations
Form Foundation	2 days	Thu 16/02/17	Fri 17/02/17	Carpenter,TowerCrane	M1a	-2nd Floor	Structural Foundations
Pour Concrete	1 day	Sat 18/02/17	Sat 18/02/17	Concrete,ConcretePump	M1a	-2nd Floor	Structural Foundations
Concrete Work	**14 days**	**Tue 28/02/17**	**Wed 15/03/17**		**M1a**	**-2nd Floor**	
Floor	**6 days**	**Tue 28/02/17**	**Mon 06/03/17**		**M1a**	**-2nd Floor**	
Rebar	3 days	Tue 28/02/17	Thu 02/03/17	Rebar,TowerCrane	M1a	-2nd Floor	Floors
Form	2 days	Fri 03/03/17	Sat 04/03/17	Carpenter,TowerCrane	M1a	-2nd Floor	Floors
Pour Concrete	1 day	Mon 06/03/17	Mon 06/03/17	Concrete,ConcretePump	M1a	-2nd Floor	Floors
Wall	**5 days**	**Fri 10/03/17**	**Wed 15/03/17**		**M1a**	**-2nd Floor**	
Form	2 days	Fri 10/03/17	Sat 11/03/17	Carpenter,TowerCrane	M1a	-2nd Floor	Concrete Walls
Rebar	2 days	Mon 13/03/17	Tue 14/03/17	Rebar,TowerCrane	M1a	-2nd Floor	Concrete Walls
Pour Concrete	1 day	Wed 15/03/17	Wed 15/03/17	Concrete,ConcretePump	M1a	-2nd Floor	Concrete Walls
Architectural Work	**16 days**	**Thu 16/03/17**	**Mon 03/04/17**		**M1a**	**-2nd Floor**	
Brick Wall	3 days	Thu 16/03/17	Sat 18/03/17	Labour	M1a	-2nd Floor	Walls
Insulation Works	2 days	Mon 20/03/17	Tue 21/03/17	Labour	M1a	-2nd Floor	Walls

Figure 4.3 Sample of master schedule and attributes assigned for activities

4.2. Test Case Developments for Material Flow Simulation

This section discusses the developments and definitions made to demonstrate on-site material flows and logistics within the simulation framework.

4.2.1. Site Layout Plan

The test case for this research consists of four residential buildings and surrounding storage areas; two of which (Storage 1 and 4) are located off-site and others located on-site as shown in Figure 4.4. Storage 4 and 5 are for Type 2 materials, and since Type 2 materials are mostly fragile and sensitive to weather changes; such materials must be kept as covered due to given properties. On the other hand, storage areas 1,2 and 3 are uncovered and will be used for Type 1 materials. A tower crane is located in the middle of the buildings to transport materials to installation locations. The dashed circle shows crane's operation area which is 60 meters. Building are close enough to share this tower crane located in the middle. The on-site logistics and travel paths are also specified within the project layout and used to transfer necessary materials from off-site storage areas to on-site storage areas if necessary.

The layout of the project is created within the BIM environment using 3D models of the buildings and storage area locations are represented accordingly. Necessary material quantities in pallets flows through storage locations to installation points by predefined routes. Following section discusses about these routes; material flow diagrams for classified material types.

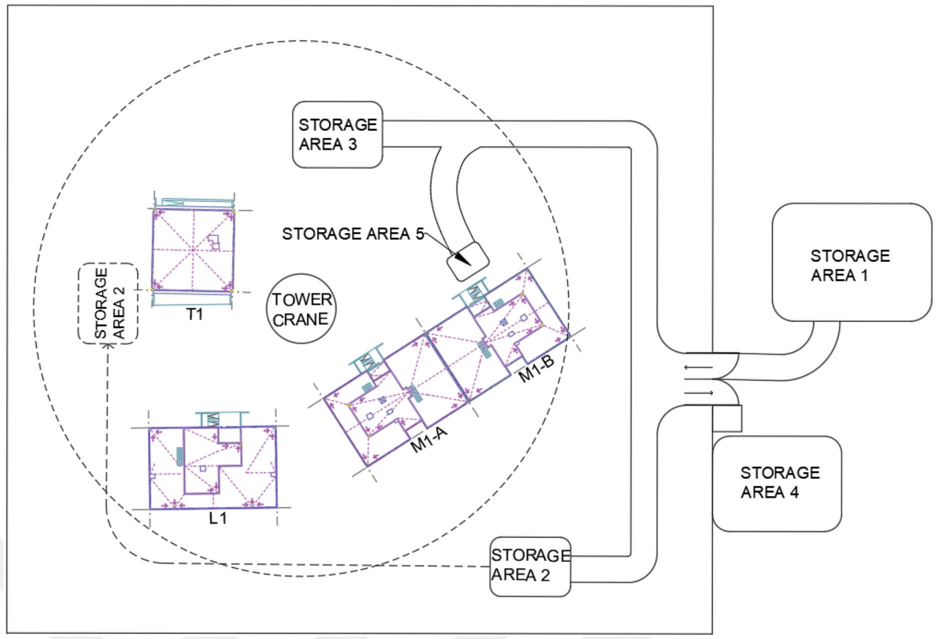

Figure 4.4 Site layout for the test case

4.2.2. Material Flow Diagrams

For the test case, two material flow diagrams for Type 1 and Type 2 materials are created (Figure 4.5). When Type 1 materials are delivered and classified, materials can be directly stored in off-site Storage 1 or materials can be transferred to on-site storage areas Storage 2 or Storage 3 respectively using on-site logistic paths after loading and unloading. If on-site storage areas are full, materials are kept in off-site storage area to be transferred later into on-site storage areas. Once the materials are needed for specific activities, necessary materials are transported using powered equipment to platforms vertically before the installation. As Type 2 materials are delivered and classified, these materials are transferred to off-site or on-site storage areas namely Storage 4 or Storage 5. Later on, these materials are transferred using either powered machinery such as tower crane, mobile crane or unpowered machinery which means manpower. Once the installation completed, both types of materials are transferred to waste management.

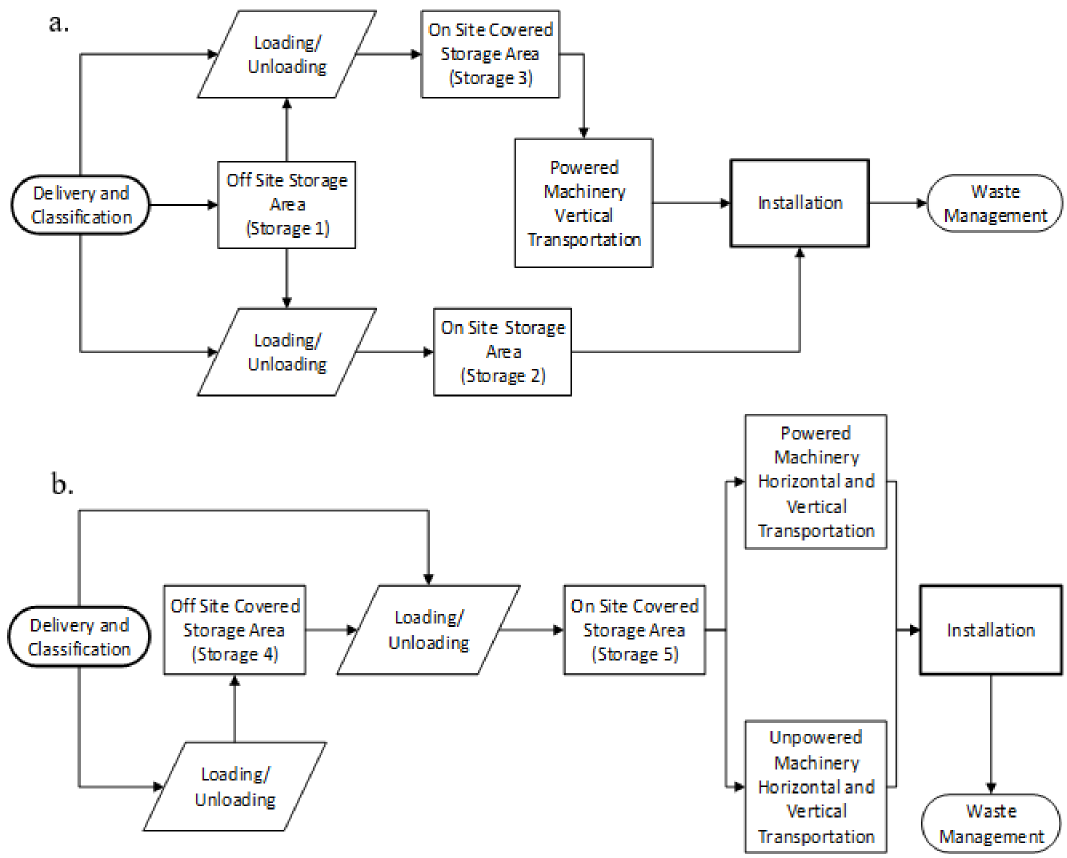

Figure 4.5 Material process flow for a. Type 1 materials and b. Type 2 Materials

In order to follow steps defined for materials to be transferred from one location to another accurately and logically, storage capacities and possible equipment properties are defined. Within these created material flow diagram for this test case, material processes are supposed to occur by the availability of storage areas and resources. Therefore, it is vital to include storage space capacities and use of equipment in the simulation. The material containers and pallets will be located at the storages and transported to required places and will follow routes as described above. Following section discusses about determination of storage space capacities and properties of possible set of hoisting equipment.

4.2.3. Storage Capacities and Equipment Properties

The capacities for the storage areas are determined using width, length and load height, which is allowable height when storage is loaded with materials on pallets. The properties of the storage areas used for this test case are given in Table 4.1. Each storage area is designed to contain either Type 1 or Type 2 material. A coefficient named floor area ratios (FAR) is used to represent area needed for hoisting equipment to load and unload required materials. Storage volumes obtained by the dimensions are reduced with this ratio to obtain storage area capacities. Each pallet will be stored according to available storage spaces. When materials are required at installation locations, required quantity of pallets will be transferred from the storage areas to installation location.

A list of equipment to transport required materials to installation location is provided. If required, new equipment with predefined properties can be added. The properties of the equipment are given in the Table 4.2 below. As seen in the Table 4.2, the list of equipment for material flow simulation includes backhoe, mobile crane, loader crane and tower crane. Each equipment can transport required materials horizontally and/or vertically. Each equipment has a loading capacity in terms of pallet amounts. Transportation speed, loading and unloading durations are also provided to calculate duration of transportation from delivery to installation. The number of specific equipment can be alternated according to project needs. For horizontal and vertical transportation, necessary equipment can be chosen from the list and added to simulation as per project needs. During simulation, GSimX calculates required material quantities for installation locations, assigns available equipment to transfer required material quantities from storage areas to required places, if materials are available in storages. If not, production waits until, required material quantities are stored in storage areas as pallets.

Table 4.1 Storage area properties and capacities

Storage Area	Material Type	Width (m)	Length (m)	Load Height (m)	Storage Area (m^3)	FAR	Storage Capacity (m^3)
1	Type 1	20	15	1	300	0.85	255.00
2	Type 1	5	5	1	25	0.95	23.75
3	Type 1	6	7.5	4	180	0.80	144
4	Type 2	20	15	1	300	0.70	210.00
5	Type 2	6	7.5	1	45	0.65	29.25

Table 4.2 Properties of available hoisting equipment

Equipment	Transportation	Load Capacity	Loading & Unloading Duration	Transportation Speed
Backhoe	Horizontal	1 Pallet	60 Sec.	5m/sec
Mobile Crane	Vertical	1 Pallet	30 Sec.	10m/sec
Loader Crane	Vertical, Horizontal	1 Pallet	30 Sec.	10m/sec
Tower Crane	Vertical	1 Pallet	30 Sec.	15m/sec
Lift	Horizontal	1 Pallet	15 Sec.	5m/sec

After building models and CPM master schedule are imported into the simulation environment according to the site layout, possible routes for transporting materials are specified, and capacities for storage areas and equipment are defined. To demonstrate material flow simulation, developed Task-Component Database should be also imported along with BOQ document. This will allow calculation of material container and pallet quantities during the simulation and GSimX will assign equipment accordingly within the range of specified properties. The following section discusses about developed Task-Component Database for this test case.

4.2.4. Task-Component Database for Material Flow Simulation

The Task-Component Database represents the construction activities and task sequences for each BIM entity. This database has been developed according to project scope and requirement. As described in the methodology chapter, it includes production rates for crews, equations and formulations for calculating material container and pallet quantities and others.

The existing version of this database based on an Excel sheet, provides information for each task types as mentioned. In addition to the existing version of the Task-Component document; required materials types for each task type, necessary equipment, transportation methods and labor requirements are determined as well. However, to manage information within this Excel based Task-Component sheet, this file has been changed into database to accurately contain information and made it suitable for simulation processes within GSimX using Microsoft Access. As seen in Figure 3.4, relations between different attributes and entities are defined. For instance, many component codes can be match with many construction materials and many construction materials can be required by many component codes. Therefore, the relationship between component codes and materials is many-to-many relations. These relationship between different attributes are defined accordingly. Using this database, updates regarding to different attributes can be managed or necessary information can be easy changed or adjusted. After the simulation is completed, material quantities in containers, pallets can be changed for each individual task in the database. If required, new materials can be added and quantities for that material can be defined accordingly. The same approach is applicable for equipment. Each task in Task-Component Database is assigned with specific equipment for vertical and horizontal transportation. Users can easily change resource parameters and obtain performance results for activities with simulation.

Table 4.3 Example of equipment table from developed database.

Equipment ID	Equipment Name	Transportation Type	Loading Capacity
E1	Backhoe	Horizontal	1 Pallet
E2	Lift	Horizontal	1 Pallet
E3	Loader Crane	Horizontal, Vertical	1 Pallet
E4	Mobile Crane	Vertical	1 Pallet
E5	Tower Crane	Vertical	1 Pallet

Table 4.4 Example of conversion factors for each material

Material ID	Material Name	Install Unit	Install Quantity Per Container	Container Per Pallet
M1	Angle Bracket	m	150	100
M2	Ano Profile	m	150	100
M3	Bolt and Joints	each	1000	10
M4	Cement Screed Powder	m2	80	20
M5	Ceramic Tile Adhesive Powder	m2	80	20
M6	Ceramic Tiles	m2	1.5	48
M7	Ceramic Wall Tiles	m2	1.5	48
M8	Cladding Adhesive	m2	80	20
M9	Cladding Structural Profiles	m	10	15
M10	Cladding Tile Adhesive Powder	m2	80	20
M11	Glass	each	1	8
M12	Glass fiber Mesh	m2	50	34
M13	Gypsum Board	m2	3	50
M14	Gypsum Screed Powder	m2	80	20
M15	Handrail	m	2	100

4.3. GSimX Simulation

To conduct simulation on the test case, first all required files have been imported into GSimX. As discussed, these are BIM models, master schedule, developed Task-Component

Database, extracted BOQ file. resource data (equipment, storage areas, pallets, containers, etc.). Task-Component Database has been used to extract BOQ document and this BOQ document provides quantities for each BIM entity. Task-Component Database and BOQ document are imported to GSimX. Next, location flows are built within the GSimX platform. By assigned activities in the master schedule with BIM entities, GSimX generates the location flows. In order to link activities and BIM entities automatically in GSimX, additional attributes that specifies building's location, level and master category of the task are used. Specific locations flows include structural and architectural parts such as columns, concrete walls, floors, walls, doors, windows and so on. Later on, necessary equipment and crews are defined. Equipment and crews can be either defined in GSimX or in master schedule using MS Project. For the simulation, equipment and crew properties are defined using MS Project. During simulation, GSimX calculates tasks, assigns required resources with tasks and defines sequences of tasks for different locations.

Once preparation of the simulation model is complete, simulation for on-site material flows and logistics within GSimX has been tested. Through simulations, GSimX generates various outputs, results for alternative material flows according to defined resources, storage capacities, material containers and created site layout. To see the impact of material flow on site performance and to test the research approach, simulation of the sample construction project has been conducted with and without site material flows and logistics. This provides an evaluation of construction site operation considering flow of materials within the site conditions realistically compared to typical simulation of construction processes excluding site material flows and logistics.

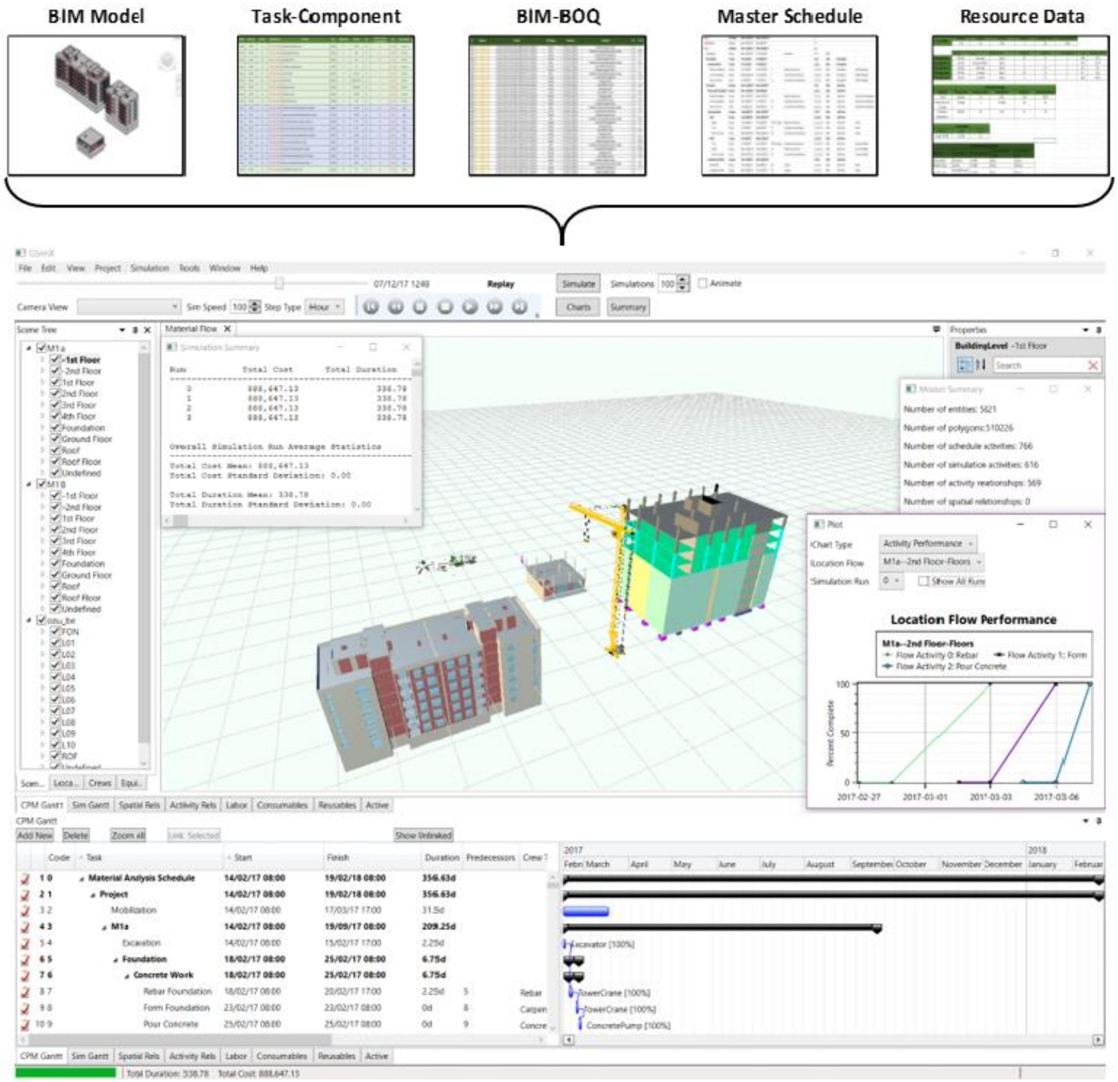

Figure 4.6 GSimX inputs and simulation sample

4.3.1. Experiment Results and Discussion

Early analysis on construction operations and on-site material processes have been done in GSimX. Results revealed that GSimX can simulate site operations and on-site material related processes including resource and storage space usage with less effort and with significantly more analysis capacity compared to other approaches. Within GSimX, more alternatives of site material flows and logistics can be generated by simply changing resource parameters.

Analyses are made with and without material flows. This allows comparison between the developed approach with site material flows and the existing simulation approach in GSimX. Table 4.5 summarizes total cost and duration of construction operations without material flows based on equipment and crew use. Crew types used for this simulation are carpenters, concrete, electrical, labor, painter, plaster and rebar. Primary equipment used for this simulation are tower crane, excavator and concrete pump. Figure 4.7 shows cost results obtained for equipment and crews. With the graphs provided, it is easy to detect daily expenses of any cost item. This can provide early arrangements on companies' expenses and cash flow parameters. GSimX also provides performance of each activity performed in project. For example, Figure 4.8 shows concrete wall activity at 1st floor of building M1A completed as percentages by time.

Table 4.5 Time and cost summary of simulation without material flows

Crews	Equipment	Total Cost ($)	Total Time (d)
Carpenters Concrete Electrical Labor Painter Plaster Rebar	Tower Crane Excavator Concrete Pump	888.647	338.78

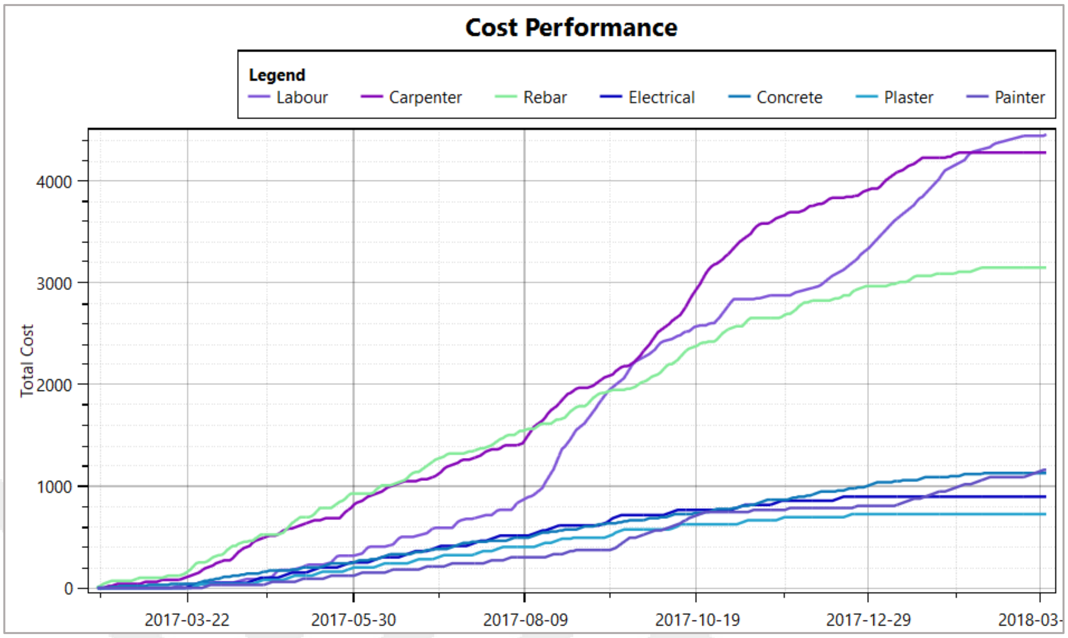

Figure 4.7 Cost performance of crews and equipment

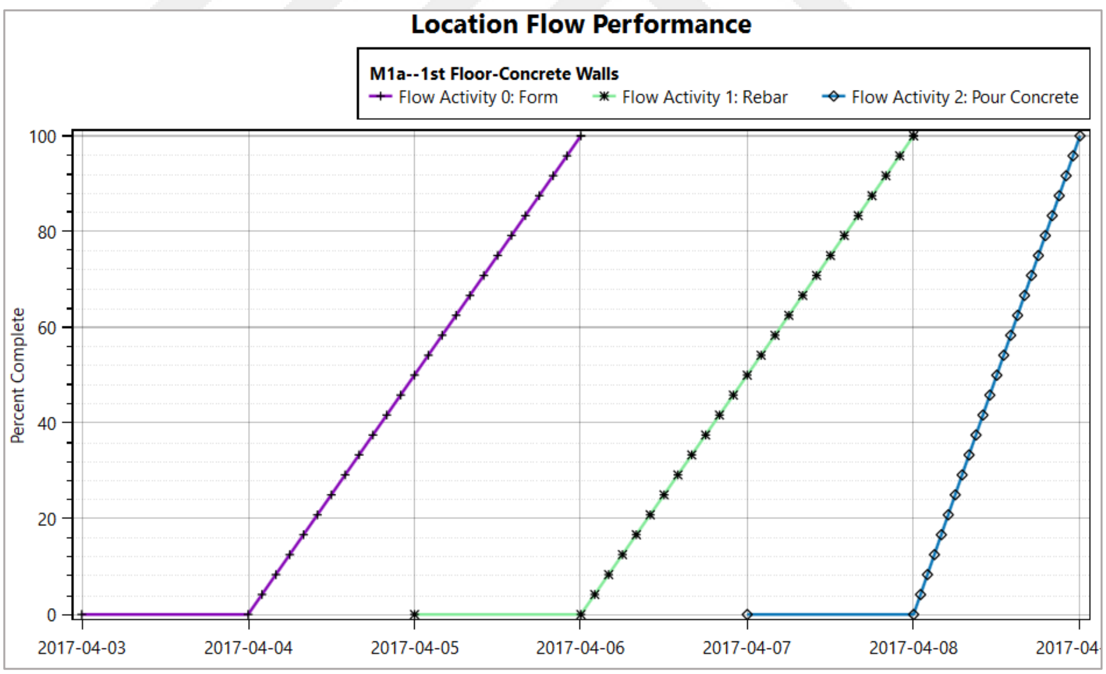

Figure 4.8 Performance of Concrete Wall activity

Once the simulation without material flows is completed, GSimX generates delivery schedule for materials based on installation of locations. Using this delivery schedule, materials are delivered to site and assigned storage areas with specific dimensions. During simulation with material flows, GSimX calculates quantities of received materials in terms of pallets and calculates volumes in storage areas over time. During simulation, required material quantities for particular tasks are calculated and necessary material quantities are transferred from storage areas to installation location with assigned equipment on a daily basis. At the end of this simulation, GSimX provides a graph that shows storage area volume over the time as shown in Figure 4.9.

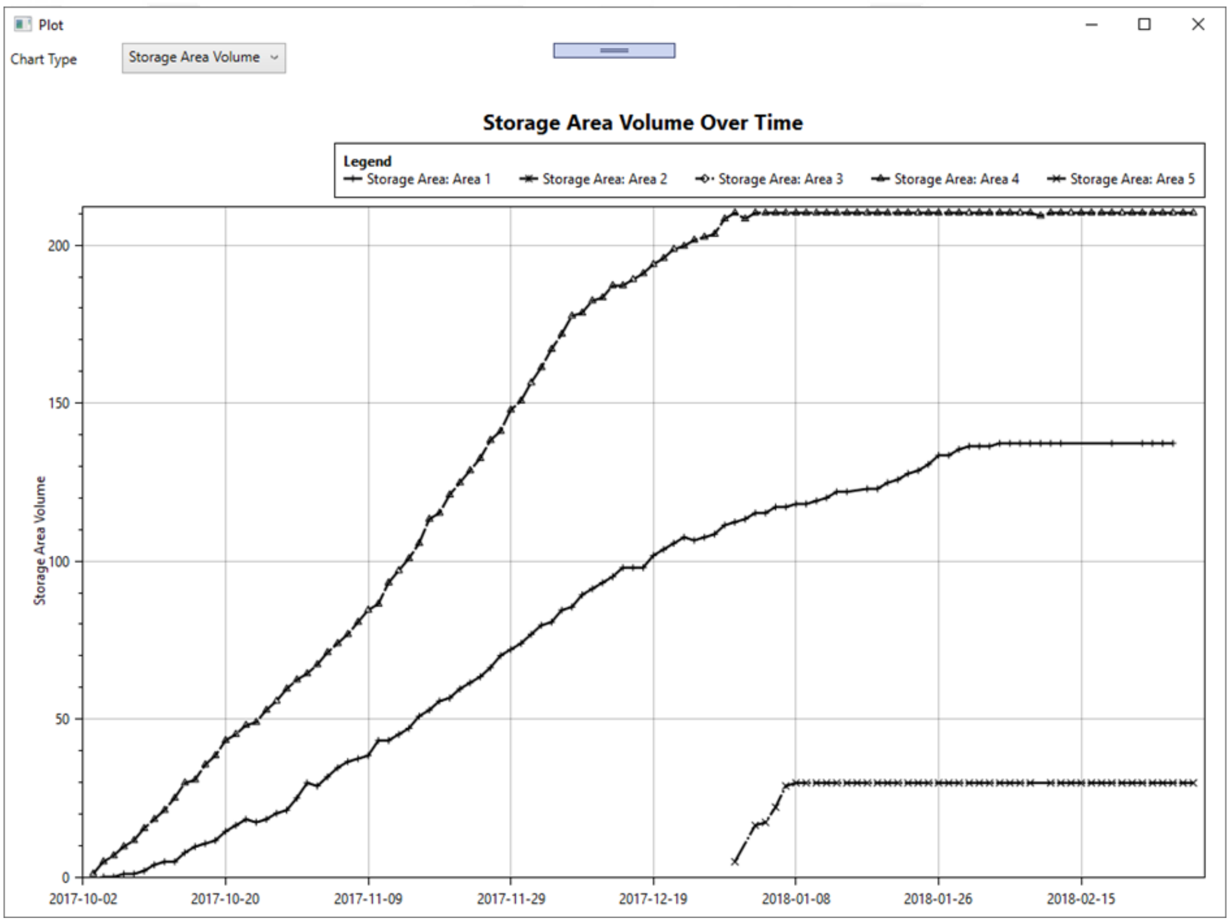

Figure 4.9 Storage area volume over time for the test case

The provided graph for the storage area volumes can be used to make decisions on actual storage capacities before the construction starts. This can provide early arrangements on sizes for storage areas. In addition to that, required equipment to transfer material containers form storages to installation locations can be assigned accordingly. By doing so, crew and equipment sizes can be calculated, and realistic project schedule can be formed. In addition, since equipment are assigned to material related processes during simulation, performance of the equipment used for handling can be extracted and proper equipment can be selected before construction starts. This can improve actions performed for on-site material supply processes and result in decreased time and cost during the flow of the materials.

CHAPTER V

CONCLUSION

The main goals of this thesis study were as follows; (1) defining requirements for demonstrating site materials flow simulation, (2) developing a database to manage information coming from varying sources and (3) developing a integration process for BIM and resource-integrated simulation tool to perform site material flows and logistics analysis. In the line of these objectives, information needed for required materials during the construction activities are extracted, necessary equipment and its properties to handle necessary materials are determined, a conversion method for converting material quantities into container quantities and pallet quantities is presented and site related aspects such as properties of storage areas, on-site material flow routes and site properties are presented. In addition to that, the developed database is described, additional information to represent site material flows are inputted and finally integrated along with several document into simulation framework called GSimX.

This thesis reviewed the literature on analysis of site material flows and logistics. It is found that the current approaches for analyzing on-site material flows and logistics are limited and maintaining these approaches are challenging. There is limited integration of BIM and simulation techniques for materials management. In order to use automation, information obtained from BIM and construction operations need to be prepared and evaluated externally by simulation tools, which is very time consuming, hard to maintain and prone to errors. For instance, if there is a change in the project, the whole analysis is being repeated from very beginning and this requires lots of manual works and efforts. Since simulation tools are mostly being used separately from BIM approach, there is an ineffective management of information which causes poor planning of construction site logistics, work conflicts, improper resource allocations and poor management of site materials.

In this thesis work, BIM and simulation technologies are used for construction planning and operations in order to analyze and evaluate alternatives of on-site material flows and logistics more effectively. This includes resource use, material quantities and site related aspects such as storage capacities and hoisting equipment. With these results, users will be able to design improved material flows for site processes, determine necessary material quantities over time for activities, and assign resources accordingly for site materials.

The BIM part of this presented work includes obtaining necessary quantities for material to be used in construction activities. To be able to use data obtained from BIM properly, a detailed database system has been formed for using information regarding to construction operations and processes within simulation analysis. By the simulation, resource use and necessary material quantities for construction activities are calculated with respect to general construction schedule.

Previously conducted researches discuss use of BIM for analysis of construction planning, rarely for material planning, and simulation using existing general-purpose platforms for site operations including materials. However, the practical use of BIM with simulation for on-site material flows are not very common. By the presented thesis work, BIM and resource integrated simulation platform called GSimX which uses discrete-event simulation approach and agent-based modelling has been used to alternate different site material flows and logistics scenarios for evaluation and discussion.

5.1. Contributions

The suggested developments in this thesis on BIM and resource-based simulation framework will support planners to generate on-site material flows given the construction methods, site layout, storage capacities, equipment capacities, crew use and material availability for satisfying master schedule within an integrated BIM and simulation environment.

The requirements for demonstrating on-site material flows and logistics are identified to support construction schedule and material processes. On-site material flow diagrams and possible routes that the materials are following from site delivery to final destination are determined, storage area capacities and properties of possible hoisting equipment are defined, conversion of material quantities into container and pallet quantities is provided and extra material related information such as types of materials, containers capacities and pallet capacities for structural and architectural components are specified. All these defined parameters will allow for realistic representation of material flows and logistics occurring in construction site.

The presented work in this thesis uses a newly developed database to transfer material related information from BIM to simulation platform. The information coming from BIM entities is managed by this developed database. Since all the relationships between different attributes and entities in Task-Component Database are structured logically, changes regarding to formulations for extracting material quantities, equipment, required materials and tasks will be executed with less errors and more practically. In other words, by the developed database; simulation of site material flows will be conducted by effective information flow. The information coming from different sources are integrated within the same platform for creating simulation model properly.

Finally, by the integrated BIM and simulation approach, availability of resources and materials will be ensured during the early phases of the construction processes and required material quantities for the construction activities will be extracted. This will provide detailed analysis of on-site material flows before the construction starts. In addition, planners will be able to see necessary material quantities and resource usage for different tasks during the construction phase by any instance of time. This will also prevent unnecessary time spend during actual construction operations for supplying required materials and ensure to continue the construction operations with planned budgets. Storage of material containers and pallets, handling of the materials, transportation of required materials quantities and installation of the materials are demonstrated and analyzed by simulation on BIM. Therefore, the developed approach improves performance of the production by resource use and planning processes.

As a result, ability to analyze materials integrated with project schedule and BIM provides new opportunities for designing material flows at site. Having the ability to evaluate process alternatives will enable project managers to compare the effect of changing material flow parameters on different scenarios and develop new strategies for possible issues throughout construction. This approach will allow important material related site decisions, such as number and size of storage areas, and specifications for material handling equipment. In addition, it is a step towards designing the whole process regarding needs of material flows. During construction, it can automatically generate detailed needs for materials regarding short-term schedules while considering different material flow alternatives.

5.2. Limitations

In this presented work, materials necessary for construction activities are assumed to be delivered to construction site when needed for use or to be stored for upcoming tasks. Within the created material flow diagrams, the processes start from delivery of the goods and ends at waste management. The on-site processes for materials that are go through several steps are represented in the analysis. However, off-site processes for materials such as manufacturing, assembling, procurement, transportation and delivery of the materials are not represented or analyzed in accordance with general schedule. Therefore, whole life cycle of the construction materials is not represented within the simulation environment detailly. This can lead to schedule conflicts and production delays since there are also off-site material related processes and these processes can affect delivery of the goods and inventory control of the materials respectively.

The presented work mostly focused on structural and architectural components. To fully represent building model; mechanical, electrical and plumping components should be included as well. Quantities for these elements should be extracted and included within the material flows. For the test case, these components haven't been included to make the analysis simpler. The mechanical and electrical part can be also represented in within the analysis approach for detailed analysis.

The presented approach has been developed for analysis on commercial and residential buildings. Other projects such as highways, dams, bridges, and other industrial projects necessities modifications in developed databases, flow diagrams and materials to obtain required material quantities and necessary resources by simulation.

The conducted analysis in the test case is based on deterministic approaches. Stochastic analysis is required for more detailed models. By stochastic modelling approach; change in costs and project duration can be represented realistically by probability distribution functions. Since the simulation inputs are based on predefined parameters, outputs in analysis will result in same numbers thus no probabilistic results will be provided.

In the provided approach, the alternatives for on-site material flows and logistics can be generated. Managers and planning participants needed to generate these alternatives for evaluation and focus on feasible on-site material flows that matches with construction conditions.

5.3. Future Work

The developed approach in this thesis can provide more information about material delivery, inventory control and material procurement. Since on-site material flows are the main objective of this thesis work, off-site material flows should be analyzed in detail representing whole supply chain of materials used in construction. Improvements on on-site material flows could be necessary for more detailed analysis. For instance, materials such as rebars are being delivered to site as bars and normally these bars are being formed as desired shapes specifically for footings, columns, beams and other structural parts. These activities and processes can be also demonstrated and analyzed by resource use and material quantities respectively. The created flow diagrams for materials can be improved for more complex construction processes.

5.3.1. Off-Site Material Supply Processes

GSimX simulation platform can support identification of resources; equipment and crews before and during the construction processes. The presented approach can provide necessary material quantities; containers and pallets to be transferred to activity locations considering handling equipment and storage capacities. The on-site construction processes can be simulated from delivery of the materials to installation including material flows and logistics. However, off-site material processes from production to transportation were not included within the simulation. Whole supply chain of the materials should be analyzed from manufacturing stages to construction phases so that right quantities of the materials can be delivered in a right time when needed for construction operations within look- ahead level.

For the analysis of off-site material processes, simulation can be linked to existing material procurement databases. The model of material flows can be improved and whole supply chain processes can be reflected to construction schedule. the process of delivering construction materials can be produced with accordance to orders placed from the job site and necessary changes or updates can be made on schedule in relevant activities. Using discrete-event simulation (DES) and agent-based modeling techniques, off-site material supply processes can be modelled and analyzed accordingly. This will allow project planners to consider delivery schedules more effectively. It can provide on-time delivery of the materials to the construction sites. In addition, planners could be able to consider supply chain processes during the decision-making steps and plan site activities accordingly.

5.3.2. Inventory Control

For the analysis of the on-site material flows, storage space capacities are represented to observe stored pallet quantities in the simulation. Each storage area is assigned with a capacity obtained by the given storage area dimensions. Using these dimensions for each storage area; total volume is found, and volume is then multiplied with coefficient called floor area ratio (FAR) to represent actual storage capacities for the pallets to be transferred to installation location with equipment. However, typical inventory management methods or analysis such as material requirement planning (MRP) or Just-in-time (JIT) method are not included in the simulation which could have impact on cost of the project or cash flow. As a future work, inventory management techniques or analysis methods can be integrated with used simulation platform to realistically represent storage use during the construction. This could allow project participants to manage material inventories more effectively compared to presented approach. Project participant could be able to conduct analysis on inventory management techniques before the construction starts and conduct site operations accordingly.

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APPENDIX A

Task Component Database Sample

The following tables show tables from the relational tables for the Task Component Database used in the presented test case.

Table A.1. Component table

Component Code	Master Category	Description	Element Type	Formula	Production Rate	SQ.
ARC-000_00_DUM	Dummy	Dummy elements for presentation purposes	group	1	NA	0
ARC-100_01_LAS-BOQ	Floor Finish	Screed type SCR201	FF	ST	35	1
ARC-100_02_LAS-BOQ	Floor Finish	Screed type SCR202	FF	ST	35	1
ARC-100_03_LAS-BOQ	Floor Finish	Water prof type WPS201	FF	ST	20	2
ARC-100_04_LAS-BOQ	Floor Finish	Water prof type WPS202	FF	ST	20	2
ARC-100_05_LAS-BOQ	Floor Finish	Ceramic type FL401	FF	ST	15	2
ARC-100_06_LAS-BOQ.A	Floor Finish	Ceramic type FL402	FF	ST	15	3
ARC-100_07_LAS-BOQ	Floor Finish	Ceramic type FL412	FF	ST	15	3
ARC-100_08_LAS-BOQ	Floor Finish	Stone tile type FL660	FF	ST	15	1
ARC-101_01_LAS-BOQ	Ceiling Finish	Gypsum board 12mm thick type CLG601	FF	ST	75	3
ARC-101_02_LAS	Ceiling Finish	Fail ceiling structural system	FF	ST*5/2	50	1
ARC-101_03_LAS	Ceiling Finish	Fail ceiling thermal insulation 50mm thick	FF	(SL+SR)/2	80	2
ARC-101_04_LAS-BOQ.A	Ceiling Finish	Metal board 15mm thick type CLG507	FF	ST	60	2
ARC-101_05_LAS-BOQ	Ceiling Finish	Gypsum board 12mm thick type CLG605	FF	ST	75	3

ARC-101_06_LAS-BOQ	Ceiling Finish	Gypsum board 12mm thick type CLG601_V	LF	(SL+SR)/2	60	3
ARC-101_07_LAS-BOQ	Ceiling Finish	Gypsum board 12mm thick type CLG605_V	LF	(SL+SR)/2	60	3
ARC-102_01_LAS-BOQ	Partition	Blok-work partition, 200mm thick, 2H fire resistance	LF	(SL+SR)/2	24	1
ARC-102_02_LAS-BOQ	Partition	Blok-work partition, 100mm thick, 2H fire resistance	LF	(SL+SR)/2	21	1
ARC-102_03-BOQ	Partition	Gypsum partition IWS-705, 144mm thick, 1H fire resistance, with insulation, LF	LF	(SL+SR)/2	NA	0
ARC-102_04_LAS	Partition	Partition structural system	LF	(SL+SR)*4/2	70	1
ARC-102_05_LAS	Partition	Vertical partition thermal insulation 50mm thick	LF	(SL+SR)/2	90	3
ARC-102_06_LAS	Partition	Gypsum partition, 1st side sheet fixation 12mm thick, LF	LF	(SL+SR)/2	80	2
ARC-102_07_LAS	Partition	Gypsum partition, 2nd side sheet fixation 12mm thick, LF	LF	(SL+SR)/2	80	4
ARC-103_01_LAS-BOQ	Plaster	Cement Plaster 14mm thick, soft finish	LF	(SL+SR)/2	50	1
ARC-103_02_LAS-BOQ	Plaster	Cement Plaster 6mm thick, hard finish	LF	(SL+SR)/2	105	1
ARC-103_03_LAS-BOQ	Painting	Paint type PT104 on fair face	LF	(SL+SR)/2	80	2
ARC-103_04_LAS	Wall Lining	Wall lining structural system	LF	(SL+SR)*4/2	70	1
ARC-103_05_LAS-BOQ	Wall Lining	Ceramic wall lining type LIN302, 8mm, fixed by glue on hard surface plaster	LF	(SL+SR)/2	30	2
ARC-103_06_LAS-BOQ	Wall Tiling	Marble cladding type LIN808, 20mm thick	LF	(SL+SR)/2	50	2
ARC-103_07_LAS-BOQ	Painting	Paint type PT305 direct to polished gypsum board	LF	(SL+SR)/2	40	3
ARC-103_08_LAS	Painting	Polishing work gypsum surface	FF	(SL+SR)*5/2	30	2
ARC-103_09_LAS	Painting	Polishing work cement surface	FF	(SL+SR)/2	20	2
ARC-103_10_LAS-BOQ	Wall Tiling	Wooden sheet cladding type LIN809, 20mm thick	LF	(SL+SR)/2	50	2
ARC-103_11_LAS-BOQ	Painting	Paint type PT104 on cement plaster	LF	(SL+SR)/2	60	3
ARC-103_12_LAS	Painting	Filling surface	LF	(SL+SR)/2	60	1
ARC-104_01_LAS-BOQ	Doors	Metal door type 105, 2H fire resistances	Cell	1	7	1
ARC-104_02_LAS-BOQ	Doors	wooden door type 101, 2H fire resistances	Cell	1	7	1
ARC-104_03_LAS-BOQ	Doors	Metal door type 106, 2H fire resistances	Cell	1	7	1
ARC-105_01_LAS-BOQ	Accessories	Metal handrail 50mm radius	Solid	Vol/(.025*.025*3.14)	25	1

ARC-106_01_LAS-BOQ	Cladding	Glass panel 1000x3500mm, 2H fire rating, 150mm thick	LF	1	15	1
ARC-106_02_LAS-BOQ	Cladding	external thermal insulation, 2H fire rating, 50mm thick	LF	(SL+SR)/2	40	3
ARC-106_03_LAS-BOQ	Cladding	Stone cladding type 08, 20mm thick	LF	(SL+SR)/2	60	4
ARC-106_04_LAS-BOQ	Cladding	Stone roof stop, length as per location	LF	LC	15	4
ARC-106_05_LAS	Cladding	Cladding structural system	LF	(SL+SR)*4/2	50	2
ARC-106_06_LAS-BOQ	Cladding	External water proofing, painting type, 2mm thick	LF	(SL+SR)/2	60	1
STR-100_01_LAS-BOQ	Formwork	Foundation foot edges formwork	FF	SA-ST-SB	50	2
STR-100_02_LAS-BOQ	Formwork	Underground beam formwork	LF	SL+SR	50	2
STR-100_03_LAS-BOQ	Formwork	Slab edges formwork	FF	PER	80	2
STR-100_04_LAS-BOQ	Formwork	Slab 250mm / Landing formwork	FF	SB	15	1
STR-100_05_LAS-BOQ	Formwork	Column formwork	FF	SA-ST-SB	17	2
STR-100_06_LAS-BOQ	Formwork	Stair formwork	FF	(SA-SB-ST)*0.43	15	1
STR-100_07_LAS-BOQ	Formwork	Shear wall formwork	LF	SL+SR+SS+SE	17	2
STR-100_08_LAS-BOQ	Formwork	Drop beam formwork	LF	SL+SR+SB	15	1
STR-100_09_LAS-BOQ	Formwork	Upstand beam formwork	LF	SL+SR	30	2
STR-101_01_LAS-BOQ	Rebar	Foundation foot steel (estimated, depends on design)	FF	VOL*250	550	1
STR-101_02_LAS-BOQ	Rebar	Underground beam steel (estimated, depends on design)	LF	VOL*200	450	1
STR-101_03_LAS-BOQ	Rebar	Slab on grad steel (estimated, depends on design)	FF	ST*20	650	1
STR-101_04_LAS-BOQ	Rebar	Structural slab steel (estimated, depends on design)	FF	ST*40	450	3
STR-101_05_LAS-BOQ	Rebar	Structural column steel (estimated, depends on design)	FF	VOL*100	450	1
STR-101_06_LAS-BOQ	Rebar	Stair steel (estimated, depends on design)	FF	VOL*50	450	2
STR-101_07_LAS-BOQ	Rebar	Drop beam steel (estimated, depends on design)	LF	VOL*100	450	2
STR-101_08_LAS-BOQ	Rebar	Upstand beam steel (estimated, depends on design)	LF	VOL*50	450	1

STR-101_09_LAS-BOQ	Rebar	Shear wall steel (estimated, depends on design)	LF	VOL*70	450	1
STR-102_01_LAS-BOQ	Concrete	Concrete B300 for foundation foot	FF	VOL	120	3
STR-102_02_LAS-BOQ	Concrete	Concrete B200 for foot bed	FF	VOL	120	2
STR-102_03_LAS-BOQ	Concrete	Concrete B300 for underground beam	LF	VOL	120	3
STR-102_04_LAS-BOQ	Concrete	Concrete B250 for slab on grade	FF	VOL	120	3
STR-102_05_LAS-BOQ	Concrete	Concrete B300 for column	FF	VOL	90	3
STR-102_06_LAS-BOQ	Concrete	Concrete B300 for structural slab	FF	VOL	120	4
STR-102_07_LAS-BOQ	Concrete	Concrete B300 for shear wall	LF	VOL	90	3
STR-102_08_LAS-BOQ	Concrete	Concrete B300 for stair	FF	VOL	105	3
STR-102_09_LAS-BOQ	Concrete	Concrete B300 for upstand beam	LF	VOL	120	3

Table A2. Material table

Material ID	MaterialName	Discipline	Material Type	Install Unit	Container Type	Quantity in Container	Quantity in Pallet
M1	Angle Bracket	Plaster	Type 1	m	package	150	15000
M2	Ano Profile	Plaster	Type 1	m	bundle	150	15000
M3	Bolt and Joints	Ceiling Finish	Type 2	each	box	1000	10000
M4	Cement Screed Powder	Plaster	Type 2	m2	package	80	1600
M5	Ceramic Tile Adhesive Powder	Floor Finish	Type 2	m2	package	80	1600
M6	Ceramic Tiles	Floor Finish	Type 1	m2	package	1.5	72
M7	Ceramic Wall Tiles	Wall Lining	Type 1	m2	package	1.5	72
M8	Cladding Adhesive	Wall Finish	Type 2	m2	bucket	80	1600
M9	Cladding Structural Profiles	Wall Finish	Type 1	m	item	10	150
M10	Cladding Tile Adhesive Powder	Cladding	Type 2	m2	package	80	1600
M11	Glass	Facades	Type 2	each	item	1	8
M12	Glass fiber Mesh	Wall Lining	Type 2	m2	roll	50	1700
M13	Gypsum Board	Partition	Type 2	m2	item	3	150
M14	Gypsum Screed Powder	Plaster	Type 2	m2	package	80	1600
M15	Handrail	Accessories	Type 2	m	item	2	200
M16	hX Wooden Beams	Formwork	Type 1	m	item	2.5	125
M17	Insulation Mix	Ceiling Finish	Type 2	m2	bucket	30	1350
M18	Lining Adhesive Powder	Wall Tilling	Type 2	m2	package	80	1600
M19	Marble Wall Tiles	Wall Tilling	Type 1	m2	package	1.5	72
M20	Membrane	Floor Finish	Type 1	m2	roll	10	160
M21	Metal Boards	Ceiling Finish	Type 1	m2	item	3	90
M22	Metal Door	Doors	Type 2	each	item	1	5

M23	Paints	Wall Finish	Type 2	m2	bucket	80	4800
M24	Plywood	Formwork	Type 1	m2	item	3	100
M38	Polish	Wall Finish	Type 2	m2	bucket	100	4800
M25	Rebar	Rebar	Type 1	kg	bundle	1000	0
M26	Rockwool	Partition	Type 2	m2	item	3.24	103.68
M27	Screed Powder	Wall Finish	Type 2	m2	bucket	80	1600
M28	Stone Cladding	Facades	Type 1	m2	package	1.5	45
M29	Stone Roof Stop	Facades	Type 1	m	package	2.5	120
M30	Stone Tile Adhesive Powder	Floor Finish	Type 2	m2	package	80	1600
M31	Stone Tiles	Floor Finish	Type 1	m2	package	1.5	45
M32	Straight Edge Profile	Wall Lining	Type 1	m	bundle	135	13500
M33	Structural Metal Profiles	Partition	Type 1	m	bundle	36	2520
M34	Wooden Cladding	Wall Finish	Type 2	m2	package	2	100
M35	Wooden Door	Doors	Type 2	each	item	1	8
M36	XPS Styrofoam	Cladding	Type 2	m2	item	0.72	21.6
M37	Concrete Block	Partition	Type 1	m2	item	3.25	351

Table A.3. Equipment table

Equipment ID	Equipment Name	Transportation Type	Capacity
E0	None	None	None
E1	Backhoe	Horizontal	1 Pallet
E2	Concrete Mixer	Horizontal	10 m^3
E3	Concrete Pump	Vertical	60 m^3/h
E4	Lift	Horizontal	1 Pallet
E5	Loader Crane	Horizontal, Vertical	1 Pallet
E6	Mobile Crane	Vertical	1 Pallet
E7	Plaster Mixer	Horizontal	1 m^3
E8	Screed Mixer	Horizontal	1 m^3
E9	Tower Crane	Vertical	1 Pallet

Table A.4. Discipline table

Main Code	Discipline
ARC-000	Dummy
ARC-100	Floor Finish
ARC-101	Ceiling Finish
ARC-102	Partition
ARC-103	Wall Finish
ARC-104	Doors
ARC-105	Accessories
ARC-106	Facades
STR-100	Formwork
STR-101	Rebar
STR-102	Concrete

VITA

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Publications:

1. Demirci, C., et al. (2019). Process Modelling of Site Material Flows and Logistics for BIM and Resource-Integrated Construction Simulation. International Civil Engineering and Architecture Conference (ICEARC 2019). Trabzon / Turkey.

2. Demirci, C. and M. Khalaf (2019). Evaluation for Energy Efficiency of Façade and Shading Systems for a School Building. Built Environment Facing Climate Change (CLIMA 2019). Bucharest / Romania.