Optimized Planning and Scheduling for Modular and Offsite Construction

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Abstract

Optimized Planning and Scheduling for Modular and Offsite Construction

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Offsite construction has gained momentum in recent years due to its improved performance in projects' schedule, quality, safety, and environmental impact without increasing cost. Several research studies have introduced planning and scheduling techniques for modular and offsite construction using Building Information Modeling (BIM) and simulation tools. In this research, a questionnaire survey was carried out in collaboration with the modular building institute (MBI), Niagara Relocatable Buildings Inc. (NRB Inc.), and the School of Building Science and Engineering at the University of Alberta. The questionnaire focused on two issues: (1) modular and offsite construction industry characteristics, and (2) barriers to increased market share in this industry. For the latter issue, effort was made to address five factors that emanated from the workshop on "challenges and opportunities for modular construction in Canada," held in October 2015, Montreal to analyze barriers to modular construction growth in Canada. Key findings of this questionnaire include requests for the use of a separate modular construction design code, innovative financing and insurance solutions, standards that consider procurement regulations, and lending institutions that partner with financial houses to create special lending programs for modular construction. Findings of this questionnaire were published on the official MBI website.

This research presents an alternative BIM-based integrated framework for modeling, planning, and scheduling of modular and offsite construction projects. BIM Vertex BD software was used in the proposed framework for automating data exchange between projects' BIM model and the proposed scheduling method. The proposed method integrated linear scheduling method (LSM), critical chain project management (CCPM), and the last planner system (LPS) into a comprehensive BIM-based framework for scheduling, monitoring, tracking, and controlling of projects while considering uncertainty associated with activity durations. A procedure for integrating offsite and onsite construction was introduced based on the proposed scheduling methodology. Then, a new multi-objective optimization model was developed using genetic algorithm (GA) to optimize the integration between the LSM and CCPM. This optimization model minimizes time, cost, and work interruptions simultaneously while considering uncertainty in productivity rates, quantities, and availability of resources. The developed model was based on the integration of six modules: 1) uncertainty and defuzzification module, 2) schedule calculations module, 3) cost calculations module, 4) optimization module, 5) module for identifying multiple critical sequences and schedule buffers, and 6) reporting module. Schedule buffers were assigned whether or not the optimized schedule allows for interruptions. This method considers delay and work interruption penalties and bonus payments. The developed integrated scheduling model for offsite and onsite construction was automated in newly developed software named "Mod-Scheduler" using the ASP.NET system coded in C# programming language. A number of case studies were presented and analyzed to demonstrate the developed methodologies' features and capabilities.

This research also introduces a novel modular suitability index (MSI), which utilizes five indices; 1) connections index (CI), 2) transportation dimensions index (TDI), 3) transportation shipping distance index (TSDI), 4) crane cost penalty index (CCPI), and 5) concrete volume index (CVI). Calculating the MSI provided a unified indicator to assist in selecting near optimum module configurations for efficient planning of modular residential construction.

This research identifies the main factors affecting the configuration of modules in hybrid construction projects to introduce a new configuration model that is expected to assist hybrid construction stakeholders in identifying the most suitable configuration for each type of modules (i.e. panels) in their projects. A hybrid construction case study was selected to demonstrate the applicability of proposed model and to highlight its capabilities in selecting the most suitable configuration of panelized projects.

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To my beloved mother, my kind father, my dear wife, and to my brother and sisters

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List of Acronyms

AG	Aggressive
AI	Agreement Index
AISI	American Iron and Steel Institute
ANP	Analytic Network Process
API	Application Programming Interface
BEA	Bond Energy Algorithm
BI	Buffer Index
BIM	Building Information Modeling
CAD	Computer-Aided Design
CAP	Controlling Activity Path
CCP	Crane Cost Penalty
CCPI	Crane Cost Penalty Index
CCPM	Critical Chain Project Management
CEV	Customer Earned Value
CHBA	Canadian Home Builders' Association
CI	Connections Index
CISC	Canadian Institute of Steel Construction
CL	Confidence Level
CMHI	Canadian Manufactured Housing Institute
CMAR	Construction Management at Risk
CMHI	Canadian Manufactured Housing Institute
CNC	Computerized Numerical Control

CPLSM	Critical Path Linear Scheduling Method
CPM	Critical Path Method
C&PM	Cut and Paste Method
CPR	Constrained Productivity Rate
CSS	Cascading Style Sheets
CT	Cycle Time
CVC	Concrete Volume Cost
CVI	Concrete Volume Index
DB	Design Build
DBB	Design Bid Build
DC	Direct Cost
DOD	Department Of Defense
DOT	Department of Transportation
DP	Dynamic Programming
EC	Equipment Cost
EPC	Engineering, Procurement and Construction
EVM	Earned Value Management
FHWA	Federal Highway Administration
FMI	Fails Management Institute
FRSM	Fuzzy Repetitive Scheduling Method
GA	Genetic Algorithm
GDP	Gross Domestic Product
GPSS	General Purpose Simulation System
GRP	Glass Reinforced Polymers

GUI Graphic User Interface

HTML Hyper Text Markup Language

HTTP Hyper Text Transfer Protocol

IC Indirect Cost

ICC International Code Council

IPD Integrated Project Delivery

JIT Just In Time

JS Javascript

JSON JavaScript Object Notation

LBMS Location-Based Management Scheduling

LCPM Linear Construction Project Manager

LGS Light Gauge Steel

LINQ Language INtegrated Query

LSM Linear Scheduling Method

LOB Line Of Balance

LPS Last Planner System

MBI Modular Building Institute

MBM Managing By Means

MBR Managing By Results

MC Material Cost

MCCB Modular Construction Codes Board

ME Measure of Effectiveness

MEP Mechanical, electrical, and plumbing

MFD Modular Function Deployment

MHAPP	Modular Housing Association Prairie Provinces
MOC	Modular and Off-site Construction
MOF	Multi-Objective Function
MPE	Mechanical and Production Engineering
MSI	Modular Suitability Index
MSI	Material Status Index
NAHB	National Association of Home Builders
NGO	Non - Government Organizations
NIBS	National Institute of Building Sciences
NRB	Niagara Relocatable Buildings Inc.
OAB	Onsite activities buffer
OPB	Overall project buffer
ORM	Object/Relation Mapping
PC	Penalty Cost
PD	Project Duration
PDM	Precedence Diagram Method
PERT	Program Evaluation and Review Technique
PMC	Permanent Modular Construction
PPC	Percent Plan Completed
PPCcr	Critical Percent Plan Complete
PPI	Percent Plan Impacted
PPMOF	Prefabrication, Preassembly, Modularization, and Offsite Fabrication
PR	Productivity Rates
PRCO	Percent Required Completed or On-going

QFD	Quality Function Deployment
RCB	Resource Conflict Buffer
RFID	Radio-Frequency Identification
ROI	Return On Investment
RSM	Repetitive Scheduling Method
SMRs	Small Modular Reactors
SSMA	Steel Stud Manufacturers' Association
TC	Total Cost
TDI	Transportation Dimensions Index
TOC	Theory Of Constraints
TPS	Toyota Production System
TSDI	Transportation Shipping Distance Index
TT	Takt Time
VPM	Vertical Production Method
WIC	Work Interruption Cost
WWP	Weekly work plan

Chapter 1: Introduction

1.1 Overview

Modular and offsite construction have received considerable attention in recent years. This is due to its impact on cost and time reduction and improved productivity and quality of constructed facilities. Modular construction improves safety on construction jobsites and reduces material waste. Many challenges affect modular construction standardization such as: 1) unifying module configuration, 2) developing more suited planning methodologies for scheduling, monitoring, and control of offsite and onsite activities, 3) choosing appropriate project delivery systems for modular construction, and 4) publicizing advantages and disadvantages of modularization and prefabrication among offsite construction stakeholders.

The literature reveals that most of the published work in this field focuses on crane selection and location and scheduling using simulation and issues pertinent to logistics without due consideration for optimized module configuration or finding alternative comprehensive planning and scheduling methods. This leads offsite construction stakeholders to develop modules based on project needs without much industry standardization and to use simulation as a trending scheduling approach for the offsite construction industry.

1.2 Problem Statement

Many studies that have investigated the practices of modular and offsite construction have overlooked important aspects such as type of project delivery systems, type of contracts, type of procurement methods, synchronization of onsite and offsite schedules, BIM applications and related software, scheduling software, and barriers to increased market share. In addition, these studies have also overviewed limiting constraints for modular construction configuration without providing a method that can accomplish optimum module configuration selection. There is also a lack of methods in the literature that can assist stakeholders of hybrid construction in identifying the most suitable configuration for each type of module. Several research studies have introduced planning and scheduling techniques for modular and offsite construction using simulation and BIM tools. These simulation models are tailored according to the nature and needs of the project or production system being considered. This process requires dedicated simulation professionals as well as historical records of productivity data which might not be available. Therefore, offsite construction suffers from a lack of generic planning and scheduling methods that consider specific features of modular construction such as its repetitive nature as well as uncertainty and variability of productivity rates. Few methods in the literature study the integration of offsite and onsite schedules and needed algorithms for identification of the overall project critical path. Consequently, this research utilizes the linear scheduling method (LSM) as a main component for the proposed scheduling method due its capabilities in modeling and visualizing repetitive activities. However, LSM lacks the tools to account for uncertainty while scheduling repetitive construction projects. Hence, there is a need to develop a comprehensive resource-driven scheduling, monitoring, and control methodology for modular and offsite construction that accounts for uncertainty of productivity rates. There is also a pressing need to study current practices of modular and offsite construction and to develop methods that accomplish near optimum selection of module configuration for planning of modular construction.

1.3 Research Objectives

This research focuses on optimized planning and scheduling of modular and offsite construction. A new method of scheduling, tracking, and control of modular and offsite construction is developed in order to account for the features of this industry. The outcome of the proposed research includes a near optimum selection method of module configuration for efficient modular residential construction. This research proposes a newly developed unified modular suitability index (MSI) which utilizes five indices: 1) connections index (CI) 2) transportation dimensions index (TDI) 3) transportation shipping distance index (TSDI), 4) crane cost penalty index (CCPI) and 5) concrete volume index (CVI). It also proposes a new configuration model to assist hybrid construction stakeholders in identifying the most suitable configuration for each type of module based on four sequential steps of checking architectural, structural, manufacturing, and transportation constraints. Finally, this research introduces a new optimization algorithm for repetitive scheduling. These objectives were achieved first by studying current practices as well as scheduling techniques for repetitive projects and modular construction and by targeting the following sub-objectives:

1. Study characteristics of modular and offsite construction and detect barriers to increased market share of this industry;
2. Study and analyze constraining factors for configuration of modular and hybrid construction, develop a new near optimum selection method for module configuration in residential construction, and a new configuration model to assist hybrid construction stakeholders in identifying the most suitable configuration for each type of modules (i.e. panels);
3. Study and analyze current planning and scheduling methods for modular and hybrid construction and develop new scheduling, tracking, and control methods by integrating LSM, CCPM, and LPS methods into one model that utilizes a BIM software package;
4. Utilize the developed integrated scheduling framework for integrating offsite and onsite construction schedules; and
5. Optimize repetitive scheduling.

1.4 Methodology Overview

The general framework for this research is shown in Figure 1.1. First, the problem statement for this research was formulated to form the research motivation. This was followed by an extensive literature review with a focus on charecteristics of modular and offsite construction, scheduling, optimization, integration of scheduling techniques, modular and hybrid construction configuration, and schedule integration of offsite and onsite construction. Gaps in existing literature were then identified to establish research objectives. This research started by investigating characteristics of modular and offsite construction as well as barriers to increased market share of this industry using a questionnaire survey. The primary components of this research included five main models for the studying of modular and hybrid construction configuration, integrated scheduling of offsite and onsite construction, optimization of repetitive scheduling, and dynamic tracking and control using the developed schedule. The developed scheduling model was implemented in a software prototype named “Mod-Scheduler”, and then evaluated by analyzing different case studies. Finally, conclusions were drawn, limitations were identified, and opportunities for future work were stated.

1.5 Thesis Organization

This thesis is presented in seven chapters. Chapter 2 presents a review of the literature, focusing on the charecteristics of modular and offsite construction, configuration of modular and hybrid construction, uncertainty in repetitive and non-repetitive scheduling, schedule buffers and criticality, the integration between scheduling techniques, the integration between offsite and onsite construction scheduling, and optimization of repetitive scheduling. The chapter concludes with a highlight of the gaps identified in literature. Chapter 3 presents the results of the questionnaire for current practices in modular and offsite construction and investigation for barriers to increase its market share. An overview of the proposed methodologies is presented in Chapter 4. These methodologies include a near optimum selection of module configuration for efficient modular construction. It also includes a new configuration model for hybrid construction and introduces the proposed BIM-based methodology for integrating the LSM, CCPM, and LPS methods and integrating offsite and onsite modular construction. Finally, another model is introduced in Chapter 4 for optimizing repetitive scheduling. Chapter 5 introduces the design, implementation, and features of the developed software prototype named "Mod-Scheduler". Chapter 6 includes five case studies for the proposed methodologies to illustrate efficiency and discuss the performance of the developed models. Chapter 7 concludes with a summary of the developments made in this research, highlighting research contributions and limitations, as well as proposed opportunities for future work.

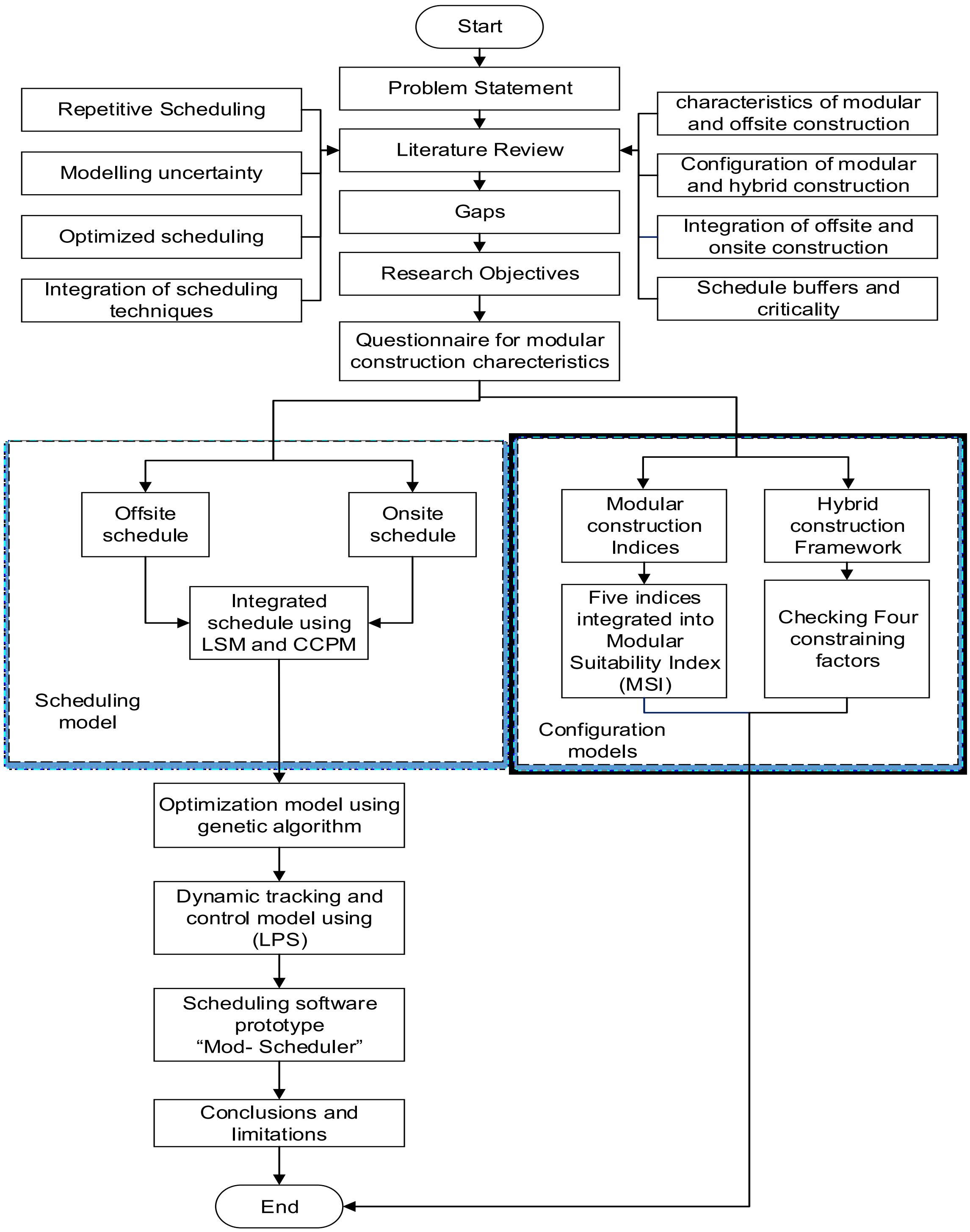


Figure 1.1: General research framework

Chapter 2: Literature Review

2.1 Introduction

The advantages of modular construction have been identified several decades ago (Tatum et al., 1987) and more recently, (O'Connor et al., 2014) investigated through a set of critical success factors and enablers for optimum industrial modularization. Studying modularization critical success factors highlights the current changes needed in the engineering, procurement and construction (EPC) processes to support optimal use of modularization.

Offsite construction and prefabrication simultaneously facilitate work on offsite and onsite deliverables to reduce project schedule considerably. Reduction in schedule leads to significant cost savings due to a reduced need for expensive and labor intensive onsite operations. McGraw-Hill's Smart Market Report (McGraw-Hill, 2011) found that 67% of firms reduced project schedules using prefabrication and modularization and 35% of firms experienced schedule reduction of four weeks or more, as shown in Figure 2.1 and 2.2. Offsite construction provides valuable assistance for tight scheduling where project deadlines are strict as the higher education buildings sector (McGraw-Hill, 2011).

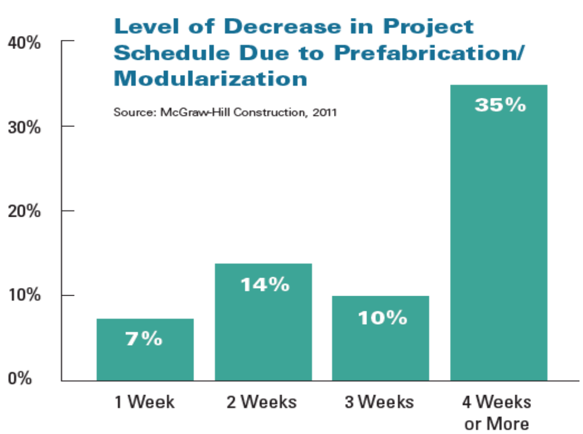


Figure 2.1: Level of decrease in project schedule due to modularization (McGraw-Hill, 2011)

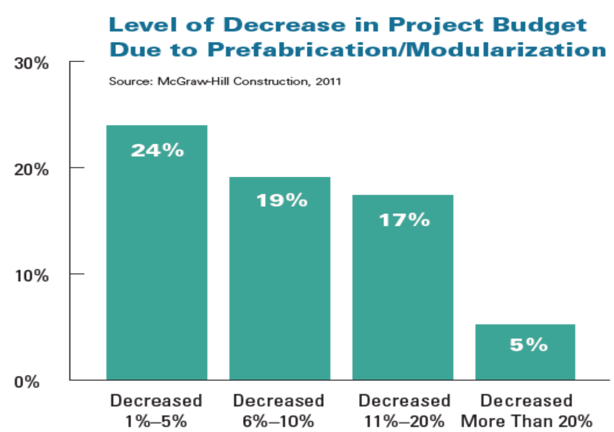


Figure 2.2: Level of decrease in project budget due to modularization (McGraw-Hill, 2011)

Two features of modular and offsite construction control the determination of its appropriate scheduling techniques. The first is the repetitive nature of manufacturing for offsite construction, and the second is the uncertainty and variability of productivity rates for these operations. Thus, a traditional scheduling technique such as CPM is not the optimum scheduling method for this industry because it does not satisfy the resource continuity constraint required for repetitive projects (Harris and Ioannou, 1998).

LSM is an advancement of the traditional line of balance (LOB) method (Kenley and Seppänen, 2010) commonly used for the scheduling of repetitive projects. LSM uses similar mathematics to LOB, though it represents the activity as a single line rather than two lines as in LOB. However, unlike LOB, LSM allows for representing non-repetitive and non-typical activities in complex construction projects.

The LSM diagram outlines time along the horizontal axis and number of repetitive units along the vertical axis. Hence, it is an effective alternative to schedule offsite and modular construction. However, few methods in the literature incorporate uncertainty with LSM. The other method for scheduling modular and offsite construction is the use of simulation engines due to their capabilities to consider cycles of repetitive activities and uncertainty. However, simulation models require dedicated simulation professionals (Hajjar and AbouRizk, 2002) and are tailored based on special needs and requirements of the project being considered. Several research studies have introduced planning and scheduling techniques for modular, panelized, and hybrid construction using BIM and simulation tools (Abu Hammad, 2003; Shafai et al., 2012; Taghaddos et al., 2012; Moghadam et al., 2013; Ajweh et al., 2014; Liu et al., 2015).

BIM is utilized to automate quantity take-off data and to visualize offsite and modular construction activities. BIM assists in automating quantity-take off for components of modular construction including properties of modules, openings, and framing. Such automation improves scheduling accuracy and it is integrated with other techniques to produce 4D and 5D schedules.

2.2 Definitions

The term "modular" means "designed with standardized units or dimensions, for easy assembly and repair or flexible arrangement and use" (MBI Annual Report, 2015). The modular process is utilized in many fields such as heavy industrial plants, residential buildings, ships and submarines, and even nuclear power plants known as small modular reactors (SMRs). The literature shows diversified definitions and terminologies to describe offsite construction as follows:

Modularization: "The preconstruction of a complete system away from the job site that is then transported to the site. Modules are large in size and possibly may need to be broken down into several smaller pieces for transport" (Haas et al., 2000);

Module: "A major section of a plant resulting from a series of remote assembly operations and includes portions of many systems; usually the largest transportable unit or component of a facility" (Tatum et al., 1987);

Prefabrication: "Manufacturing processes, generally taking place at specialized facility, in which various materials are joined to form a component part of a final installation" (Tatum et al., 1987);

Preassembly: "A process by which various material, prefabricated components and/or equipment are joined together at a remote location for subsequent installation as a unit. It is generally focused on a system" (Tatum et al., 1987);

Offsite fabrication: “The practice of preassembly or fabrication of components both off the site and onsite at a location other than at the final installation location” (CII, 2002); and

PPMOF (prefabrication, preassembly, modularization, and offsite fabrication): Several manufacturing and installation techniques, which move many fabrication and installation activities from the plant site into a safer and more efficient environment (CII, 2004).

Another categorization approach follows size and complexity of manufactured components (Schoenborn, 2012). This categorization approach depends on the amount of finishing work done in an offsite manufacturing facility and labor work required for onsite assembly. Five categories/systems are described in this approach, as shown in Figure 2.3. These categories/systems are used to differentiate between different types of offsite construction starting with the category that requires the least offsite finishing work as follows:

1- Modular construction: Includes three dimensional volumetric components that form a complete partition of the building;
2- Hybrid construction: Blends between modular and panelized construction categories where bathrooms and kitchens are manufactured as separate modules, and panels are utilized for the rest of the building ;
3- Panelized construction: Includes production of a series of two dimensional planar components/ panels that form a shell of a building which requires more finishing work onsite than modular construction;
4- Prefabricated components: Includes manufacturing of separate components because they cannot be assembled onsite; and
5- Processed material: Manufactures most building components (micro level manufacturing) offsite and components are shipped to the site.

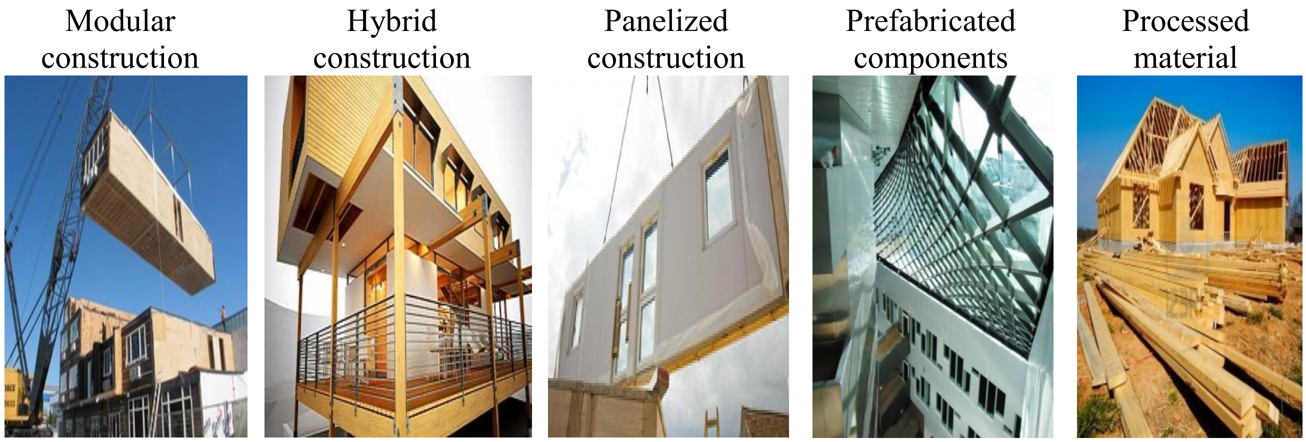


Figure 2.3: Categories of offsite construction

Modular construction has the highest proportion of offsite manufacturing between all offsite construction systems. The proportion of offsite manufacturing for modular construction ranges between 60 to 70% as compared to 30 to 50% for hybrid construction and 15 to 25% for panelized construction. This proportion accounts for 50 to 60% of construction time reduction for modular construction as compared to 30 to 40% for hybrid construction and 20 to 30% for panelized construction (Lawson et al., 2014).

2.3 Characteristics of modular and offsite construction

Many studies have investigated modular and offsite construction characteristics. Buildoffsite campaigning organisation have promoted offsite construction in the United Kingdom (UK) by publishing offsite construction industry surveys results to measure the contribution of offsite industry to UK's gross domestic product (GDP) and to understand the depth of its supply base (Buildoffsite, 2006). McGraw-Hill Construction partnered with MBI and NIBS, among other collaborators, to publish prefabrication and modularization survey results (McGraw-Hill, 2011). This report investigated the impact of prefabrication and modularization on productivity metrics such as project cost, schedule, quality, safety, BIM utlilization, creation of green buildings, and waste elimination. Fails Management Institute (FMI) Corp. (2013) also introduced survey results for prefabrication and modularization, which investigated labour savings, market growth, return on investment (ROI), strategic marketing approach, benefits of prefabrication, annual sales, and factors driving prefabrication demand. Meanwhile, a report presented by NIBS (2014) focused on annual revenues, project types, stakeholder collaboration, benefits of offsite construction, and barriers of implementing offsite construction. Smith and Rice (2015a, 2015b) collaborated with MBI and NIBS to study offsite processes of modular construction by analysing case studies. These studies identified performance metric parameters for schedule, cost, risk, quality, safety, and scope, as well as compared modular to traditional construction to investigate added value, benefits, and barriers of implementing modular construction. Canadian Manufactured Housing Institute (CMHI) (2016) conducted a survey for producers of factory-built homes to study the value of manufactured buildings in Canada, volume of international trade for manufactured buildings, annual construction investment by sector, jobs generated by the manufactured building industry, economic activity and impact, wages and business profits, and federal and provincial taxes for manufactured buildings. MBI introduces modular industry analysis regularly through its annual reports for permanent modular construction (PMC) and modular advantage publications (MBI-PMC, 2015; Modular advantage, 2017). MBI collects data internally through its members while renewing annual memberships. MBI data represents about 75% of industry assets and revenue of relocatable buildings industry in North America (Modular Advantage, 2017). MBI reports focus on studying market share, growth forecasts, size of market, and production benchmarks. The goal of MBI is to focus efforts and resources to increase market share of the modular building industry from its current estimate of 2.5 to 5% by 2020 using a 5-in-5 industry growth initiative introduced in 2015. Smith and Quale (2017) conducted a comparative analysis of the McGraw-Hill Construction, NIBS, and FMI Corp. reports and provided a quantitative and qualitative analysis of Smith and Rice's (2015a, 2015b) work. However, these studies did not investigate some of current practices for modular construction such as type of project delivery system, type of contracts, type of procurement method, synchronization of onsite and offsite schedules, BIM applications and software, scheduling software, and barriers to increased market share.

2.4 Configuration of offsite construction

Current literature in the offsite construction domain focuses on cranes selection and more suited scheduling methods without due consideration for optimum module configuration.

Each offsite construction category has its own unique configurations based on its own constraints such as transportation, manufacturing, and craning limitations. Choosing between the use of any offsite construction system depends on project needs regarding cost, schedule, and the proportion of offsite manufacturing it can utilize.

Current offsite construction systems are in competition to gain more ground on the market. This competition is clear when offsite construction managers compare between systems when choosing which one to use in their offsite construction projects. They usually balance between project schedule, cost, quality, and project's unique constraints such as transportation, manufacturing, and craning limitations. This analysis requires the use of advanced tools to identify unique constraints for each offsite construction project and to compare between the possibilities of applying any system.

2.4.1 Configuration of modular construction

Modularization is a concept of mass customization for products that have been successfully adapted by various industries (Erixon, 1998). Product configuration focuses on structuring and standardizing products models to fulfill customer needs (Hvam et al., 2008). In the construction industry, customer needs are identified based on building geometrical shapes, arranged in a manner that maximizes the quality function deployment (QFD) in design phase (Gargione, 1999; Ozaki, 2002). QFD analysis requires the input of customer requirements. This is often evaluated in market surveys where different market segments are investigated using statistical methods and questionnaires (Eldin and Hikle, 2003). However, standardized products impact design of buildings considerably, especially when the design needs to be adapted to satisfy customer requirements. Thus, such adaptation causes waste and quality problems in production systems (Malmgren et al., 2010). The demand for customization compels the manufacturing industry to develop new methods of mass production adaptation to satisfy individual needs of customers (Erixon, 1998; Hvam et al., 2008). A method called modular function deployment (MFD) was developed by Erixon (1998) to investigate different strategies in product modularization. MFD relies on product QFD to find customer needs for any specific market using market surveys and systematic analysis.

Cameron and Carlo (2007) investigated the limitations of modular construction for a multi-family housing projects that affect modularity as design parameters. It was noted that real modular design limitations were transportation limitations and the structural nature of the modular box. Site assemblage, craning, and vendor selection and location were also mentioned as important factors that impact modular construction design. Thus, the main concern of this study was to study the benefits and limitations of modular construction without focusing on configuration of modular construction. Jensen et al. (2009) developed another method to standardize production and configuration processes by conducting functional requirement analysis to identify design parameters for modular construction. This method constrains modularization of projects using four views: 1) customer view that controls modular design according to customer requirements, 2) engineering view that constrains modular design according to deflection, strength, wind loads, fire, acoustics, and national regulations, 3) production view that identifies product dimensions and transportation constraints according to factory regulations and capacity; and 4) site view for assembly constraints according to site plans.

Smith (2010) introduced a comprehensive contribution to modular design and construction by investigating the role of offsite construction, theory, history, and technical information of fabrication stakeholders. Smith (2010) presented the most common modular dimensions after obtaining contributions of modular builders and after analyzing transportation restrictions. Steel module common width was outlined to be 13-ft, and 16-ft for oversized module, length of common module is 52-ft for common module, and 60-ft for oversized module, with the common maximum module height outlined to be 12-ft.

Velamati (2012) extended the work of Cameron and Carlo (2007) by investigating design and financial aspects of modular construction by studying practical project case studies. However, the design and financial issues were not integrated into one framework. Another method was introduced by Jensen et al. (2012) which integrated the rules and constraints of a modular building or product platform in a family of architectural computer-aided design (CAD) applications such as Revit structures.

Azari et al. (2013) reviewed modular construction constraints and opportunities including market conditions, transportation, logistics, costs, manufacturing, architectural design, codes, and standards for both factory-built and site-built housing. Lawson et al. (2014) brought together information on timber, steel, and concrete modules and discussed their key design aspects. This information was drawn from the Concrete Centre, Steel Construction Institute and UK Buildoffsite organizations, and refers to the Eurocodes and modern design standards.

However, these studies have no systematic procedure for optimizing modular building designs and do not provide a systematic process for quantifying the degree of modularity between different modular construction projects. This quantification enables the modular construction system to compete with the hybrid construction system since more manufacturers are beginning to use hybrid construction to eliminate some of the dimensional limitations that modular manufacturers currently face (Cameron and Carlo, 2007).

2.4.2 Configuration of hybrid construction

Offsite construction that utilizes light gauge steel (LGS) includes three main systems: volumetric or modular, panelized, and hybrid (Lawson et al., 2005). The "hybrid" system combines modular and panelized systems to optimize the use of three-dimensional (3D) and two-dimensional (2D) components in respect to space provisions and manufacturing costs (Lawson et al., 2008). Hybrid systems that utilize LGS are a cost-effective solution for mid-rise residential buildings because LGS provides robustness during transportation and lifting, good resistance during vertical and horizontal loading, and durability with fire resistance for framing (Lawson et al., 1999). LGS construction is based on assembling steel framed panels through several processes inside manufacturing facilities using manufacturing tables or computerized numerical control (CNC) machines. These panels are transported to the construction site, erected to each other, and connected to 3D modules (e.g. bathroom pods) as well as floor cassettes that are constructed onsite. Market share of steel in mid-rise residential buildings represents 3% in the UK, 10 to 15% in the United States (US) and Australia, but less than 1% in Europe (Lawson et al., 2005).

Offsite construction requires consideration of production, transportation, and installation performance (Moghadam et al., 2012). Offsite construction project design takes into account constructability, site logistics, and fabrication process. Architectural design requires early collaboration between all potential suppliers of modules/panels for adequate planning of these buildings to accommodate any variation in size and layout (Lawson et al., 2005). The structural design also controls offsite construction configuration due to the loads acting on modules during fabrication, transportation and site loadings, as well as long-term sustained loads. Lack of specific design, code requirements, and construction guidelines has led to the use of finite element modeling (Ramaji and Memari, 2013) and BIM structural processes (Solnosky et al., 2014) in modular and offsite construction building design. The composite nature of modular and offsite construction means that traditional codes such as the American Iron and Steel Institute (AISI) code, Canadian Institute of Steel Construction (CISC) code, Eurocode 3: Design of steel structures, and the British Standards Institute Steel code used for structural design of cold formed steel do not apply (Lawson et al., 2005). Hence, other studies have discussed serviceability, robustness, and deflection of LGS framing and modular construction by testing full scale modules (Lawson et al., 2005) to illustrate the influence of module configuration on their characteristics. Transportation limitations also affect the configuration of modules/panels to facilitate shipping (BC Housing et al., 2014). Architecture of modular and offsite construction buildings is constrained by manufacturing and transportation requirements, which may accommodate some variation in size and layout (Lawson et al., 2005). The literature highlights the need for a framework that considers the identified constraints to select the most suitable panelized project configuration.

2.5 Scheduling of construction projects

Two main categories are used when categorizing construction project scheduling according to project nature. The first is the repetitive scheduling for projects that contain cycles of repetitive activities such as pipelines, railways, manufacturing, etc. The second is the non-repetitive scheduling (network scheduling) for construction projects that do not require continuity of resources. These two systems are sometimes referred to as location-based scheduling and activity-based scheduling (Kenley and Seppänen, 2010) but the main difference between the two concepts is the ability to maintain continuity of resources.

2.5.1 Repetitive Scheduling

Graphical techniques for repetitive scheduling were first introduced by a Polish professor named Karol Adamiecki in 1896 when he introduced a novel method of displaying the interdependencies of activities to increase visibility of schedules, which he named "harmonograms" (Kenley and Seppänen, 2010). Linear graphical techniques were used as early as 1929 for the Empire State building, as shown in Figure 2.4, then fruther developed by the Goodyear Company in the 1940s, and later developed into LOB by the US Navy around the time of World War II (Kenley and Seppänen, 2010). LOB was initially utilized in manufacturing to maintain flow of products through production lines. Then, it was transferred to the construction industry but did not gain the same popularity in the domain of commercial scheduling software as network scheduling had (Arditi and Albulak, 1986).

The linear scheduling method (LSM) was developed based on LOB and many researchers refer to LSM as LOB. LOB and LSM are the two main methods for repetitive project scheduling though both techniques have different features (Bakry, 2014).

When comparing LOB to LSM, the difference is simply in emphasis (Johnston 1981; Harmelink 1995). The LOB technique visualizes the progress chart and balance line as two parallel lines, while LSM visualizes the time space graph as one continuous line. LSM can represent non-repetitive/discrete activities, while LOB represents only repetitive activities.

Since the early 1970's, many variations of LSM have been proposed under different names. For example, Peer (1974) presented the construction planning technique. O'Brien (1975) introduced the vertical production method (VPM) for high-rise construction. Birrell (1980) presented the time-location matrix model to maintain work continuity of different squads.

Dressler (1980) introduced velocity diagrams. Johnston (1981) then pulled together the various variations and placed it under the LSM name. Stradal and Cacha (1982) introduced the time-space scheduling method. Harris and Ioannou (1982) suggested the repetitive scheduling method (RSM) as a generic term. Whiteman and Irwig (1988) introduced disturbance scheduling, while Thabet and Beliveau (1994) presented horizontal and vertical logic scheduling for multi-story projects. Kenley (2010) introduced location-based management scheduling (LBMS) to connect linear schedules to their location. Each of these methods was developed for a particular objective but they all share scheduling visualisation capabilities by plotting activities as progress versus time.

On the other hand, network scheduling (e.g. CPM) has been criticized for not providing repetitive scheduling with the ability to maintain resource continuity as it is very complicated to view produced schedules for large and complex projects with CPM (Stradal and Cacha, 1982; Harmelink, 1998; Arditi et al., 2002).

Maintaining continuity constraint for repetitive scheduling prevents construction crews from leaving construction sites to work on other projects, which disrupts work flow and affects project cost and causes rework (Slorup, 2012). Coordinating work continuity between different crews reduces conflicts of simultaneous work in the same locations and increase work productivity (Russell and Wong, 1993). An interesting comparison between CPM and LSM was presented by Yamin and Harmelink (2001), as shown in Table 2.1. It addresses two important vital differences instrumental to this research. The first is the limited methods available in literature that allow LSM to schedule uncertainties, and the second is the difference between CPM and LSM criticality due to the continuity constraint in LSM that changes the usual critical path of the CPM. Both aspects are discussed thoroughly in the next sections.

2.5.2 Uncertainty in repetitive scheduling

The planning of construction projects should consider variability and uncertainty to reflect the dynamic nature of the construction industry. A limited number of methodologies have incorporated uncertainty for repetitive scheduling (Trofin, 2004). Simulation is utilized to account for uncertainty in most of these methodologies, while few other attempts were developed to use buffers for linear schedules (Slorup, 2012 & Bakry, 2014). Schoderbek and Digman (1967) were the first to include uncertainty for repetitive scheduling by introducing the "third generation" of program evaluation and review technique (PERT) scheduling that integrates LOB and PERT in one planning and control framework. However, this method did not include cost data for the developed schedule as well as the learning curve effect on productivity. Various simulation-based attempts were performed to incorporate uncertainty with repetitive scheduling starting with Ashley (1980) who used general purpose simulation system (GPSS) language. The main limitation of this method is that it does not account for resource continuity, which is not suitable for repetitive projects. Moreover, with this method, project scheduler must understand a simulation language to create the schedule and a new code must be programmed for each different project (Kavanagh, 1985). Lutz and Halpin (1992) utilized CYCLONE (Halpin, 1973) to generate production curves and LOB for road construction projects and to locate bottlenecks in production to improve system performance while accounting for uncertainty. El-Sayegh (1998) presented linear construction project manager (LCPM) software, which accounts for uncertainty using the Monte Carlo simulation. LCPM allows the planner to input production rates as probability distributions and then determines project completion probability within a certain period. However, Yamin (2001) concluded that the LCPM method does not show which activities are critical and takes a long time to run probabilistic models. DYNAProject software was introduced by Kankainen and Seppänen (2003) as a commercial location-based scheduling tool that uses the Monte Carlo simulation to assess risk level. The DYNAProject is stochastic flowline software that extends beyond deterministic flowline software named REPCON developed by Russell (1990). Polat et al. (2009) combined the use of LOB and discrete event simulation to schedule both onsite and offsite activities of a highway project. The proposed method accounts for resources constraints as well as the probabilistic nature of activities and enables contractors to schedule uninterrupted work flow between offsite and onsite activities. The initial schedule was developed using LOB, and a simulation model for activities was performed using probabilistic data to investigate if trucks would fulfill required work continuity for the initial LOB schedule. VICO commercial software was developed by Olli Seppänen (2009) as an extension of the DynaProject. VICO is an integrated LBMS software suite that utilize four-dimensional (4D) and five-dimensional (5D) BIM for visualization, quantity takeoff, and cost estimation. VICO incorporates a risk analysis model, which uses probability distributions to model uncertainties of productivity rates, resources availabilities, weather conditions, and planned quantities.

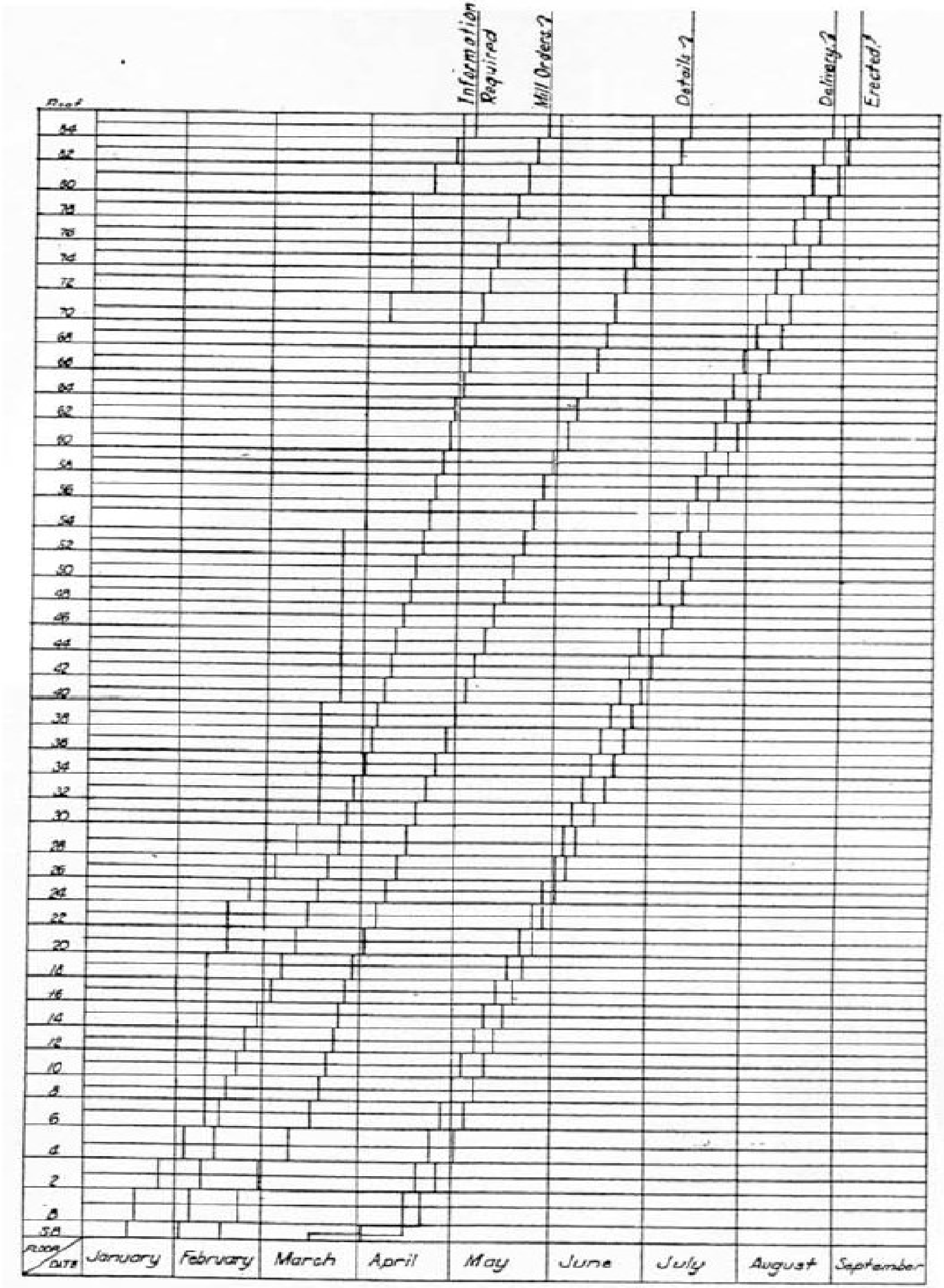


Figure 2.4: Repetitive scheduling for the empire state building (Kenley and Seppänen, 2010).

Table 2.1: Comparison between CPM and LSM (Yamin and Harmelink, 2001)

Attribute/dimension	CPM	LSM
Aid in reduction of uncertainty/risk	Although CPM schedules use fixed duration for activities, it can be easily complemented by PERT with statistical capabilities. This feature helps planners to get a better idea of time and schedule risks.	There is no formal method developed to date that could allow LSM to determine uncertainties in time completion.
Aid in improving production and economical operation	With the incorporation of resource leveling/allocation techniques, CPM schedules can improve the overall completion time and costs by affecting production (add or remove resources). Some limitations have been identified when scheduling continuous projects—difficult to maintain continuity in crew utilization.	Limited capabilities in improving production by changing resources. Easy to schedule continuity on linear projects, improving coordination and productivity.
Aid in achieving better understanding of objectives	In complex projects, CPM network can be very convoluted. This complexity makes them difficult to understand and communicate.	LSM is very easy to understand, and it can be used at every level of the construction project.
Accurate calculations	CPM allows the PM to calculate the time it would take to complete a project, and together with the PERT could provide statistical insights to this process. It is difficult to accurately determine and represent space restrictions (if any).	Location/time calculation is easily done. This is the greatest advantage of LSM over CPM when scheduling linear projects. This capability allows PM to accurately plan activities both in time and location.
Critical path	It is the main feature of the CPM, which can be done very easily.	The LSM algorithm calculates the controlling activity path (CAP) which is equivalent to the critical path, with the additional feature of location criticality.
Ease of use	Extensive computerization has made the CPM method easier to use. However, the user needs a considerable amount of training before actually being able to produce valuable information for controlling purposes.	Very intuitive and easy to understand. It can be used at all levels of the company (managers, superintendents and crew). Lack of computerization makes it difficult to use in large and complex projects.
Easy to update	The method could be difficult to update. Once several updates have been done, it becomes difficult to read. Updated schedules are usually out of date when they are finished.	Updating LSM is simple. Linear schedules can be used as as-built documents for claim purposes or for historical productivity databases.

The Monte Carlo simulation is then utilized to estimate iterations of various scenarios to provide an overall overview of risk in project schedule. Each iteration estimates different resource availabilities, productivity rates, weather conditions, and quantities. A combination of these factors then generates many possible outcomes where each iteration represents one futuristic possibility. Aggregated outcomes from the risk analysis provide distributions for production cost, activity completion times, and project end date. Generated distributions show probability of cost targets or achieving project milestones while considering uncertainty factors. VICO software utilizes stage buffers to reduce uncertainty effects for activities. Expected cost and risk levels are observed after each simulation run to identify optimal size of stage buffers. Then, stage buffer size is changed to reduce risk levels to an acceptable level by project stakeholders. VICO software does not have certain equations for buffer sizing. However, size of buffers is assigned subjectively; larger if the predecessor activity has high variability, when activities have little or no total float, or when activities are planned to be performed continuously. Methods other than simulation attempted to incorporate uncertainty with repetitive scheduling. Maravas and Pantouvakis (2011) introduced a scheduling algorithm named fuzzy repetitive scheduling method (FRSM), which accounts for uncertainty in productivity of different crews. FRSM algorithm starts with a deterministic baseline schedule and then represents uncertainty with three lines representing three values of fuzzy productivity rates (a, b, c). However, FRSM did not include a practical planning framework that illustrates how it could be implemented and controlled. Bakry (2014) presented an extension to FRSM by introducing a comprehensive framework for project scheduling, monitoring, and control. The developed model for scheduling and buffering considers uncertainty illustrated as fuzzy durations and costs. However, only triangular fuzzy membership numbers were utilized to model uncertainties for different input parameters. Slorup

(2014) introduced a conceptual approach using CCPM buffering techniques with LBMS to account for uncertainty while scheduling repetitive projects. This concept is based on reducing activity duration by eliminating safety times/stage buffers to reduce waste, and aggregating these safety times in strategic places to finish activities as quickly as possible while ensuring work flow for construction crews. However, Slorup did not provide any formulation or automation for his conceptual approach.

2.5.3 Uncertainty in non-repetitive scheduling

Kelley and Walker (1959) first introduced CPM, which belongs to the category of non-repetitive or network-based scheduling. Then, Malcolm (1959) introduced PERT, which accounts for uncertainty in activity-based scheduling by utilizing three different possible activity times as optimistic, pessimistic, and most likely possibilities. CPM is the dominant scheduling method though it has been criticised in the construction industry because it does not consider required work flow of construction crews (Stradal and Cacha, 1982). CCPM, introduced by Goldratt (1997), is considered the most innovative breakthrough in project scheduling since the introduction of CPM and PERT because it provided a conceptual understanding of uncertainty in scheduling (Leach, 2001). However, Leach (1999) and others clarified that CCPM is an extension of the continuous improvement concepts presented by Shewhart (1939) and flow concept of Toyota Production System (TPS) introduced by Ohno (1988). CCPM extended the principles of theory of constraints (TOC) first introduced by Goldratt (1984). Goldratt asserted that schedule delays are caused by two psychological behaviors: student syndrome and Parkinson law. Student syndrome or procrastination is the postponing of work for some activities due to multitasking until the deadline is near, or in other words, leaving everything to the last minute. Parkinson's Law (Parkinson, 1955) proposes that work expands to fill the planned time until activity completion even if workers have the ability to finish their assignments early. Goldratt (1997) indicated that planners assign durations for activities with 95% of completion probability. Hence, safety times are wasted because this time is added to activity duration. Goldratt suggested removing safety times from individual activities and aggregating safety times for all activities at the end of each chain. Figure 2.5 shows the key features that create the critical chain, which include the following steps (Leach, 2000): 1) reducing activity times by deducting safety times, 2) removing resource conflicts from schedule before identifying the critical chain, 3) defining the critical chain as the longest path for activities after considering both activities precedence and resources constraints, 4) aggregating uncertainty into one project buffer assigned at the end of the critical chain, 5) adding resource buffers without allocating any time to ensure availability of resources for the critical chain, 6) protecting critical chains from merging with non-critical chains by adding feeding buffers between both chains, and 7) monitoring schedule performance by measuring project and feeding buffers to control the project. A comprehensive overview of current status and future potential for research on the CCPM domain was presented by Ghaffari and Emsley (2015) who reviewed 120 studies related to CCPM. The application of the LBMS in CCPM was identified among 21 futuristic areas of research relevant to CCPM. Both LBMS and CCPM share the idea of using buffers to protect schedules in construction projects. However, the continuity constraint is the main difference between LBMS and the network-based CCPM.

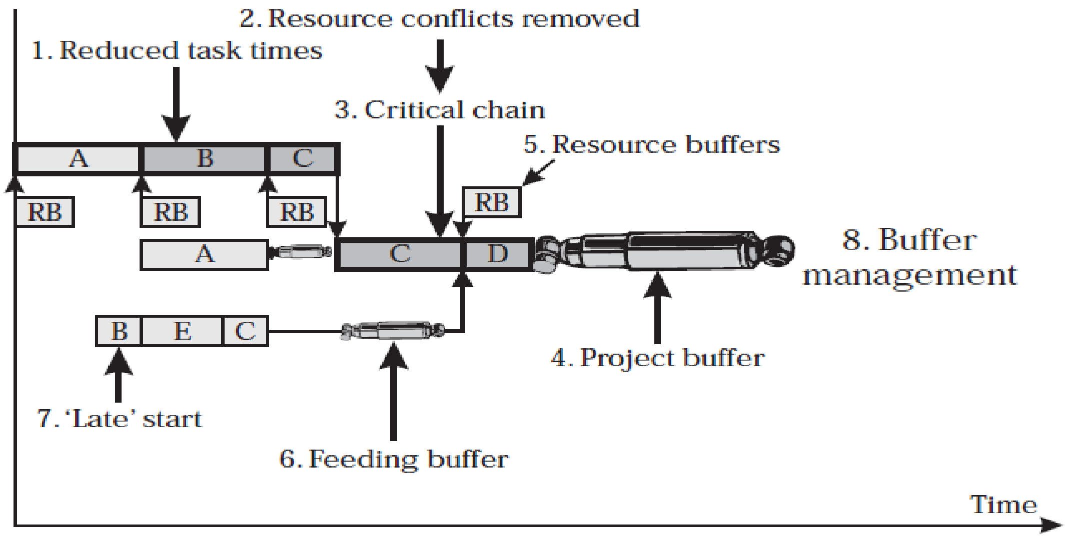


Figure 2.5: Key features of the CCPM system requirements (Leach, 2000)

2.5.4 Schedule buffers

Utilization of buffers is a strategy for risk management to ensure smooth workflow of schedules. However, buffers appear similar to time lags and floats but have different definitions and functionalities as follows:

Buffer: An additional absorbable allowance for the absorbtion of any disturbance between two activities as a component of the logical connection between two activities (Kenley and Seppänen, 2010);

Lag: The required fixed duration of a logical connection between two activities such as curing time (Kenley and Seppänen, 2010); and

Float: A time contingency that give schedule flexibility for scheduling start of activities within maximum time available (Uher, 2003).

Many buffer types have been mentioned in the literature based on their functionality and schedule location in linear scheduling. Lumsden (1968) defined two types of time buffers for repetitive scheduling, which are activity buffers and stage buffers. Activity buffers are defined as an allowance included in each activity time to protect schedules against minor productivity fluctuations. Stage buffers are allocated between major projects stages to protect against unforeseen circumstances such as weather, as shown in Figure 2.6. Moreover, location or space buffers were also discussed by Russell and Wong (1993). Location buffers have horizontal representation in linear scheduling diagrams, as shown in Figure 2.7, and are used so that crews can continue working despite unforeseen incidents at specific locations.

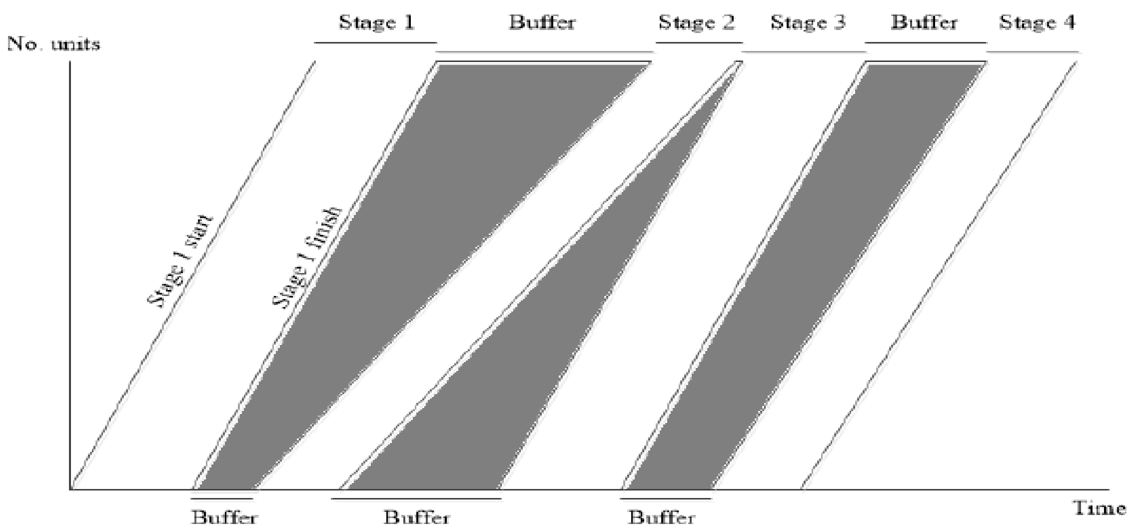


Figure 2.6: Stage buffers in LOB scheduling (Lumsden, 1968)

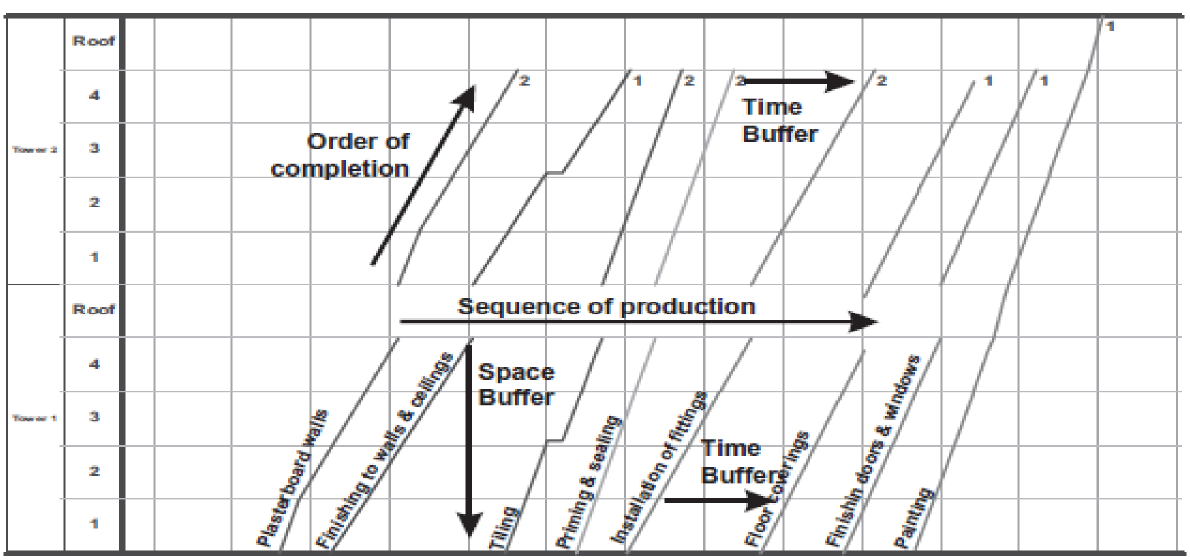


Figure 2.7: Time buffer and space buffer (Kenley and Seppänen, 2010)

Three conceptually different buffers were presented by Goldratt (1997) for network-based scheduling including resource, feeding, and project buffers as previously explained and shown in Figure 2.5. Goldratt (1997) suggested that all activity safety times be deducted, including activity and stage buffers, and replaced with the cut and paste method (C&PM). This method cuts 50% of all activity durations and pastes them at the end of the critical chain as the project buffer or at the end of non-critical chains as the feeding buffers. C&PM was criticized by many researchers (Herroelen and Leus, 2001; & Herroelen et al., 2002) because of its focus on single unit resources such as work crews and because it utilizes a linear procedure in identifying buffer size. Buffer size increases linearly with the length of chain (for example a two year project ends up with a year-long project buffer). Hence, C&PM generates an unnecessarily large amount of protection that leads to loss of business opportunities. Bakry (2014) presented a comprehensive literature review for buffer sizing techniques after grouping these techniques into two groups. The first considers building buffers based on general representation of uncertainty without addressing specific sources of uncertainty using historical data or fuzzy set theory. The second considers specific sources of uncertainty such as chain length, influence level, activity location in schedule, and human behavior during estimation.

2.5.5 Criticality

Studying schedule criticality is essential for the integration of CCPM and LSM because CCPM follows the criticality approach of network-based scheduling after resolving resources constraints. Any activity that delays the project completion date is considered critical. However, network-based scheduling criticality is totally different than linear scheduling criticality due to the continuity constraint (Harmelink, 1998). The critical path in CPM is a network of activities with zero total float, which is the same critical path as for CCPM without resources conflicts.

Resource conflicts shift the critical path based on the longest path of activities constrained by resources (Goldratt, 1997).

Carr and Meyer (1974) explained that the slowest activity in linear scheduling is critical because any reduction in productivity will delay the project. Moreover, if all activities are aligned to the slowest critical activity then all activities are critical (Carr and Meyer, 1974). However, production buffers are needed to protect activities from local variability. Peer (1974) discussed the difference in criticality approach between LSM and CPM and found that project schedule is determined by the slowest flowline, which is the critical activity. Peer (1974) stated that balancing non-critical flow lines with critical ones is essential to to achieve production continuity, while not aligning flowlines causes discontinuous work or waiting times for some production lines. Handa et al. (1992) presented the position weights technique, a numerical approach to identify critical segments in repetitive scheduling. Russell and Wong (1993) introduced the first automated model to identify critical activities in REPCON software by integrating CPM algorithms while fulfilling the required continuity constraint. However, REPCON software did not include usual features of planning and scheduling such as work breakdown structure, multiple calendars, and resource leveling. Harmelink and Rowings (1998) stated that LSM gained little influence in construction industry due to the absence of criticality methodologies in linear scheduling; they introduced the controlling activity path (CAP) method to identify critical segments. CAP divides one continuous activity into controlling critical vertices and non-critical segments. However, CAP is a graphical method that lacks mathematical formulation.

Harris and Ioannou (1998) introduced the concept of controlling sequence for repetitive scheduling method (RSM, similar to the CAP method presented by Harmelink and Rowings

(1998). This method introduced a new feature named control points for positioning successive flow lines that may diverge or converge based on their relative slopes; however, this method is also a graphical method. Ammar and Elbeltagi (2001) presented an algorithm that utilizes a CPM criticality engine while considering resourced continuity. This algorithm was automated and presented as software named critical path linear scheduling method (CPLSM) and uses visual basic as a Microsoft macro language. Thus, CPLSM does not account for variability in productivity rates nor allow resources leveling for repetitive projects.

Hassanein (2002) developed a methodology for identifying the most critical activities or segments. This methodology is similar to the minimum moment algorithm (Hiyassat, 2001) and is based on balancing successive crews to balance production that expidites construction. However, this method is mainly graphical. Kallantzis and Lambropoulos (2004) introduced a new concept to determine critical path for linear scheduling by utilizing minimum and maximum time and distance constraints. Minimum time or distance constraints are equivalent to the time buffer, which indicates that when a specific amount of time or distance has been reached, two successive activities can no longer approach each other. Maximum time and distance constraints indicate that, when a specific amount of time or distance has been reached, two successive activities cannot move further away from each other. However, this methodology does not account for the learning curve effect or resource optimization. Kallantzis and Lambropoulos (2007) converted linear schedules into equivalent networks according to a set of rules. Results showed that linear schedules produce longer durations and different critical paths when compared to their network equivalents. Thus, if resource continuity constraint is removed, project completion times and critical paths are identical. Zhang et al. (2013) introduced a comparison between RSM and network scheduling; the backward controlling segment was found to be the key in ensuring that the controlling path in linear scheduling does not coincide with the critical path of an equivalent network (Kallantzis et al., 2007). Zhang et al. (2013) developed PrjGen software to assist schedulers in transforming linear schedules into equivalent networks in P3 format for commercial scheduling. However, PrjGen software does not account for uncertainty in productivity rates, and does not include resources allocation algorithms. Bakry et al. (2013) identified critical segments of each activity by locating the shortest distance between two activities to insert a time buffer that absorbs delay in successor activity without affecting overall critical sequence. However, Bakry et al. (2013) did not include a procedure that identifies multiple critical sequences for repetitive scheduling.

2.5.6 Integration of scheduling techniques

Integration of repetitive and non-repetitive scheduling methods utilizes merits and unique features of these methods. Previous attempts for integrating CPM and LOB indicate that both methods are complementary. LOB primarily utilizes a graphical technique in scheduling of repetitive projects. However, it lacks the capability to consider concurrencies and logic dependencies of CPM scheduling. Integration of repetitive and non-repetitive scheduling can be clustered into two categories: deterministic and stochastic, as shown in Figure 2.8. The capabilities and limitations of these methods as cited in the literature are summarized in Table 2.2. A group of deterministic methods has utilised CPM/PDM and linear scheduling algorithms without optimization (Laramee, 1983; Russell and Wong, 1993; Suhail and Neale 1994; Ammar, 2013). Laramee (1983) integrated CPM and linear scheduling without considering a model to forecast project completion date or a tracking and control system for the developed schedule. Russell and Wong (1993) introduced a software named REPCON that identifies critical activities. However, this method did not include work breakdown structure, multiple calendars, or resource leveling. Suhail and Neale (1994) introduced a CPM/LOB integration method that utilizes a CPM/LOB chart to ensure work continuity and to determine number of crews. However, accuracy of this method increases when decimal, instead of integer, number of crews is used. Ammar (2013) presented a non-graphical LOB and CPM integration without considering learning curve effects and work interruprions.

Another group considered optimization in an effort to minimize project duration (Selinger, 1980; Russell and Caselton, 1988), and/or cost (Moselhi and El-Rayes, 1993; El-Rayes, 1998; Hassanein, 2002; Hassanein and Moselhi, 2004; Ranjbaran, 2007). Selinger (1980) utilized dynamic programming (DP) to optimize project duration without allowing for work interruptions. Russell and Caselton (1988) proposed a DP method that accounts for pre-determined work interruptions. However, this method focused on reducing project duration. El-Rayes (1998) used DP in an algorithm that presents a set of heuristic rules to reduce the number of feasible interruptions. However, this method does not provide a tracking and control module nor generate effective reports. Hassanein and Moselhi (2002, 2004) presented a method that utilizes DP to optimize schedules for highway construction considering combined impacts of project cost and duration. However, this method does not allow real time tracking of equipment and does not highlight conflicts between existing utilities. Ranjbaran (2007) extended the work of El-Rayes (1998) by presenting an object-oriented model for planning, scheduling, and control of high-rise buildings without optimizing resource sharing between multiple projects.

Table 2.2: Features of the integration methods

	Schoderbek and Digman (1967)	**Selinger (1980)**	**Laramee (1983)**	**Russell and Caselton (1988)**	**Russell and Wong (REPCON) (1993)**	**Suhail and Neale (1994)**	**El-Rayes and Moselhi (LSCHEDULER) (1998)**	**Hassanein and Moselhi (HWPLANNER) (2002)**	**Kankainen and Seppänen (DynaProject) (2003)**	**Ranjbaran (2007)**	**Seppänen (VICO) (2009)**	**Ammar (2013)**	**Bakry (2014)**	**Slorup (2014)**
Deterministic	N	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	N
Stochastic	Y	N	N	N	N	N	N	N	Y	N	Y	N	Y	Y
Optimized	N	Y	N	Y	N	N	Y	Y	N	Y	N	N	Y	N
Identify critical path for repetitive activities	N	N	N	N	Y	N	N	Y	N	N	Y	N	Y	N
Allow Interruptions	N	N	N	Y	Y	N	Y	N	Y	Y	Y	N	N	N
3D Visualization	N	N	N	N	N	N	N	Y	N	N	Y	N	N	N
Buffer modeling	N	N	N	N	N	N	N	N	Y	N	Y	N	Y	Y
Learning curve effect	Y	N	Y	N	N	N	Y	Y	N	Y	N	N	N	N
Typical activities only	N	N	Y	N	N	Y	N	N	N	N	N	Y	N	-
Integrated time and cost planning	N	N	N	N	N	N	Y	Y	N	Y	Y	N	Y	N

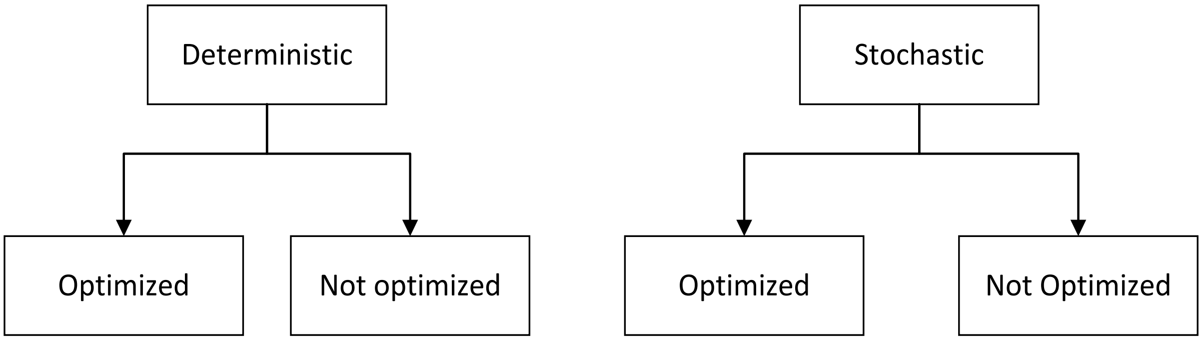


Figure 2.8: Groups for integrating repetitive and non-repetitive scheduling

The second category considered uncertainty for integrating repetitive and non-repetitive scheduling. A group of stochastic methods was presented without optimization (Schoderbek and Digman, 1967; Kankainen and Seppänen, 2003; Seppänen, 2009; Slorup, 2014; Salama et al., 2016 and 2017b). Schoderbek and Digman (1967) integrated linear scheduling and PERT in one planning and control framework to benefit from resource continuity in linear scheduling and uncertainty modeling in PERT. However, the provided method is not structured. Kankainen and Seppänen (2003) introduced DYNAProject software that uses the Monte Carlo simulation to assess schedule risk. However, the DYNAProject does not include 3D, 4D, or 5D modelling capabilities and does not consider cost effects of control actions. Seppänen (2009) developed VICO commercial software as an extension to the DynaProject (Kankainen and Seppänen, 2003). VICO is an integrated location-based software that utilizes 3D, 4D and 5D BIM for visualization, quantity take-off, and cost estimation. VICO does not have a structured model for buffer sizing. VICO assigns buffers subjectively; larger if the predecessor activity has high variability, when activities have little or no total float, or when activities are planned to be performed continuously.

Slorup (2014) applied CCPM buffering techniques to LBMS. However, Slorup (2014) did not present a formulation for this method or a procedure for identifying the critical chain in respect to constraining resources. Salama et al. (2016) suggested a BIM-based integrated framework for planning and scheduling of modular and offsite construction projects using LSM and CCPM. However, this framework utilizes a visual method for identifying the critical chain.

Another group considered schedule optimization to minimize project duration or cost (Bakry et al., 2013). Bakry et al. (2013) produced a basic LSM schedule with deterministic activity durations and a buffer component that utilizes fuzzy sizing and insertion of buffers to account for uncertainty. However, this algorithm is a single objective optimization method that addresses either duration or cost but not both.

Shen and Chua (2008) compared CCPM with LPS and suggested the incorporation of CCPM at high planning levels with LPS at low planning levels (process control) to find a balance between CCPM aggressiveness and LPS reliability. CCPM works under the umbrella of TOC while LPS belongs to lean construction; Goldratt (2007) thus emphasized that TOC follows the same concepts of continuous improvement and flow associated with TPS, which is the foundation for lean construction. Shen and Chua (2008) presented a seven step model which adopts the best of both methods and introduced an additional performance index named percent plan impacted metric (PPI) besides the percent plan completed (PPC) to measure plan reliability.

A simulation model was introduced to illustrate the effect of CCPM scheduling in a last planner production control system by assuming two variables in the schedule: activity duration and delivery time of prerequisites. It was concluded that the critical chain approach reduces project duration and it was illustrated that it is important to minimize delays and uncertainties to reduce project duration, reduce PPI and increase PPC. However, project cost implications were not incorporated in this study.

Seppänen et al. (2009) suggested integrating LBMS and LPS because the aim of both is to decrease waste and variability while increasing productivity. Research related to LBMS reliability shows that LBMS reliability metrics and PPC (LPS reliability metric) are highly correlated (Seppänen, 2009) and integrating LBMS continuity constraints and LPS social processes is beneficial for repetitive projects. LBMS projects data was useful for Seppänen's empirical research though there were deficiencies in applying LPS' social processes.

Koskela et al. (2010) compared CCPM and LPS to analyze similarities and differences between the two methods. Flow conceptualization was found necessary for both CCPM and LPS to address how work actually flows. However, it was illustrated that CCPM avoids uncertainty through operating aggregated buffers, while LPS reduces cause of buffers, which is production variability. The main difference between both methods is that CCPM represents a centralized push management, while LPS represents a decentralized pull management. However, both methods contain mixed push-pull methods (Koskela et al., 2010). CCPM and LPS were found to address physiological issues in scheduling such as student syndrome, Parkinson's Law, and multi-tasking in CCPM, as well as public promises, statistics for non-completions reasons, and public checking for task completion. The authors suggested integrating CCPM, LBMS and LPS as ingredients to create an integrated alternative for CPM because they are complementary to each other. However, they did not provide a framework or formulation for that suggested framework.

2.5.7 Integration of offsite and onsite construction

A recent survey of 800 engineers, architects, and contracting professionals revealed the advantages of modular construction, including shorter project schedules (66% of respondents), lower cost (65% of respondents), and reduced construction waste (77% of respondents) (MBI, 2016). Klynveld Peat Marwick Goerdeler (KPMG) conducted an independent research study on offsite construction projects financial net savings. Savings are found to be around 7% due to the shortened construction period (Southern, 2016), without considering savings from interest of borrowing, improved time and cost predictability, reduced construction noise, and improved health and safety. These savings enable faster rental income as well as reduced construction inflation costs. These combined savings reached 36 million £ for a 50 storey office building in central London (Southern, 2016). Modularization and standardization have a significant effect on productivity (McKinsey and Company, 2017). Modular construction improves project schedule by synchronizing offsite and onsite operations. However, there is a lack of scheduling methodologies that perform this synchronization.

Parallel scheduling for offsite and onsite construction schedules saves 30 to 50% of project duration when comparing to stick-built traditional construction processes, as shown in Figure 2.9 (MBI, 2016). Many studies have used simulation to schedule offsite construction processes— Abu Hammad (2003), Xie et al. (2011), Taghaddos et al. (2012), Ajweh (2014), and Altaf et al. (2015), while other studies— Moghadam (2013), Liu et al. (2015), and Liu et al. (2016) have integrated simulation with BIM to automate quantity take-off data and to visualize offsite and modular construction activities. Furthermore, linking the simulation model of the module yard (onsite) to the simulation model of the fabrication shop (offsite) is the main limitation of simulation models where the scheduler has to link both schedules manually (Taghaddos et al., 2009). Bu Hamdan et al. (2015) presented a system that integrates simulation with BIM techniques to provide an inventory planning and management tool while considering the interactions between different construction phases from manufacturing to assembly. However, this system has a less user-friendly graphic user interface (GUI), which makes it difficult for those who are not familiar with simulation tools. Moreover, the probabilistic simulation is fed manually by distribution functions.

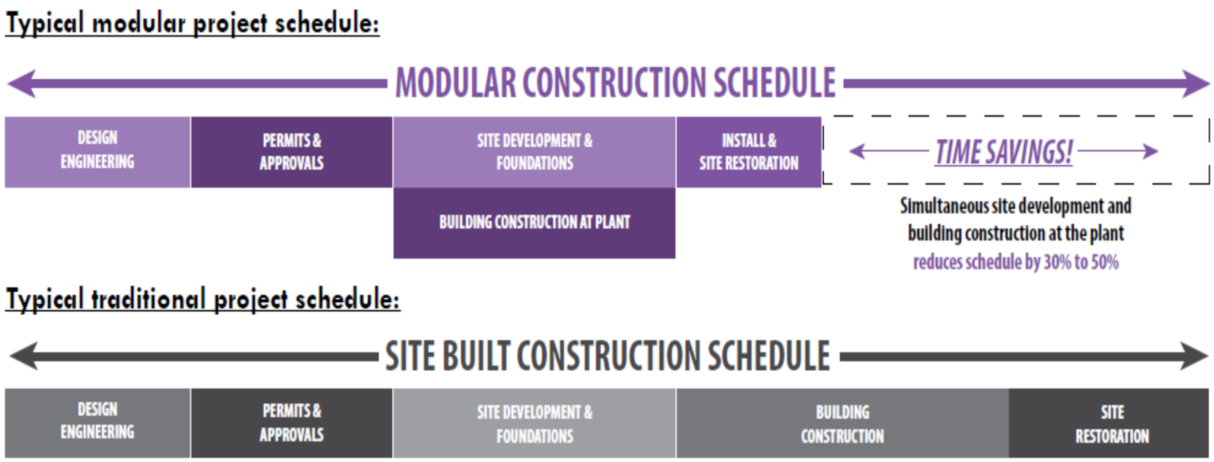


Figure 2.9: Comparison between modular and traditional construction schedules (MBI, 2016)

Simulation is a good tool for probabilistic problems because the simulation model assesses the effect of uncertainties in construction projects (Lutz, 1990; Yang 2002). However, simulation cannot eliminate or control idle times by itself (Yang, 2002; Ioannou and Likhitruangsilp, 2005). Hence, an external algorithm must be implemented in the simulation model to solve the problem of repetitive scheduling effectively (Lutz 1990; Yang 2002). Without developing and implementing an external algorithm into simulation, simulation gives the same results as CPM, as shown in Figure 2.10, where activities are scheduled at their early start dates, while interruptions exist between units (Srisuwanrat, 2009).

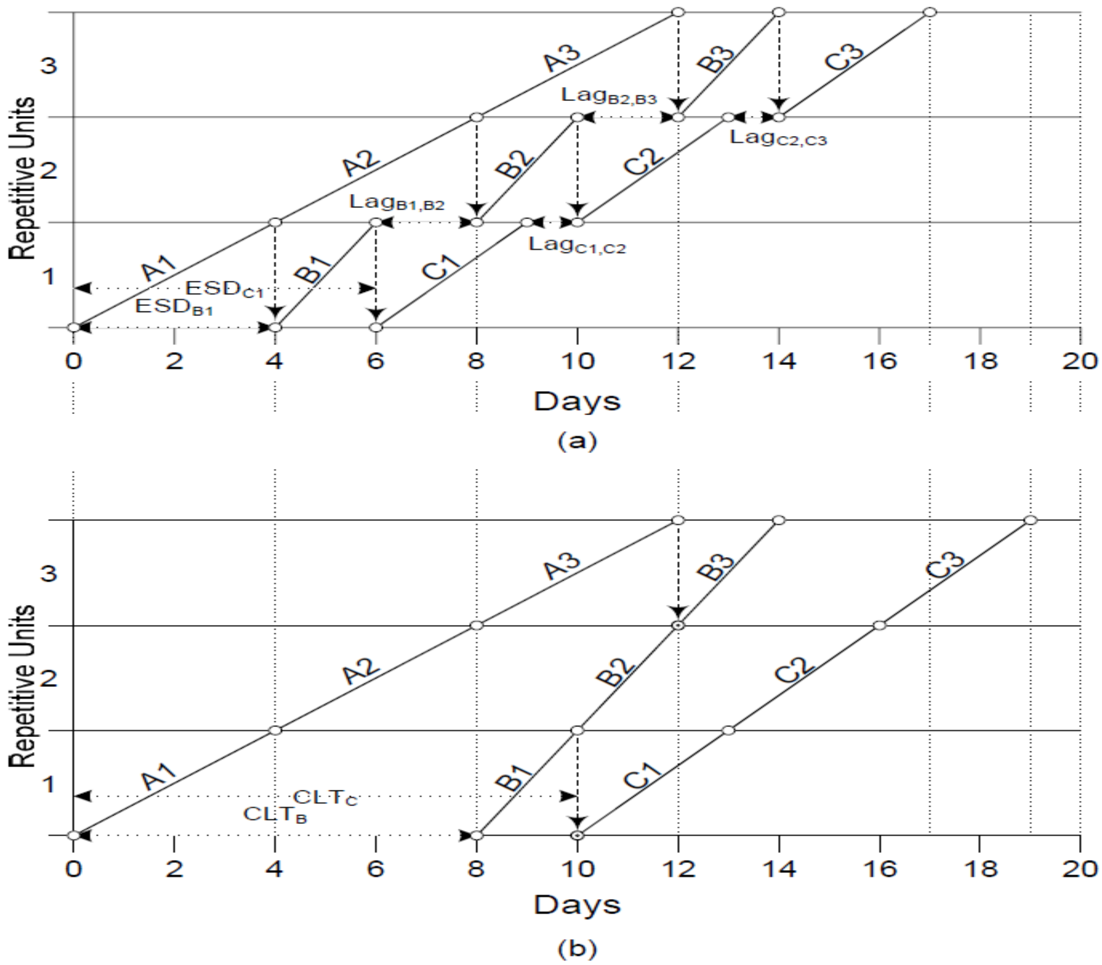


Figure 2.10: CPM vs. RSM scheduling (a,b) (Ioannou and Srisuwanrat, 2006)

On the other hand, linear scheduling maintains resource continuity and allows work interruptions in time-cost optimization problem. Analyzing and balancing the trade-off between work interruptions and continuity achieves minimum project cost by relaxing resource continuity constraints (Srisuwanrat, 2009). However, the LOB presentation was criticized by Arditi and Albulak (1986) and it was suggested that colored graphics be used to assist schedulers in differentiating between overlapping activities that have equal rates of production. LSM was also criticized for its inability to show task relationships and parallel activities graphically (Francis and Miresco, 2013). Manusr (1990) presented an approach that allocates critical activities on the upper side of the LOB chart and non-critical ones on the lower part for better presentation of LOB charts. Hegazy et al. (1993) introduced the BAL system as an extension to Manusr's work, which depends on an algorithm for scheduling and control of linear projects with an enhanced presentation to avoid activities overlapping, as shown in Figure 2.11.

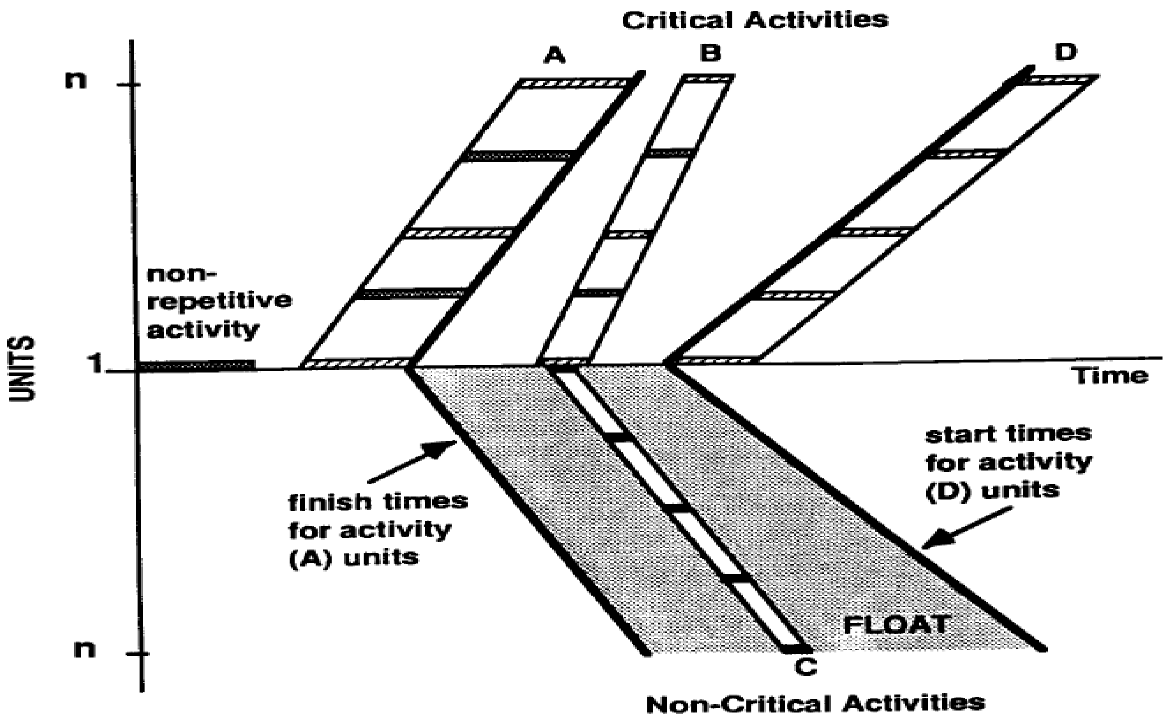


Figure 2.11: Enhanced schedule presentation (Hegazy et al., 1993)

2.6 Project tracking and control methods

Different studies have introduced several performance measurement methods for efficient project controls (Nassar and AbouRizk, 2014). Johnson and Broms (2000) proposed two competing concepts of management: managing by results (MBR) and managing by means (MBM). Earned value management (EVM) is based on MBR, while LPS is based on MBM (Kim and Ballard, 2010). However, project control methods that utilize MBR are inappropriate for management at the operational level because activities are highly interdependent. EVM systems were criticized because they assume that a project is broken into independent packages, with contractual obligations and targets (McConnell 1984). Managers isolate activities or accounts from interaction with each other to cope with uncertainty (Howell et al., 1993). EVM ignores the concepts of value-generation and work flow control based on customer needs (Kim and Ballard, 2000). Some studies have integrated linear scheduling and CCPM (Bakry et al., 2013; Slorup, 2014; and Salama et al., 2016, 2017a, and 2017b). Bakry (2014) introduced a monitoring and control method for this integrated schedule using a buffer consumption index (BCI). However, BCI is presented as a project performance indicator in a subjective way, as it does not present different thresholds for project activities.

Project control systems used in construction industry utilize two methods predominantly: EVM and LPS. EVM was initially introduced by the US Department of Defense (DoD) for cost control in the 1960s; over time, it gradually shifted from cost to schedule control (Lipke, 2003). EVM schedule measures were criticized for their flaws in describing schedule variance in terms of monetary values (Anbari, 2003; Moselhi, 2011). Many researchers have introduced extensions to improve the application of EVM metrics. Naeni et al. (2011) presented a fuzzy approach to EVM. Moselhi and Azarm (2013) introduced the material status index (MSI), which reveals material related factors behind schedule performance. Kim et al. (2015) introduced customer earned value (CEV), which provides project managers with information on level of collaboration.

Utilizing lean-in construction reduces effect of variability on continuous flow of work (Koskela, 1992; Ballard and Howell, 1997; Tommelein et al., 1999). LPS is an effective lean tool for project control that improves project performance and planning reliability (Ballard, 1994; Ballard and Howell, 1998; Ballard 2000). Lean literature criticizes EVM control mechanism because EVM focuses on budget related productivity, but it does not address doing the right work at the right time in the right way (Ballard, 2000). Kim and Ballard (2010) compared EVM and LPS and concluded that EVM is not suitable for controlling projects with highly interdependent activities at the operational level and that LPS is more appropriate. LPS enhances reliability of work flow, thereby reducing project cost and duration (Ballard et al., 2007).

LPS transforms what should be done into what can be done using feedback of planning stakeholders (Ballard, 2000). LPS includes five sequential processes: 1) generating master schedule using average productivity rates while considering phase milestones (Kim, 2014), 2) preparing phase scheduling that divides master schedule into phases to identify operational conflicts through collaborative planning by crews who conduct works and provide feedback using pull techniques, 3) preparing look-ahead schedules that divide phase schedules into planned assignments of four to eight weeks ahead to ensure constraints are resolved and production is shielded against unreliable commitments, 4) preparing weekly work plans which detail assignments based on commitment of last planners for what they actually can do to insure that quality of assignments meets five criteria: soundness, definition, size, sequence, and learning criteria (Ballard and Howell, 1998; Ghosh et al., 2017), and 5) learning by measuring the PPC indicator (planned activities completed/total number of planned activities). After the start of the project, PPC is measured at agreed upon time intervals. If actual PPC equals or more than the PPC targeted by project stakeholders, then root causes of delay are not analyzed. However, if the actual PPC is less than the targeted PPC, then roots causes of delay are analyzed for any unfulfilled commitments, control actions are developed, and lessons learned are documented for future planning. Integrating LPS with other scheduling methods helps managers make better control decisions. This integration is grouped into two categories: with non-network-based scheduling (Seppänen et al., 2009; Olivieri et al., 2016) and with network-based scheduling (Shen and Chua, 2008; Koskela et al., 2010).

The first category is beneficial for non-network-based projects due to its use of linear scheduling continuity constraints and LPS social processes. Seppänen et al. (2009) integrated LPS with LBMS to decrease waste and variability while increasing productivity. Research related to LBMS shows that reliability metrics of LBMS and PPC (LPS reliability metric) are highly correlated (Seppänen, 2009; Seppänen et al., 2010). Olivieri et al. (2016) extended the work of Seppänen (2009) by presenting a model that integrates CPM, LBMS, and LPS. This model links work processes horizontally (between distinct phases) and vertically (within the same phase). However, this model does not consider uncertainty of productivity rates and needs to be tested in real case studies to demonstrate its practicality. The second category benefits from social processes of CCPM and LPS while considering uncertainty of productivity rates. Shen and Chua (2008) integrated CCPM at high-planning level with LPS at low-planning level to a balance between CCPM aggressiveness and LPS reliability. However, the introduced case example was not related to a specific industry domain. Koskela et al. (2010) compared CCPM and LPS to analyse similarities and differences. Flow conceptualization was found necessary for both CCPM and LPS. Koskela et al. (2010) suggested integrating CCPM, LBMS, and LPS to create an integrated alternative for CPM since they are complementary to each other. However, the authors did not provide a methodology for the suggested framework.

Other studies integrated linear scheduling with CCPM to benefit from the merits of both methods (Bakry et al., 2013; Slorup, 2014; and Salama et al., 2016, 2017a, 2017b). Bakry et al. (2013) presented a method that produces a basic linear schedule with deterministic activity durations and a buffer component that utilizes fuzzy sizing and insertion of buffers to account for uncertainty. Intermediate buffers were assumed to absorb the delay of critical sequence. However, this delay may not happen, rendering intermediate buffers as redundant (Salama et al., 2017b). Slorup

(2014) applied the buffering techniques of CCPM in LBMS without presenting a formulation for this method. Salama et al. (2017b) extended the work of Bakry et al. (2013) and Slorup (2014) by presenting a generic method of LSM and CCPM integration that considers uncertainty of resources and productivity rates. However, Salama et al. (2017b) did not provide a tracking and control technique for the developed method. In summary, there is a lack of methods that track and control the integration between linear scheduling and CCPM.

2.7 Optimization of repetitive scheduling

Existing optimization methods for scheduling are grouped into two main categories based on scheduling type: non-repetitive and repetitive scheduling. Optimization methods for non-repetitive scheduling have two categories: deterministic (Feng et al., 1997; Li and Love, 1997, 1999; Hegazy, 1999; and Zheng et al., 2004), and stochastic (Feng et al., 2000; Leu et al., 2001; Eshtehardian et al., 2008; Eshtehardian et al., 2009; Ghoddousi et al., 2013). The main objective of optimization is to balance the trade-off between work interruptions and resource continuity to assist in achieving least project cost by relaxing resource continuity constraints in the time-cost optimization problem. Available methods can be categorized into four main categories according to optimization objectives: 1) minimizing resource fluctuation, 2) minimizing resource idle times, 3) minimizing project cost and 4) minimizing project duration (Esfahan and Razavi, 2015).

This research focuses on optimization methods for repetitive scheduling which are also grouped into two categories: deterministic and stochastic. All methods included in Table 2.3 are deterministic except method developed by Bakry et al. (2016). These methods were selected because each one of them provided a unique contribution to the area of optimizing repetitive scheduling. For example, Selinger (1980) provided the first method to optimize repetitive scheduling using dynamic programming. Russell and Caselton (1988) provided the first optimization method that allows for work interruptions. Moselhi and El-Rayes, 1993 provided the first optimization method that considers the cost of repetitive projects, and Bakry et al. (2016) provided the first stochastic optimization method for repetitive scheduling. Capabilities and limitations of these methods are summarized in Table 2.3. The first category of optimization methods for repetitive scheduling either focuses on minimizing project duration (Selinger, 1980; Russell and Caselton, 1988; Hyari and El-Rayes, 2006; Agrama, 2014), and/or cost (Moselhi and El-Rayes, 1993; El-Rayes, 1997; Hegazy and Wassef, 2001; Moselhi and Hassanein, 2003; Ipsilandis, 2007; Long and Ohsato, 2009; Liu and Wang, 2012). However, collectively, none of these methods consider uncertainty in productivity rates nor utilize buffers to provide protection against project delay. The second category of optimization methods includes the method presented by Bakry et al. (2016). This method produces a deterministic linear schedule and a buffer component using fuzzy sizing and insertion to account for uncertainty. It is a suitable optimization method for the integration of LSM and the CCPM (Salama et al., 2017b). However, this method is a single objective optimization method that considers either cost or duration, but not both, and does not allow for work interruptions or consider delay penalties and uncertainty in availability of resources.

Optimization methods are also categorized according to utilized optimization technique such as DP, GA, linear programming, and constraint programming. DP is used without interruptions in Selinger (1980), El-Rayes and Moselhi (1993), Moselhi and Hassanein (2003), and Bakry et al. (2016). It is also utilized with pre-determined work interruptions, as shown by Russell and Caselton (1988), to optimize duration without considering project cost or by accounting for cost while modelling interruptions based on a set of heuristic rules as in El-Rayes (1997).

Most optimization methods that utilize DP optimize a single objective only. GA is evolutionary searching tool that differs from conventional ones because it operates on a set of solutions rather than a single solution (Zheng and Ng, 2005). Therefore, GA conducts complicated multi-objective optimization problems. GA works by encoding parent solutions into chromosomes to generate the initial generation. Three operators named selection, crossover, and mutation are then utilized to generate a new generation of solutions (offspring) ready for the next cycle (Zheng et al., 2004).

All methods that utilize GA in Table 2.3 allow for work interruptions, either while considering cost as in Hegazy and Wassef (2001), Long and Ohsato (2009), and Agrama (2015), or without considering cost as in Hyari and El-Rayes (2006) and Agrama (2014). However, GA optimization methods do not utilize an objective function, which uses importance weights for time, cost, and work interruptions simultaneously. Other methods have been utilized for time and cost optimization such as linear programming (Ipsilandis, 2007) and constraint programming (Liu and Wang, 2012), which allow for work interruptions without considering uncertainties associated with schedule inputs.

Table 2.3: Capabilities and limitations of optimization methods

Reference														
Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Optimization technique	DP	DP	DP	DP	DP	GA	DP	GA	linear programming	GA	Constraint programming	GA	GA	DP
Multi-objective optimization	N	N	N	N	N	Y	Y	Y	Y	Y	N	Y	Y	N
Deterministic	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Stochastic	N	N	N	N	N	N	N	N	N	N	N	N	N	Y
Allow for interruptions	N	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Utilize Buffers	N	N	N	N	N	N	N	N	N	N	N	N	N	Y
Consider cost	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	N	Y	Y
Consider delay penalties	N	N	N	N	N	Y	N	N	Y	N	N	N	N	N
Consider uncertainty of resource availability	N	N	N	N	N	N	N	N	N	N	N	N	N	N

(1) Selinger, 1980. (2) Russell and Caselton, 1988. (3) El-Rayes and Moselhi, 1993. (4) El-Rayes 1997. (5) El-Rayes and Moselhi, 2001. (6) Hegazy and Wassef, 2001. (7) Moselhi and Hassanein, 2003. (8) Hyari and El-Rayes, 2006. (9) Ipsilandis, 2007. (10) Long and Ohsato, 2009. (11) Liu and Wang, 2012. (12) Agrama, 2014. (13) Agrama, 2015. (14) Bakry et al., 2016. * DP: dynamic programming, GA: genetic algorithm.

2.8 Findings of the Conducted Review

The following gaps were identified:

1. Lack of studies that investigate critical issues in current practices such as type of project delivery system, type of contracts, type of procurement method, synchronization of onsite and offsite schedules, BIM applications and software, scheduling software, and barriers to increased market share;
2. Lack of systematic methodoligies that allow project stakeholders to compare and select near optimum module configurations for modular construction;
3. Lack of systematic procedures that help identifying the most suitable configuration for each type of module (i.e. panels) for hybrid construction of residential buildings;
4. Simulation tools are used in most planning and scheduling techniques currently available for modular and offsite construction. However, these tools require dedicated simulation professionals as well as historical records of productivity data which might not be available;
5. Integration of offsite and onsite schedules and available schedule optimization methods for modular construction depends also on simulation;
6. Linear scheduling lacks the tools to account for uncertainty while scheduling repetitive construction projects. Hence, there is a need to develop a comprehensive resource driven methodology for scheduling, tracking, and control of modular and offsite construction that accounts for uncertainty of productivity rates;
7. EVM was criticized as a tool for project tracking and control becasue it considers projects as independent packages and ignores concepts of value-generation and work flow control

based on customer needs. LPS was found more appropriate for project control since it enhances work flow reliability and reduces project cost and duration; and

8. Lack of multi-objective optimization methods for the integration of LSM and CCPM that minimize cost, time, and work interuptions and consider uncertainties of productivity rates, quantities, and availability of resources.

Chapter 3: Questionnaire

3.1 Introduction

This thesis introduces the results of a new questionnaire carried out in collaboration between the Department of Building, Civil & Environmental Engineering (BCEE) at Concordia University, Modular Building Institute (MBI), Niagara Relocatable Buildings Incorporation (NRB Inc.), and School of Building Science and Engineering at University of Alberta (Salama et al., 2018 a). Full results of this study were published on the official MBI website (Salama et al., 2018b) and can be found in Appendix I. This questionnaire focused on two issues; (1) the characteristics of the modular and offsite construction industry, and (2) detected barriers to the increased market share of this industry. For the latter, effort was made to address five hypothesis points, which emanated from workshop on "challenges and opportunities for modular construction in Canada" held in Montreal in October 2015 to analyze barriers to modular construction growth in Canada (ccinnovations, 2015). These hypothesis points included negative stigma, shortage of examples of past success, standards and regulations, procurement strategies, and project financing.

The questionnaire was available online using Google Forms starting from 16th of April until the 4th of August, 2017 and 58 responses were received from 11 countries including Canada, USA, UK, China, Australia, New Zealand, Brazil, Russia, Slovenia, Saudi Arabia, and the United Arab Emirates (UAE). The questionnaire was sent to nearly 1000 modular construction professionals using LinkedIn messaging and emails. Key findings of this questionnaire included requests for use of separate code of modular construction design, innovative financing and insurance solutions, standards that consider procurement regulations, and lending institutions that partner with financial houses to create special lending programs for modular construction.

3.2 First part (industry characteristics)

This study captures current practices in modular construction such as: 1) type of material used, 2) type of produced modules, 3) type of modular construction project, 4) responsibility for activities of modular construction projects, 5) scheduling software used, 6) synchronization of onsite and offsite schedules, 7) collecting productivity rates for onsite and offsite construction, 8) type of project delivery system, 9) type of procurement method, 10) type of contracts, 11) square footage for modular projects, 12) difficulties in modular projects, 13) distance between manufacturing facility and project construction site, 14) average transportation cost, 15) crane type, 16) daily placing rate, 17) average lifting capacity for crane, and 18) BIM applications and software.

Modular construction proved to be the most promising offsite construction category. Percentage of responses for utilizing modular, prefabricated components, panelized, hybrid and bathroom pods was 77.8, 48.1, 37, 35.2, and 24.1% , respectively. Steel was found the dominant material type with 79.6% of the responses when comparing to 63 and 27.8% for wood and concrete, respectively. Emerging materials such as polyurethane foamed panels, glass reinforced polymers (GRP), and aluminum received 3.8, 1.9, and 1.9 % of the responses, respectively. Nearly half of the respondents indicated that daily placing rate for modules onsite (lifted modules per day) ranges between 5 to 10 and that hydraulic truck cranes are utilized for this mission. Majority of modular and offsite projects utilized design build (DB) as a project delivery system. This result matches Smith's (2010) conclusions that DB facilitates early decision making, required by modular construction to improve constructability and coordination. Design bid build (DBB) contracts declined steadily in use, while integrated project delivery (IPD) systems were emerging (Smith, 2010). Logical results were drawn from comparing investigated characteristics based on percentage of responses for DB, DBB, and IPD, while a low number of responses for construction management at risk (CMAR) did not allow for comparing results. For example, percentage of respondents that reported utilizing a bidding strategy of "best value," which combines the two envelopes procedure plus negotiations, was the highest in IPD. DB, DBB, and CMAR descended in percentage in a logical manner, while no lower bidder procedure was utilized with IPD and no personal bidding with DBB. The same logic was found in the percentage of respondents that reported utilizing MS Project for scheduling; 65, 57, and 46% for IPD, DB, and DBB, respectively. This is because MS Project increases interoperability among project stakeholders, by its popularity which is mostly needed in IPD. Importance of adequate scheduling was investigated by studying synchronization of offsite and onsite schedules and for collecting productivity rates of offsite and onsite operations. Percentage of responses for schedules synchronization was 87, 82, and 72% respectively. Percentage of responses for collecting productivity rates of IPD, DB, and DBB contracts was 73, 61, and 28% , respectively. This indicates that IPD contracts have the best scheduling features that fit short schedules of modular construction. Percentage of responses for BIM utilization followed same increase trend as IPD: 57, 48 and 50% for IPD, DB, and DBB, respectively, due to the need for better collaboration among project stakeholders for IPD contracts. Using popular BIM software was found to facilitate this collaboration. Revit was commonly utilized for modular construction with 64, 61, and 56% of the responses for IPD, DB, and DBB, respectively. Nearly half of the respondents considered computer numeric control (CNC) of manufacturing processes and virtual reality (VR) goggles as the future applications of their operations, while 42, 42, and 28% of the respondents considered radio-frequency identification (RFID), 3D printing, and 3D point cloud technologies, respectively. Obstacles and difficulties faced by modular builders were ranked based on percentage of respondents who reported the following: 1) contractors experience is not enough in applying modularization (61.5%), 2) design scope was not frozen early in project schedule (50%), 3) onsite and offsite schedules were not synchronized (34.6%), 4) module envelope limitation (dimensions limitation) restricted architectural design (32.7%), 5) scheduling method utilized was not suitable for project (7.7%), 6) selected project delivery system was not suitable for project (5.8%), and 7) attitudes of public inspectors (1.9%). Commonly experienced distance between manufacturing facility and construction site was investigated by clarifying two limits (minimum and maximum) as well as its relative average costs per module square footage.

3.3 Second part (barriers to increased market share)

3.3.1 First hypothesis (negative stigma)

More than half of the respondents agreed that there is negative stigma associated with modular construction. This was attributed to the misconception that modular is intended primarily for temporary, single-storey applications. Percentage of responsdents which agreed that significant advantages of modular construction were not communicated properly with owners was 70%. While 80% of the respondents agreed that there is a shortage of well-designed marketing campaigns conducted by modular institutions and manufactures and 90% agreed that owners are not familiar with the different products offered by the modular industry. Most respondents also agreed that there is lack of academic research highlighting the advantages of modular construction. Respondents suggested conducting international cooperation for all parties of modular construction industry to show American and Canadian ideas to the European industry and vice versa. They also suggested establishing an advertisement campaign in North America for modular construction to communicate the pros and cons of modular construction in terms of quality, environment, flexibility in design, and ROI. Engaging industry and academic partners was also suggested for strategic planning of research and development of modular construction as well as offering university and training courses.

3.3.2 Second hypothesis (shortage of examples of past success)

Most respondents agreed that there is lack of promotional materials that depict successes and advantages of modular construction. They also agreed that there is a lack of worldwide documentation for lessons learned and owner knowledge about modular construction compatibility with different structure types and materials. Respondents also agreed on a lack of government-sponsored case studies that highlight obstacles and opportunities for modular construction and available data to support decision making. Respondents recommended that MBI, PreFab Australia, and PreFab New Zealand produce more publications highlighting modular construction advantages, outreach to owners to convince them of advantages, education for architects, the use of social media for marketing, and that online modular construction courses be offered. They also recommended institutes and universities publish more papers, highlight modular advantages in academic courses, and promote modular advantages to authorities. In May 2017, MBI and Clemson University developed a new online course for modular construction after developing a textbook for this course named “Introduction to commercial modular construction” (2015). Meanwhile, PreFab Australia publishes a bi-monthly magazine named “Built Offsite” to highlight offsite construction case studies, developments, and advantages in Australia and New Zealand (2017).

3.3.3 Third hypothesis (standards and regulations)

Most respondents disagreed that existing regulations were not obstacles for the modular industry. Percentage of respondents who agreed that transportation regulations affect cost, time, and design of modular construction was 83.6%. Respondents recommended that MBI, PreFab Australia, and PreFab New Zealand support the use of a separate design code for modular construction and to contact governments at all levels to lobby for modular friendly regulations as well as educate the modular construction inspection community. They also recommended institutes and universities develop research that ties codes and standards with modular construction theoretical backgrounds, while finding gaps between modular construction and current standards, as well as introducing modular concepts to architectural departments. In fact, PreFab Australia partnered with Monash University, Modular Construction Codes Board (MCCB), Government of Victoria, Engineers Australia, and Australian Steel Institute to develop a handbook for design of modular structures (2017). In June 2017, MBI and International Code Council (ICC) developed a series of modular-themed guidelines and resources to help code officials become better informed of offsite construction process. Canadian manufactured housing institute CMHI and MHICanada created the modular construction council of the Canadian Home Builders Association (CHBA) to monitor and participate in developing codes, standards and regulations, liaising with code governmental officials, regulatory bodies, related organizations, and the public, as well as facilitating research to identify technical problems and supporting development of codes and standards. The first meeting of the Modular Construction Council was in May 2017 in St. John's, Newfoundland and Labrador.

3.3.4 Fourth hypothesis (procurement strategies)

Most respondents agreed that modular construction imposes changes in perception of ownership when comparing to traditional construction. They also agreed that the project execution plan has to be communicated up front and incorporated into the bidding process due to the nature of the modular industry, which freezes design in the early stages of a project while having short schedules. Respondents recommended that MBI, PreFab Australia, and PreFab New Zealand develop codes and standards that consider procurement regulations for modular construction while increasing credibility of suppliers. It was also suggested that procurement strategies of solar/renewable energy industries be studied as examples of applying innovative procurement, financing and insurance solutions. They also recommended institutes and universities develop new procurement methods that account for modular construction characteristics. Another recommendation was that more research and publications be conducted to demonstrate the value of automated production, quality control, and the strength of modular construction versus stick built.

3.3.5 Fifth hypothesis (project financing)

Most respondents agreed that predictability of cost and schedule offers the modular industry advantages over conventional construction and that a lower level of risk associated with modular construction encourages stakeholders to adopt new payment methods. Respondents recommended that MBI, PreFab Australia, and PreFab New Zealand cooperate with financial houses to create financial models that consider characteristics of modular construction as well as create special conferences for lenders. They also suggested creating special lending institutions while lobbying for banks to change lending policies for modular builders and to convince insurance companies to insure modular buildings at a lower rate. They also recommended institutes and universities design lending programs and cost management methods that account for the characteristics of modular construction.

Chapter 4: Methodology

4.1 Introduction

This chapter describes the five main developed models designed to study the configuration of modular and hybrid construction, integrated scheduling of offsite and onsite construction, optimization of repetitive scheduling, and dynamic tracking and control of developed schedules, as shown in the general esearch ramework in Figure 1.1. The first model for configuration of modular construction integrated five newly developed indices named connections index (CI), transportation dimensions index (TDI), transportation shipping distance index (TSDI), crane cost penalty index (CCPI), and concrete volume index (CVI) into newly developed unified modular suitability index (MSI). The five developed indices represent the most influencing factors found in literature which affect modular configuration. The second model presented a systematic procedure to identify the most suitable configuration for each type of module (i.e. panels) for hybrid construction based on actual production of a manufacturing facility in Edmonton, Alberta. This procedure identifies the most common panel size after checking four constraining factors which are architectural, structural, manufacturing, and transportation constraints. This framework helps offsite construction stakeholders in designing their production and manufacturing facility according to the logical aforementioned constraints. The third model presented a generic integration of LSM and CCPM to create a new scheduling method that suits repetitive projects. It produced an integrated overall schedule for modular and offsite construction. The case study related to this module is described in Chapter 6 to illustrate the features embedded in this method such as the insertion of a resource conflict buffer (RCB) and identification of multiple critical sequences which are constrained by controlling resources.

The fourth model presented a newly developed multi-objective optimization method using GA for time, cost, and work interruptions for repetitive scheduling while considering uncertainties associated with different input parameters. The fifth module introduced a new method for project tracking and control of integrated offsite and onsite activities in modular construction that considered practical characteristics associates with this industry. This method embraces BIM and integrates LPS, LSM, and CCPM. Figure 1.1 illustrates schematically how the five models are organized after the literature review and questionnaire survey on modular and offsite construction were conducted.

4.2 Near optimum selection of module configurations

Offsite construction prefabricated systems vary depending on the size of the prefabricated components which affect the need for onsite construction. Modular construction system has great potential as an emerging technology after being utilized successfully in shipbuilding and automotive industries, since modular construction has the highest proportion of offsite manufacturing between all offsite construction systems. This thesis presents a novel methodology for near optimum selection of module configuration. The methodology addresses the lack of knowledge by architects about the limitations of the manufacturing process of the modules, which was identified in an earlier study (Schoenborn, 2012). In fact, it is recommended that architects design modules as production designers to standardize the process of module manufacturing (Smith, 2010). The developed methodology was accomplished by considering a set of practical constraints and factors that affect module configuration such as the connections limitation, transportation and weights limitations, crane cost limitation, and the required concrete quantities for project foundation. It utilized five indices, which account for connections of modules onsite (CI), transportation of fabricated modules to construction jobsite (TDI and

TSDI), crane operating condition and related cost (CCPI), and project concrete foundation (CVI). These developments were described in a published paper by Salama et al. (2017c) and presented subsequently.

4.2.1 Connections Index (CI)

The presented CI accounts for connections quantity and cost implications of modules' connections to compare between different modular construction designs and identify suitability of design and configuration of project modules. A connections cost penalty is simply the summation of the calculated hypothetical cost penalties. Hence, it is the summation of half of the hypothetical cost penalties indicated in the symmetrical clustered matrix. The CI is calculated by indexing/dividing connections cost penalties for any design over the least possible connections cost penalties for alternative modular design that has the same plan area in any city, as shown in Equation 4.1:

$$CI = \frac{\sum \text{connections cost penalties}}{\text{least possible connections cost penalties for other design}} \qquad \text{Equation 4.1}$$

Investigating module's main connection types is necessary to reach a full understanding of the modular construction process as well as for assigning needed resources and costs for each connection existing in the modular design. It is also essential in identifying and comparing the suitability of modular design and configuration of modules. Connection types depend on module material whether it is a wooded, steel, or precast module. Connection types are also different from manufacturer to manufacturer and are based on the practices of each manufacturer. The connections studied in this research were designed for steel modules of Kullman Buildings Corporation (KBC).

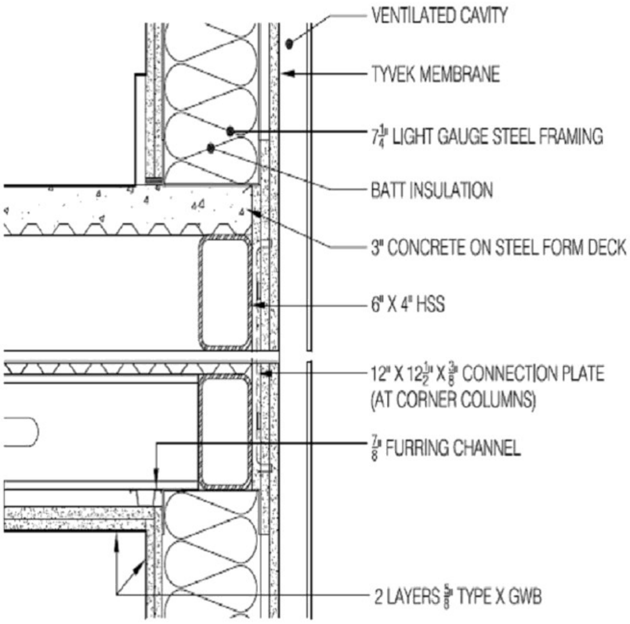


Figure 4.1: External connection side view (Garrison and Tweedie 2008)

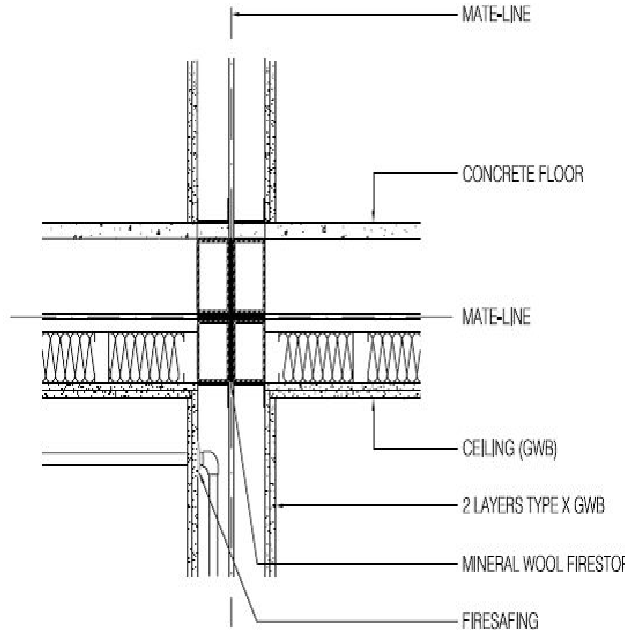


Figure 4.2: Internal connection plan view (Garrison and Tweedie 2008)

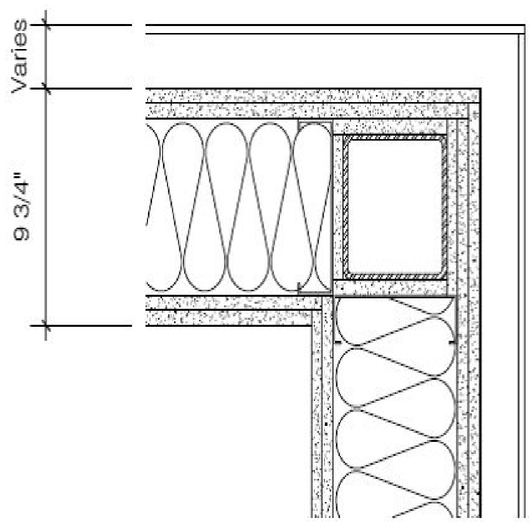


Figure 4.3: Corner connection details (Garrison and Tweedie 2008)

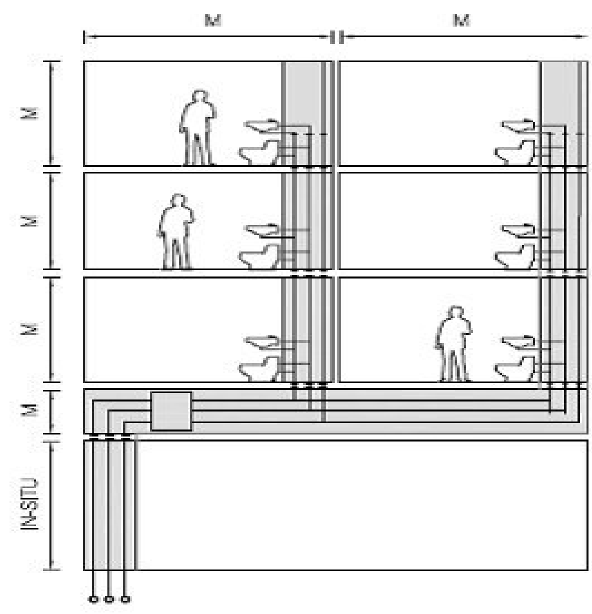


Figure 4.4: Mechanical, electrical, and plumbing (MEP) connection between vertically aligned modules. (Garrison and Tweedie 2008)

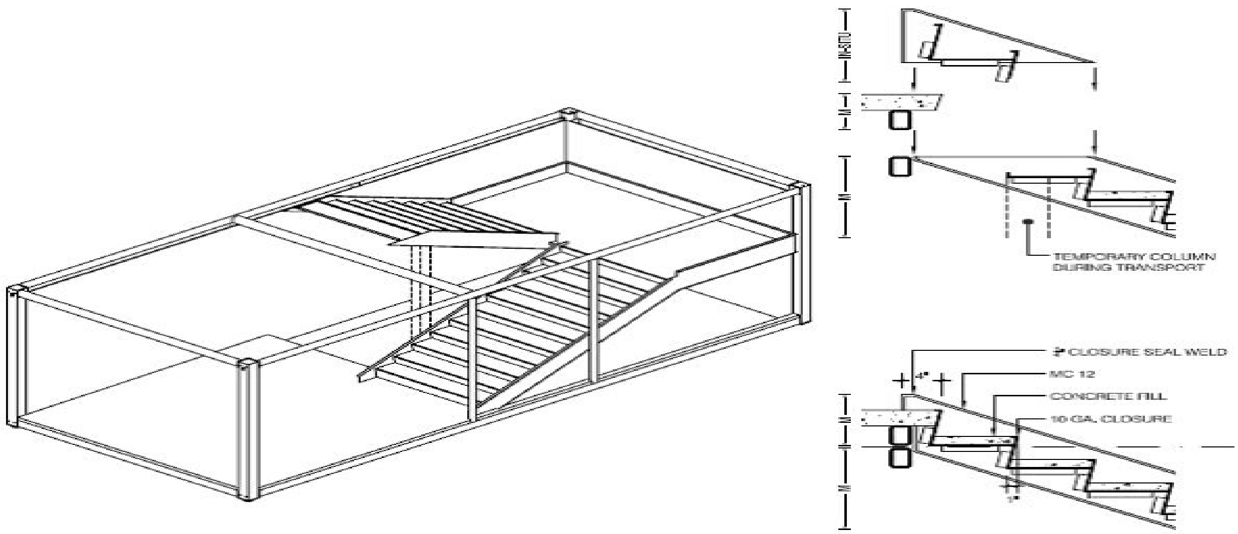


Figure 4.5: Vertical circulation connection details (Garrison and Tweedie 2008)

The main types of connections considered were external, internal, corner, vertical circulation, mechanical, electrical, and plumbing connections, as shown in Figures 4.1 to 4.5. Reducing the number of modules in any modular design is cost efficient as long as transportation limitations are satisfied. 4.5. Reducing the number of modules in any modular design is cost efficient as long as transportation limitations are satisfied. This is because increasing connections of modules increases construction and maintenance costs and requires more lifts by the crane as well as more trucks for transportation. Most of modular construction contractors do not identify cost of module connections separately and the pinning costs of these connections are usually included within the cost of installing the nearest structural element. However, analyzing costs of module connections is very beneficial to understand how each connection adds penalty costs due to installation, material, and maintenance. Two different modular designs with identical plan areas were used to analyze module connections, as illustrated in Figure 4.6.

Each design consists of three stories, however, design A comprises 18 modules, as shown in Table 4.1, which require 16 truckloads and would take two days for the crane onsite to set them into their positions. While, design B comprises only nine modules, which require only eight truckloads and would take only one day for the onsite crane to set them into their final positions. The red lines in Figure 4.6 refer to module interfaces and the red circles refer to module connection positions. Cost efficient configuration of modules depends on connections cost, number of transportation trucks, and cost of onsite crane. The optimum module configuration should target fewer connections and module interfaces. The proposed CI asseses modular suitability through evaluating and comparing the connections in each modular design.

Matrix clustering technique was used in a previous study (Lapp and Golay, 1997) to identify modularity advantages for modular nuclear power plants The same technique was used in this research to analyze the interdependencies between residential modules after configuring and quantifying the connection type between them. The importance of the developed matrices for project stakeholders was to assign priority to some module interfaces regarding resources and budget allocation. The modules were clustered as per the following steps:

1) Arbitrary cost penalties were assigned hypothetically to demonstrate the use of developed methodology. Penalties assigned to each connection type were included in Table 4.2 to quantify modules interfaces' connections;
2) All the identified connections were multiplied by their assumed arbitrary cost penalty for all module interfaces to reach the unclustered cost penalty matrix, as presented in Table 4.3;
3) Rows and columns of the unclustered matrix were reordered to cluster the array of connections' cost penalties with large values. This task was accomplished by multiplying

element a(ij) of the matrix by the sum of the elements surrounding it to the left, right, top, and bottom (McCormick et al., 1969), as illustrated in Figure 4.7. Then, the over rows (or columns) of the multiplications were summed to acquire the bond energy algorithm (BEA) value. Afterwards, the rows and columns were reordered within the matrix until this reordering gave the largest BEA value. Taking into consideration that optimal matrix clustering is obtained by reaching the maximum measure of effectiveness (ME), where the ME is identified as follows:

a- Assuming that the relationships matrix's dimension M by N with non-negative elements a(ij);

b- Identifying the quantity A (ij) as indicated in Equation 4.2:

$$A_{ij} = 0.5 \times [\, a_{i+1,j} + a_{i-1,j} + a_{i,j+1} + a_{i,j-1} \,].$$ Equation 4.2

c- Identifying the measure of effectiveness (ME) as indicated in Equation 4.3:

$$ME = \sum All\ i, j \left[a_{ij} \times A_{ij} \right]$$ Equation 4.3

4) Representing the final clustered matrix as presented in Table 4.4.

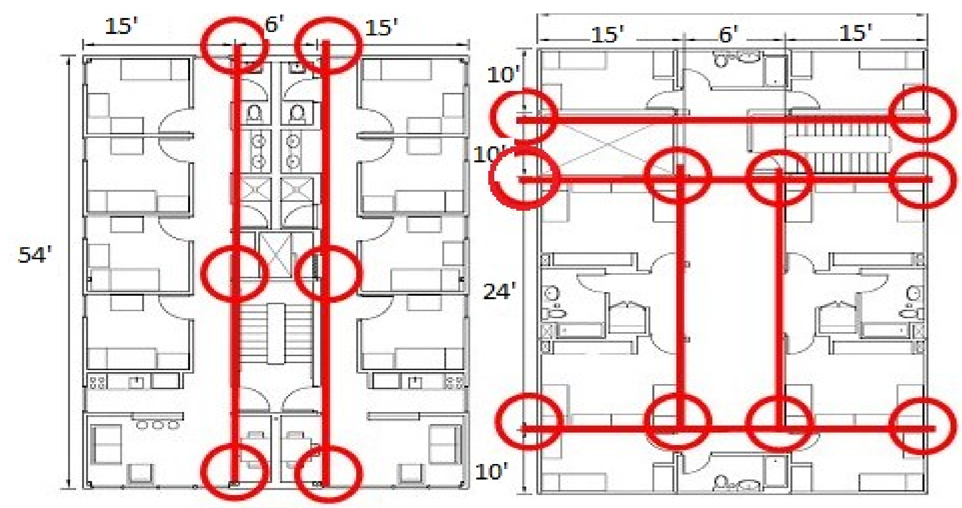


Figure 4.6: Design A to the right, and design B to the left (Cameron and Carlo, 2007)

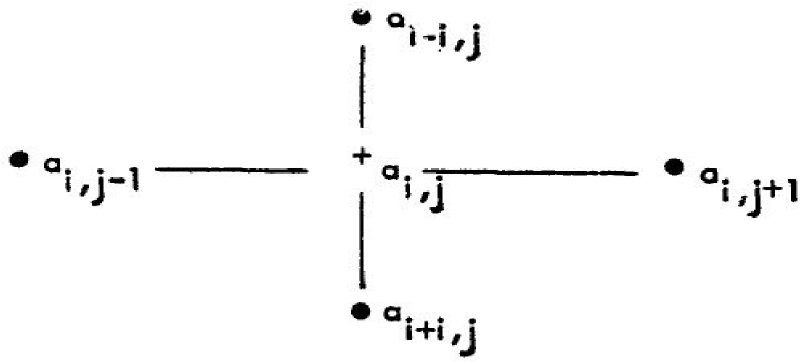


Figure 4.7: Representation of Bond Energy ME (Lapp and Golay, 1997)

Table 4.1: Numbering of modules for design A

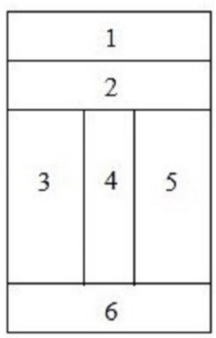
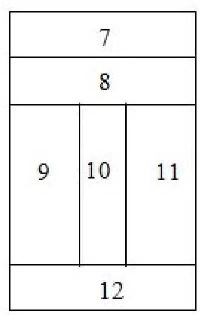
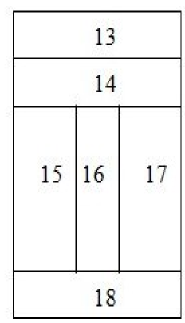
First Floor	**Second Floor**	**Third Floor**
		

Table 4.2: Connection codes and their arbitrary cost penalty

Connection	**Code**	**Arbitrary Cost Penalty**
External connection	1	20
Internal connection	2	15
MEP connection	3	10
Vertical circulation connection	4	20
Corner connection	5	10

Module connection cost penalty clustering is beneficial in prioritizing the resource assignment to certain connections and interfaces depending upon its priority, as illustrated in Table 4.4. The capability of this technique is beneficial when analyzing more complex modular construction projects that need robust budget and resources allocation based on the priority of each grouped interfaces. This priority can be noticed when comparing the clusters of modules number 2, 7, 8, 13, and 14 to the clusters of modules 16 and 18, since the first clustering group has higher cost penalty values for connections than the second clustering group where the clustering group area is bigger. This means it requires that more attention be paid towards its cost and construction.

Comparing the nature of clusters complexities between modular projects is another advantage of using this technique. Finding less complicated clusters would be the optimum solution for any modular project, leading to less complex modular design and construction. More complex clusters means that many resources and trades will be needed to work on the same module interface and coordinating such complex resources and trades takes more effort and time.

4.2.2 Transportation Dimensions Index (TDI)

Modular transportation and trucking plans include many studies of transportation methods, transportation routes, and transportation handling equipment. However, “the first design parameter established for a modularized plant is the maximum size and weight of a module that is practical and economical to transport from its construction yard to the plant site" (Bolt and Arzymanow, 1982). Minimizing the number of modules (boxes) that should be manufactured for any modular construction project is a clear economical solution for modular designs, since the most cost efficient module is the largest module that could be transported with the most amount of interior finishes. Hence, designing fewer larger modules is more advantegous than smaller modules because there is less cost when getting more square footage per truckload (Cameron and

Carlo, 2007). Transportation routes control affects practical module dimensions, since some routes require different transportation ways from the manufacturing facility to the construction site. Such intermodal transportation requires a great deal of planning and coordination since size constraints is different from shipping method to another and from a state to another.

Currently, there are many ways of transporting manufactured modules such as trucks/trailers, railways, and boats. The main advantage of railway transportation is its capabilities to transport heavier truckloads and it should be considered as an alternative if its location is close to the manufacturing facility or construction site. It can transport an 11-ft wide module without permits and modules with 11 to 14-ft width with a permit. However, if a modules' width is 14-ft or more, a special train will be needed to run on its own without the convoy (Smith, 2010). Railway height constraint is17-ft from the top of the rail and railcars can accommodate modules up to 88-ft in length (Smith, 2010). However, the major disadvantage of railways is their higher overall cost as compared to regular trucks. Moreover, transporting offsite construction by boat is more affordable but transit time on the ocean may affect overall project schedule.

International intermodal transportation for offsite construction may use the three aforementioned ways of transportation in one route, especially for rural areas. In that case, the minimum practical dimensions for the three ways of transportation are used to reduce any transportation conflicts.

For local transportation, the most commonly used way of transportation is by truck. Accordingly, trucks and their related limitations were considered in the developed methodology. There are three standard types of trailers used to transport manufactured modules and their limitations are described in a previous study conducted in Utah (Smith, 2010):

Table 4.3: Quantifying module interfaces' connections for unclustered matrix of Design A. Number of connections *(Connection Code)

Module #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	2(1)+2(4)	0	0	0	0	2(1)+2(4)+2(5)+1(3)	0	0	0	0	0	0	0	0	0	0	0
2	2(1)+2(4)	1	1(1)	0	1(1)	0		4(1)+2(4)	0	0	0	0	0	0	0	0	0	0
3	0	1(1)	1	3(3)	0	1(1)+1(2)	0	0	2(1)+2(2)+1(3)	0	0	0	0	0	0	0	0	0
4	0	0	3(3)	1	2(2)	2(2)	0	0	0	4(2)	0	0	0	0	0	0	0	0
5	0	1(1)	0	3(3)	1	1(1)+1(2)	0	0	0	0	2(1)+2(2)+1(3)	0	0	0	0	0	0	0
6	0	0	1(1)+1(2)	2(2)	1(1)+1(2)	1	0	0	0	0	0	2(1)+2(4)+2(5)+1(3)	0	0	0	0	0	0
7	2(1)+2(4)+2(5)+1(3)	0	0	0	0	0	1	2(1)+2(4)	0	0	0	0	2(1)+2(4)+2(5)+1(3)	0	0	0	0	0
8		4(1)+2(4)	0	0	0	0	2(1)+2(4)	1	1(1)+1(2)	0	1(1)+1(2)	0		4(1)+2(4)	0	0	0	0
9	0	0	2(1)+2(2)+1(3)	0	0	0	0	1(1) +1(2)	1	2(2)	0	1(1)+1(2)	0	0	2(1)+2(2)+1(3)	0	0	0
10	0	0	0	4(2)	0	0	0	0	2(2)	1	2(2)	2(2)	0	0	0	4(2)	0	0
11	0	0	0	0	2(1)+2(2)+1(3)	0	0	1(1) +1(2)	0	2(2)	1	1(1)+1(2)	0	0	0	0	2(1)+2(2)+ 1(3)	0
12	0	0	0	0	0	2(1)+2(4)+2(5)+1(3)	0	0	1(1)+1(2)	2(2)	1(1)+1(2)	1	0	0	0	0	0	2(1)+2(4)+2(5)+1(3)
13	0	0	0	0	0	0	2(1)+2(4)+2(5)+1(3)	0	0	0	0	0	1	2(1)+2(4)	0	0	0	0
14	0	0	0	0	0	0		4(1)+2(4)	0	0	0	0	2(1)+2(4)	1	1(1)	0	1(1)+1(4)	0
15	0	0	0	0	0	0	0	0	2(1)+3(2)+3(3)+	0	0	0	0	1(1)	1	2(2)	0	1(1)+1(2)
16	0	0	0	0	0	0	0	0	0	6(2)	0	0	0	0	3(3)	1	1(2)+1(4)	2(2)
17	0	0	0	0	0	0	0	0	0	0	2(1)+3(2)+3(3)+	0	0	1(1)	0	3(3)	1	1(1)+1(2)
18	0	0	0	0	0	0	0	0	0	0	0	2(1)+2(4)+2(5)+1(3)	0	0	1(1)+1(2)	2(2)	1(1)+1(2)	1

Table 4.4: The clustered cost penalty matrix for Design A

Module #	13	8	14	7	2	1	9	15	3	10	12	6	18	16	11	4	5	17
13	1	0	80	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1	120	80	120	0	35	0	0	0	0	0	0	0	35	0	0	0
14	80	120	1	0	0	0	0	20	0	0	0	0	0	0	0	0	0	40
7	110	80	0	1	0	110	0	0	0	0	0	0	0	0	0	0	0	0
2	0	120	0	0	1	80	0	0	20	0	0	0	0	0	0	0	20	0
1	0	0	0	110	80	1	0	0	0	0	0	0	0	0	0	0	0	0
9	0	35	0	0	0	0	1	80	80	30	35	0	0	0	0	0	0	0
15	0	0	20	0	0	0	80	1	0	0	0	0	35	30	0	0	0	0
3	0	0	0	0	20	0	80	0	1	0	0	35	0	0	0	30	0	0
10	0	0	0	0	0	0	30	0	0	1	30	0	0	60	30	60	0	0
12	0	0	0	0	0	0	35	0	0	30	1	110	110	0	35	0	0	0
6	0	0	0	0	0	0	0	0	35	0	110	1	0	0	0	30	35	0
18	0	0	0	0	0	0	0	35	0	0	110	0	1	30	0	0	0	35
16	0	0	0	0	0	0	0	45	0	60	0	0	30	1	0	0	0	35
11	0	35	0	0	0	0	0	0	0	30	35	0	0	0	1	0	80	80
4	0	0	0	0	0	0	0	0	30	60	0	30	0	0	0	1	30	0
5	0	0	0	0	20	0	0	0	0	0	0	35	0	0	80	30	1	0
17	0	0	40	0	0	0	0	0	0	0	0	0	35	35	80	0	0	1

1- Standard flatbed trailer: A two-axle trailer used when weight and height are not an issue. The trailer bed is 8-ft, 6 in. wide and 48-ft long, though the maximum module height is limited to 8-ft, 6 in. because the bed is so high off the ground. Using this trailer, the module maximum weight is 48,000 lbs;

2- Single-drop deck/ trailer: Can be two or three axles which has a single-drop deck. In a triaxle single-drop deck trailer, the module length can reach 50 ft., a width of 13-ft, and a height of 12-ft. When using this trailer, the module maximum weight ranges from 44,000 to 45000 lbs;

3- Double-drop deck/trailer: Known in the market as the "lowboy," and its main advantages are that it is able to transport higher loads without permitting as well as providing extra feet of height for modules due its lower bed. The module length can reach 40 ft, a width of 13 ft, and a height of 15-ft, 6 in.

These limitations are different from one state/priovince to another and should be checked before planning any transportation routes between different states. For practical optimization of modules' dimensions, limitations of trailers' dimensions should be integrated with commercial trucking regulations such as those stipulated by two agencies in the US. The first is at the federal level—(federal size regulations for commercial motor vehicles), US Department of Transportation, Federal Highway administration (FHWA)—and the second is at the state level. In Canada, every province has its own stipulated regulations according to the department of transportation's (DOT) published regulations and to "the heavy truck weight and dimension limits for interprovincial operations memorandum of understanding" published by the Council of Ministers responsible for Transportation and Highway Safety in Canada (Report for Heavy Truck Weight, 2014).

In the US and Canada, every state/province has three categories for shipping dimensions. The first is legal dimensions, which do not require any permits and the second is oversized permitted shipments that require routine trucking permits for usual oversized shipments. These permit fees are marginal when compared to overall shipping cost. The third is super load shipments for unusual module dimensions or weights and requires special permits.

The legal dimensions for a semitrailer in Utah, for example, are 14-ft for height, 8-ft, 6in. for width, and 48-ft for length (Smith, 2010), knowing that these legal dimensions are different from one state to another and are updated with changes from time to time. The oversized permitted dimensions in Utah are 14-ft for height, 14-ft, 6 in. for width, and 105-ft for length (Smith, 2010). Hence, modular manufacturers tend to pay for marginal permits to get the extra 6-ft of width in particular because the room width architecturally cannot depend on the allowable legal width of 8-ft, 6in. A list of truck transportation regulations was developed by KBC, as shown in Figure 4.8, which identifies dimensional requirements and indicates possible special permits or escorts for over-dimensioned loads.

Considering cost of renting the three standard types of trailers depicted in Figure 4.9, the lowest trailer rental cost is the standard flatbed trailer, followed by the single-drop deck, and the highest rental cost being the double-drop deck. Moreover, the standard flatbed trailer might enable a better length for module transportation though its limitations regarding module width and height makes the single-drop deck a better alternative. However, the double-drop deck would allow modules to have a heavier weight and an extra one ft of module height. In addition, this trailer has the same width limitations as the single-drop deck and its allowable module length is less than the single-drop deck by 10ft, as shown in the Figure 4.10, as well the highest rental cost among all trailers. Hence, the single-drop deck is the most commonly used alternative between the three types of trailers for module transportation, unless the module has overweight components, in that case, the double-drop deck is the best alternative.

Based on the aforementioned facts, the optimum residential modules' dimensions are in line with the modular builders contribution to "the guide to modular design and construction" (Smith, 2010), as presented in Table 4.5. This research presents a TDI to represent the dimensional optimality of a module in conjunction with its cost per sq. ft per truckload and the number of modules in the project, as presented in Equation 4.4. Equation 4.5, represents a simplified form of Equation 4.4, which can be used to calculate the TDI as the sum of all ratios of modules divided by the total number of modules in the design being considered. Each module ratio is calculated as the ratio of the square footage of a truck over the module square footage of that module, as follows:

$$\text{TDI} = \frac{1}{\text{number of modules}} \times \sum \frac{\text{proposed module design square footage cost per truckload}}{\text{Truck square footage cost per truckload}} \qquad \text{Equation 4.4}$$

$$\text{TDI} = \frac{1}{\text{number of modules}} \times \sum \frac{\text{Truck square footage}}{\text{Module square footage}} \qquad \text{Equation 4.5}$$

State	Width	Height	Length	State	Width	Height	Length
Alabama	12' (16')	* (16')	76' (150')	Montana	12'-6" (18')	* (17')	* (120')
Alaska	10' (22')	*	100' (*)	Nebraska	12' (*)	14'-6" (*)	85' (*)
Arizona	11' (14')	* (16')	* (120')	Nevada	8'-6" (17')	* (16')	105' (*)
Arkansas	12' (20')	15' (17')	90' (*)	New Hampshire	12' (16')	13'-6" (16')	80' (100')
Califonia	12' (16')	* (17')	85' (135')	New Jersey	14' (18')	14' (16')	100' (120')
Colorado	11' (17')	13' (16')	85' (130')	New Mexico	* (20')	* (18')	* (190')
Connecticut	12' (16')	14' (*)	80' (120')	New York	12' (14')	14' (*)	80' (*)
Delaware	12' (15')	15' (17'-6")	85' (120')	North Carolina	12' (15')	14'-5" (*)	100' (*)
District of Columbia	12' (*)	13'-6" (*)	80' (*)	North Dakota	14'-6" (18')	* (18')	75' (120')
Flordia	12' (18')	14'-6" (18')	95' (*)	Ohio	14' (*)	14'-10" (*)	90' (*)
Georgia	12' (16')	15'-6" (*)	75' (*)	Oklahoma	12' (16')	* (17')	80' (*)
Idaho	12' (16')	14'-6" (16')	100' (120')	Oregon	9' (16')	*	95' (*)
Illinois	* (18')	* (18')	* (175')	Pennsylvania	13' (16')	14'-6" (*)	90' (160')
Indiana	12'-4" (16')	14'-6" (17')	90' (180')	Rhode Island	12' (*)	14' (*)	80' (*)
Iowa	8' (16'-6")	14'-4" (20')	85' (120')	South Carolina	12' (*)	13'-6" (16')	(125')
Kansas	* (16'-6")	* (17')	* (126')	South Dakota	10' (*)	14'-6" (*)	*
Kentucky	10'-6" (16')	14' (*)	75' (125')	Tennessee	10' (16')	15' (*)	75' (120')
Louisana	10' (18')	* (16-'5")	75' (125')	Texas	14' (20')	17' (18'-11")	110' (125')
Maine	8'-6" (18')	8'-6" (*)	80' (125')	Utah	10' (17')	16' (17'-6")	105' (120')
Maryland	13' (16')	14'-6" (16')	85' (120')	Vermont	15' (*)	14' (*)	100' (*)
Massachuetts	12' (14')	13'-9" (15')	80' (130')	Virginia	10' (*)	15' (*)	75' (150')
Michigan	12' (16')	14'-6" (15')	90' (150')	Washington	12' (16')	14' (16')	*
Minnesota	12'-6" (16')	*	95' (*)	West Virgina	10'-6" (16')	15' (*)	75' (*)
Mississippi	12' (16'-6")	* (17')	53' (*)	Wisconsin	14' (16')	*	80' (110')
Missouri	12'-4" (16')	15'-6" (17'-6")	90' (150')	Wyoming	* (18')	* (17')	* (110')

Figure 4.8: Module dimensions regulations for truck transportation according to the state (Garrison and Tweedie, 2008) * () indicates maximum possible dimension required for permits or escorts

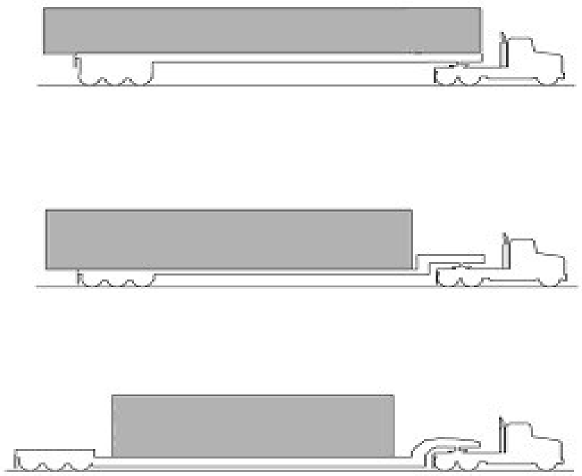


Figure 4.9: The three standard types of trailers used to transport modules; Top: standard flatbed trailer; Middle: single-drop deck; and Bottom: double-drop deck (Smith, 2010)

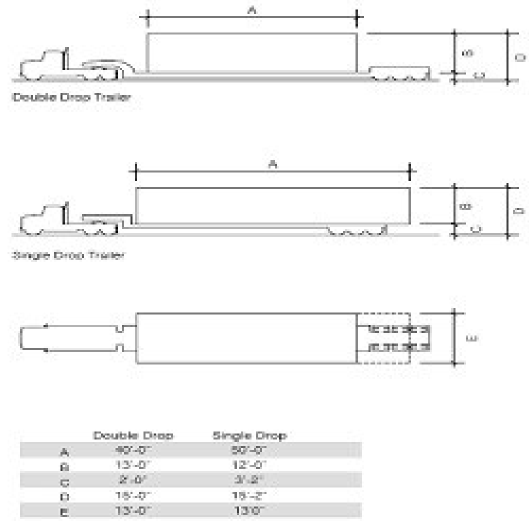


Figure 4.10: Generalized trailers and modules limiting dimensions (Garrison and Tweedie, 2008)

Table 4.5: The optimum residential modules' dimensions

Dimensions	**Common Maximum**	**Oversized Maximum**
Module Width	13 ft	16 ft
Module Length	52 ft	60 ft
Module Height	12 ft	

4.2.3 Transportation Shipping Distance Index (TSDI)

Manufacturing plant locations in relation to construction sites compliment the selection process for the optimum module transportation route, since the locations of manufacturing plants affects the transportation method, module weight, and dimensions. Hence, planning the optimum transportation route has a great effect on selecting the optimum module configuration that has the best manufacturing plant location which will have the least expensive transportation cost to the construction site. Construction sites which are located far from industrialized cities usually have less chance of utilizing offsite construction capabilities. A transportation route study should be conducted to select qualifying manufacturing plants for any project. This study should identify potential obstacles, such as bridges, tunnels, and overhead utilities that might require extra preparation. In fact, the modular construction industry can change the transportation industry due to requests from modular manufacturers to change the allowable weight and dimension limits on highways. In 1985, the Canadian government began to construct the high-load corridor in the province of Alberta, which had overhead utility lines raised to accommodate loads up to 9.0 m to support the increasing transportation demands of modular construction manufacturers in the oil sands industry in Alberta. The high-load corridor is expanded every year by the government and permit fees are collected from the industry to recover its costs, as shown in Figure 4.11.

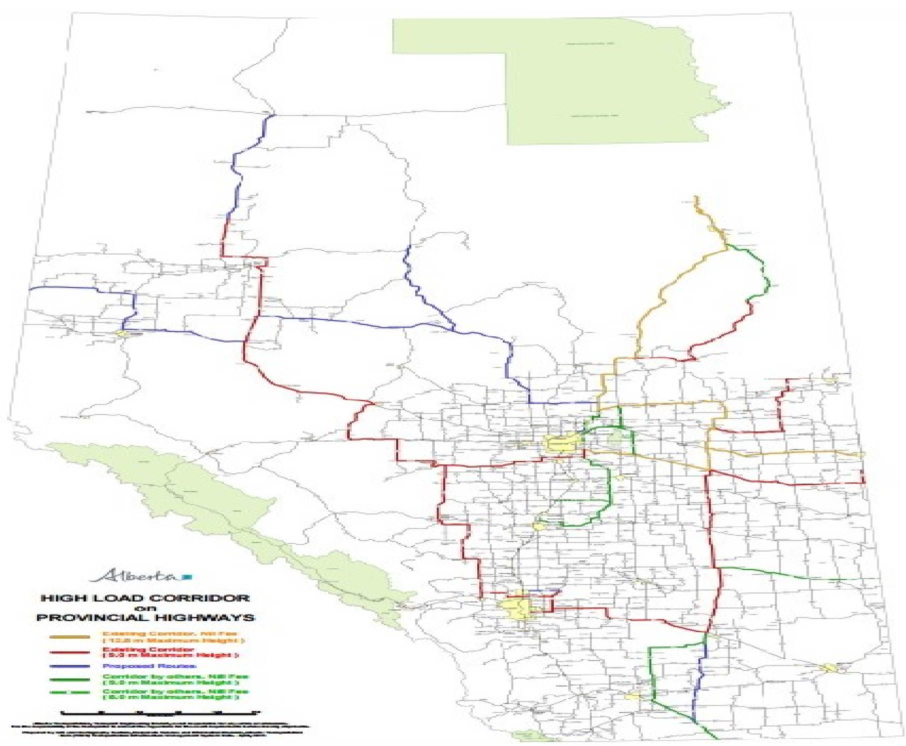


Figure 4.11: High- load corridor on provincial highways in Alberta province, Canada (Transportation Alberta website)

Several studies indicate that the industry generally recognizes 125 miles as the maximum practical distance for modules to travel from manufacturing plant to construction site (Smith, 2010). Moreover, shipping modules become cost prohibitive when they travel more than 150 to 200 miles from manufacturing plant to construction site. In the case of offsite modules with a width of 12-ft or greater, transportation cost increases exponentially (Smith, 2010).

Furthermore, studies indicate an average cost for transporting residential modules that has a width of 8.5 to 12-ft to be $3.27/ sq. ft ., while the average cost for modules with a width greater than 12-ft at $5.00/ sq. ft; however, these average costs reflect the average cost for module transportation without including the cost associated with the distance between manufacturing facility to construction site. Hence, this cost estimate can be used to choose between different manufacturing facilities for supplying modules to construction site based on their distance from the construction site.

This research presents a TSDI, as shown in Equation 4.6, representing the effect of shipping distance from offsite manufacturing/assembly facility to construction site on module transportation cost. The TSDI in this research assumed a practical transportation distance of 125 miles to be the optimum transportation distance and assigned it an optimum transportation value of 1. Any transportation distance up to 200 miles was assigned a transportation value, which is linearly proportional to this optimum transportation value, as follows:

$$\text{TSDI} = \frac{1}{\text{number of modules}} \times \sum \frac{\textit{Transportation value} \times \text{overall truck cost}}{\text{module square footage} \times \textit{average transportation cost}} \quad \text{Equation 4.6}$$

4.2.4 Crane Cost Penalty Index (CCPI)

In the last two decades, the modular construction industry has rapidly gained momentum with the help of advanced computer aided modelling and new heavy lift crane capacities.

This has allowed for constructing larger modules as needed.

Crane cost may range between 3500 to 4500$ per day without counting road permits or closures. Hence, cranes require careful planning so the crane will never be idle (Velamati, 2012). Crane type planning must be made in conjunction with the design of any offsite construction system. The main types of cranes are mobile cranes and fixed tower cranes. Mobile cranes are usually used in modular construction since fixed tower cranes are more expensive when used to lift fewer modules. However, fixed tower cranes can be used if multiple levels of module placement exist. Choosing the right crane requires a comprehensive study of many variables as indicated in a number of previous studies (Han, 2014 and Al-Hussein et al., 2005) such as the required lifting capacity, working radius, lifting height, clearances, and optimal crane path. Boom size also has an effect when choosing the best crane based on the load capacity it can provide. A standard truck-mounted hydraulic crane with a smaller 25 to 70ft boom can handle 22 tons. A 100-ft boom crane can handle 33 tons (Smith, 2010). Selection of crane type is based on weight and reach. However, a rule of thumb in choosing the right crane for a modular construction project is to choose a small and accessible crane to lift multiple modules rather than choosing a large crane to lift one or two lifts.

Generally, modular construction of buildings requires a crane with a capacity of 40 to 75 tons, depending on design (Garrison and Tweedie, 2008). Choosing the right crane requires the definition of average weight of modules per square feet, as well as the largest module onsite, which controls crane capacity. Regular traditional module weight ranges from 10 to 25 tons depending on floor size (Velamati, 2012). Knowing that daily placing rate of modules (i.e. speed of construction) is different from one project to another; this rate can be seven modules per day (Velamati, 2012), or eight modules a day as considered by a Seattle-based modular fabrication facility. In other cases, estimates of 10-12 modules per day were considered (Azari, 2013). This placing rate depends on module dimensions, site constraints, crane capacity, and weather conditions.

The crane cost penalty (CCP) considerered here accounts for crane cost per module, taking into consideration cost of renting the crane per hour including mobilization and demobilization costs, hourly module placing rate, and number of modules in the project as per Equation 4.7. The CCPI was calculated as the ratio of CCP for any design over the least CCP for the same modular design plan area in any city as per Equation 4.8:

$$\mathrm{CCP} = \frac{\text{Crane renting cost per hour} \times \text{number of project modules}}{\text{hourly module placing rate}}$$ Equation 4.7

$$\mathrm{CCPI} = \frac{CCP \quad for\ any\ design}{\text{least CCP for the same plan area}}$$ Equation 4.8

4.2.5 Concrete Volume Index (CVI)

Wooden framed modules in housing construction commonly transfer the load to the foundation uniformly and can result in strip footings. On the other hand, steel framed modules, such as those produced by the KBC generate a point load rather than a distributed load. Hence, perimeter and isolated footings foundation systems are the best solution (Smith, 2010).

Considering steel framed modules, such as those produced by KBC, the more module connections exist in any modular design, the more isolated footings shall be required, as shown in Figure 4.12 and 4.13. Smith (2010) stated that foundations for modular construction can either be piers, linear footings, or continuous footings.

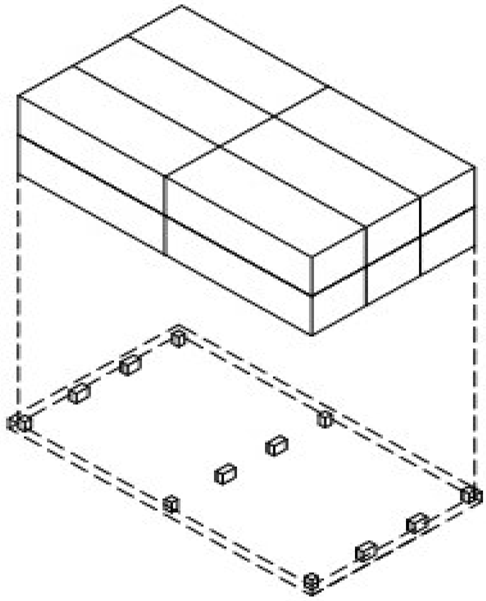


Figure 4.12: Isolated footings for modules' foundation (Garrison and Tweedie, 2008)

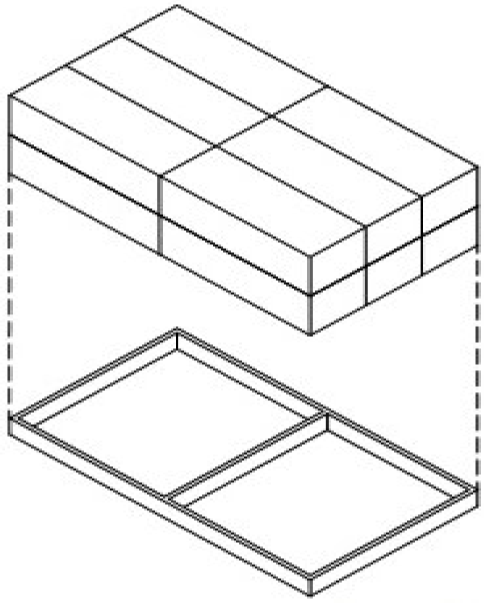


Figure 4.13: Perimeter basement foundation (Garrison and Tweedie, 2008)

This research presents a CVI, which evaluates suitability of a modular design based on required concrete volume. This index accounts for quantities of concrete for the foundation and is referred to in this research as concrete volume. The foundation concrete volume cost (CVC) was calculated for any design using Equation 4.9. The index CVI accounts for volume of concrete used in the project foundations and relates it directly to project cost. The CVI was calculated as the ratio of volume for concrete foundation over the least concrete cost for foundation of each alternative modular building that has same plan area in any city as per Equation 4.10:

$$\mathrm{CVC} = \text{total concrete volume} \times \text{concrete cost per unit volume} \qquad \text{Equation 4.9}$$

$$\mathrm{CVI} = \frac{\mathrm{CVC}\ \text{ for specific design}}{\text{least}\,\mathrm{CVC}\ \text{ for other modular design}} \qquad \text{Equation 4.10}$$

4.2.6 Modular Suitability Index (MSI)

The MSI integrates the above mentioned five indices into one unified index to be used as an indicator of modular suitability based on reducing economic implications for costs of different projects. Modular construction cost needs considerable attention to the process of suitability evaluation of different configurations for modular designs. The integrated MSI was calculated using the weighted sum expressed by Equation 4.11:

$$MSI = (W1 \times CI) + (W2 \times TDI) + (W3 \times TSDI) + (W4 \times CCPI) + (W5 \times CVI) \qquad \text{Equation 4.11}$$

Where, W1 to W5 are the relative weights that account for the preference of project stakeholders. This preference could be based on real data extracted from actual modular projects to make sure that each relative weight does not affect overall modular suitability index more than it should. The integration of the proposed five indices indicates by numbers how modular designs are properly optimized to reach optimum modular overall design based on optimum module configuration. Hence, if the modular design is properly modularized, extra penalty costs should not be generated.

4.3 Developoed model for hybrid construction

This research presents a systematic model that identifies optimal module/panel configuration based on architectural, structural, manufacturing, and transportation constraints, as illustrated in Figure 4.14. The presented model provides a decision support tool that assists project stakeholders to select near-optimum dimensions of panels utilized in hybrid construction in accordance with regulations and standards.

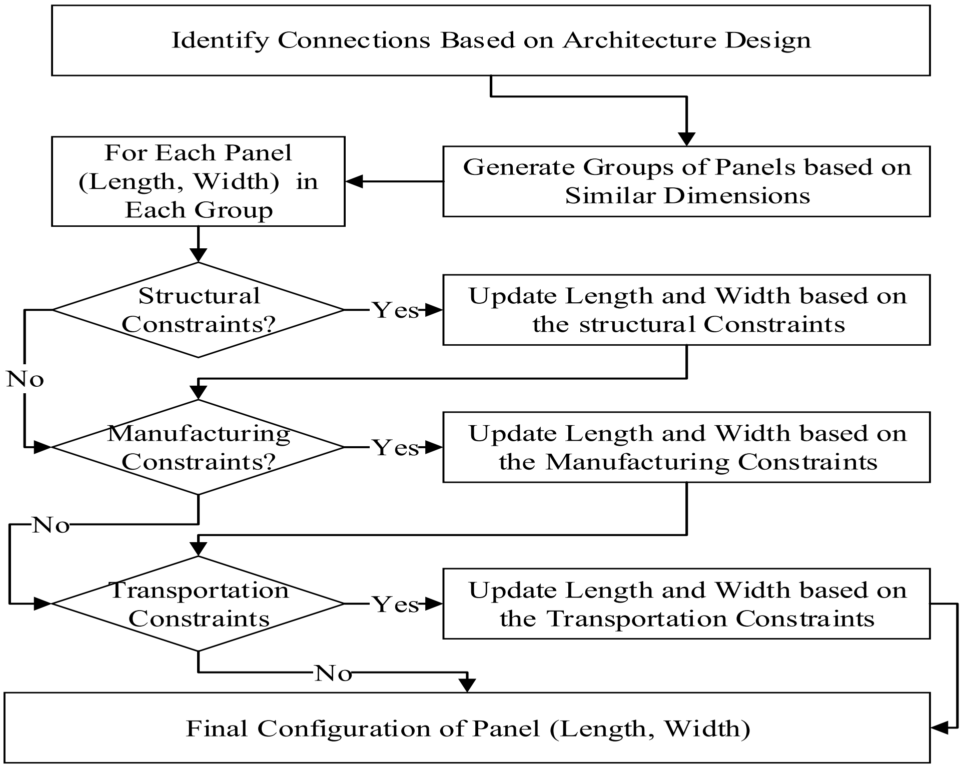


Figure 4.14: Systematic framework for most suitable module/panel configuration

4.3.1 Architectural design check

Building architecture considerably affects the configuration of panels. The hybrid construction approach is based on combining the 3D-modules/units of building high value parts such as kitchens and bathrooms, with long spanned 2D-panels for floors and walls in open areas, such as living rooms and bedrooms. The long span floor cassettes typically span up to 6 m between separating walls or the sides of the modules (Lawson and Ogden, 2008). Hybrid construction flexibility in design is gained from the planar nature of panels where any panel dimension can be manufactured to suit required architectural needs.

There are two main connection types between light steel gauge framing components. The first is the factory production connections and the second is the construction site connections (Lawson et al., 2005). Onsite wall connections can also be classified into two main categories: panel to panel connection and connection between panels and modular units (i.e. kitchen or bathroom). Panel connections have different shapes according to panel type and location, as shown in Table 4.6. Panels were categorized into ten groups in respect to their location: external panels, interior bearing walls, interior non-bearing walls, party, corridor walls, plumbing walls, elevator walls (interior and exterior), and mechanical shaft walls.

Based on panel type and its location, the possible connections based on architectural design were located on panel to panel, panel to modular units, and corner (internal and externals) joints, as indicated by red circles in Figure 4.15. This step identified the width and length of each panel as per architectural constraints using Equations 4.12 and 4.13:

$$W_A = \begin{cases} w, & no\ architectural\ constraints \\ w_A, & architectural\ constraints\ exist \end{cases}$$ Equation 4.12

$$L_A = \begin{cases} l, & no\ architectural\ constraints \\ l_A, & architectural\ constraints\ exist \end{cases}$$ Equation 4.13

Where, w and l represent the initial panel width and length, respectively; w_A and l_A represent panel width and length due to architectural constraints; and W_A and L_A, respectively, represent the updated panel length and width due to architectural constraints.

Table 4.6: Panel categories

Wall Name	Wall Code	Position	Wall Height
Exterior wall	EX362S162_68-68	External wall (façade)	120.375’’
Interior Bearing wall	IN2x362S162_97/6	Internal wall perpendicular to floor joists	120.375’’
Interior Non Bearing wall	IN362S162-18/18	Internal wall parallel to floor joists	110.375’’
Party wall	IN-362S162-54_PT	Internal wall separating two suites	120.375’’
Corridor wall	IN-362S162-68CR	Internal wall between corridor and suites	120.375’’
Plumbing wall	IN-600S162_68-PL	Internal wall between bathroom and kitchen but never between suites	102.375’’ 1st floor 120.375’’ repetitive floor 138.375’’ last floor
Exterior Elevator wall	EX800S162-43_EL	Exterior wall for elevator shafts	120.375’’
Interior Elevator wall	IN-600S162-68_EL	Interior wall for elevator shafts	120.375’’
Exterior Mechanical Shaft wall	EX600S162_68/54 EX600S162_54/43	Exterior wall for Mechanical Shafts beside elevators	120.375’’

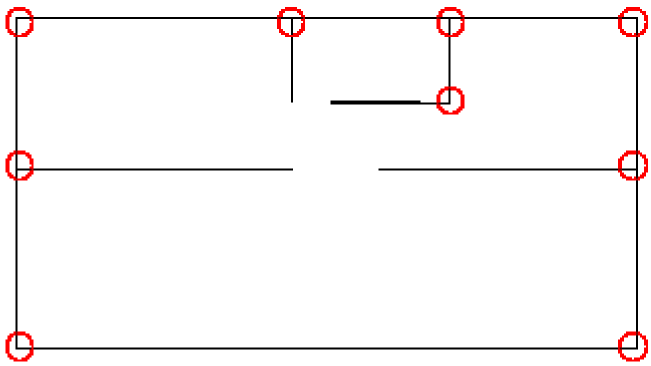


Figure 4.15: Identifying connections based on architectural design

4.3.2 Structural design check

Structural design was checked against panel buckling depending on the load sustained by each wall according to the structural design and the position of each panel in the building to identify possible panel length and height. This structural check considers whether changing panel studs thickness is an economical solution or changing panel length. Light gauge steel framing consists of galvanized steel C-sections of typically 65 to 200mm depth and in steel thicknesses of 1.2 to 2.4mm (Lawson and Ogden, 2006).

Walls are generally pre-fabricated as 2D- storey-high panels and floors are installed as joists or in 2D-cassette form (Lawson and Ogden, 2006).

Hybrid construction building consists of several types of panels according to their location in the building and to the required load they should sustain depending on the structural design of the building. Wall code 600S162-54 was defined according to the Steel Stud Manufacturers Association (SSMA) products report (SSMA, 2010). This code consists of four parts: member depths, style, flange width, and material thickness, as shown in Figure 4.16.

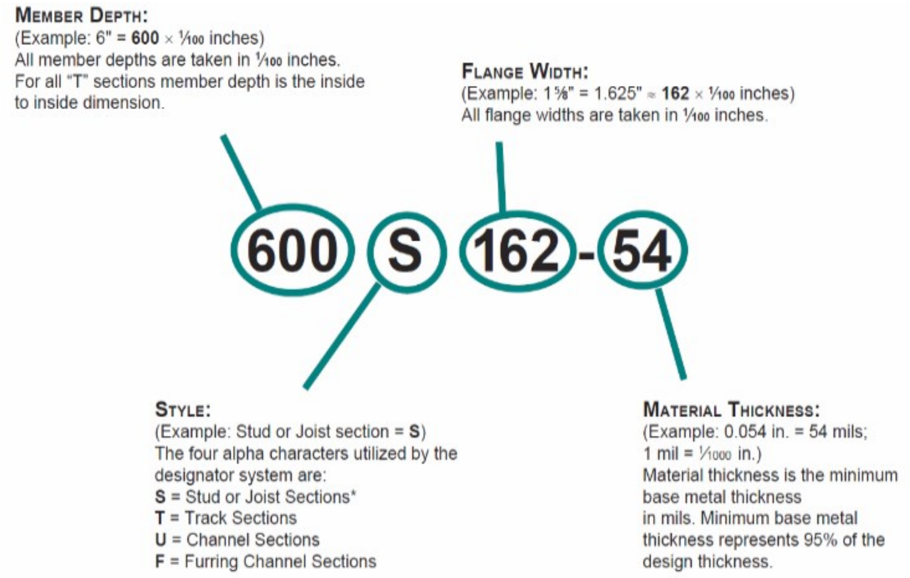


Figure 4.16: Product identification by the SSMA

Panel strength is relative to steel C-section type/thickness and spacing. The design strength of panels depends on the amount of gravity loads, location of panel/ module, and lateral load magnitude. The connections between panels must have adequate strength to transfer gravity loads where bracing elements support panel resistance to lateral load.

Considering building layout in Figure 4.15, where the length of one or more panels was assumed to be larger than the allowable length as stated by the standards and regulations, a new connection was added to prevent buckling as indicated by the blue circle in Figure 4.17 and using Equations 14 and 15.

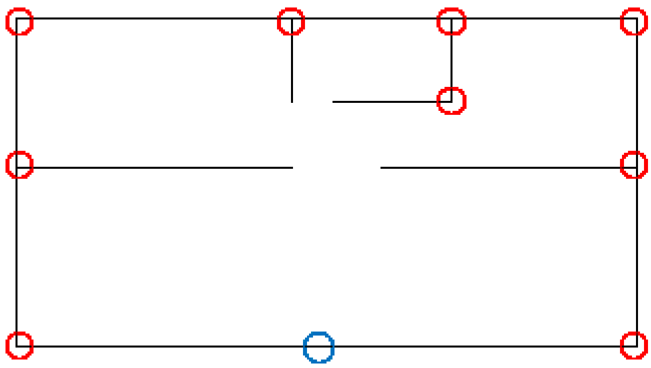


Figure 4.17: Identifying connections based on structural design

Based on the structural constraints, panel length and width were updated using Equations 4.14 and 4.15 as follows:

$$W_{AS} = \begin{cases} W_A, & \text{no structural constraints} \\ w_S, & \text{structural constraints exist} \end{cases} \qquad \text{Equation 4.14}$$

$$L_{AS} = \begin{cases} L_A, & \text{no structural constraints} \\ l_S, & \text{structural constraints exist} \end{cases} \qquad \text{Equation 4.15}$$

Where, w_S and l_S represent panel width and length due to structural constraints and W_{AS} and L_{AS}, respectively, represent the updated panel length and width due to architectural and structural constraints.

4.3.3 Manufacturing limitations check

The third step was to check the limitations of the manufacturing facilities to confirm if those facilities have the capacity to produce the required panel size. The production capacity of a manufacturing facility depends on a production table or CNC machine size. In this respect, panel dimensions should be less than the production table or CNC machines' dimensions. Space limitation is a constraint for the production table or CNC machines size. Panel sizes are also affected by the automation level followed in any manufacturing facility.

The three main types of manufacturing systems for offsite manufacturing are static, linear, and semi automated linear production (Lawson et al., 2014). Static production means that modules/panels are manufactured in one position while all materials and personnel move to the module position (Lawson et al., 2014).

Linear production is a non-automated production line where the manufacturing process is conducted according to different sequential stages similar to the automotive industry (Lawson et al., 2014). Modules/panels are manufactured on fixed rails and move between stations. In this type of offsite manufacturing, modules/panels move from one station to another while every station has a dedicated crew working on a specific process at that station. Semi-automated lines manufacture panels as a linear production system but with highly automated specialized equipment, accompanied with manual operations (Lawson et al., 2014). For example, semi-automated lines use turning or "butterfly" tables that allows crews to work on both sides of panels. Considering building layout in Figure 4.17 and constraints of manufacturing, other connections were added as indicated by the blue circles in Figure 4.18.

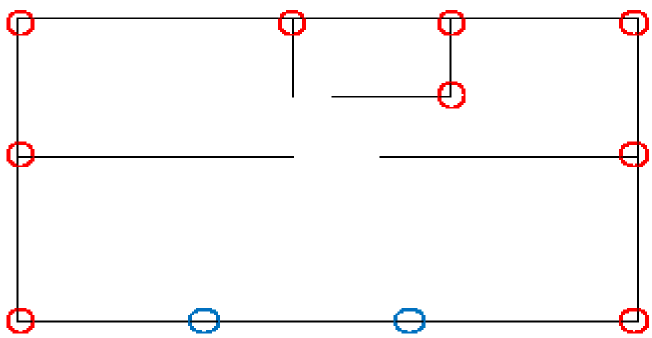


Figure 4.18: Identifying connections based on manufacturing limitations

Based on manufacturing constraints, panel length and width were updated using Equations 4.16 and 4.17 as follows:

$$W_{ASM} = \begin{cases} W_{AS}, & \text{no Manufacturing constraints} \\ w_M, & \text{Manufacturing constraints exist} \end{cases} \quad \text{Equation 4.16}$$

$$L_{ASM} = \begin{cases} L_{AS}, & \text{if no Manufacturing constraints} \\ l_M, & \text{if Manufacturing constraints exists} \end{cases} \quad \text{Equation 4.17}$$

Where, w_M and l_M represent panel width and length due to manufacturing constraints and W_{ASM} and L_{ASM}, respectively, represent the updated length and width of panel due to architectural, structural, and manufacturing constraints.

4.3.4 Transportation limitations check

Finally, transportation limitation was checked if panels can be accommodated on trailers based on dimensions of available trailers and transportation regulations that are usually stipulated by department of transportation. Hybrid and panelized manufacturing systems are more flexible than modular manufacturing systems and can more easily accommodate variations in plan and detailed design than volumetric systems. Moreover, panelized manufacturing systems can be stacked and transported easier in one truckload due their flat shape, as shown in Figure 4.19. On the contrary, modular construction systems have many constraints in transportation. However, finishing of panels have a greater possibility of being damaged during transportation to the construction site as compared to modular transportation (Lawson et al., 2005). Transportation trailers for panelized construction are equipped with special steel frames to fix panels during transportation to reduce panel damage, as shown in Figure 4.20. Based on manufacturing constraints, panel length and width were updated using Equations 4.18 and 4.19 as follows::

$$\mathrm{W_{ASMT}} = \begin{cases} \mathrm{W_{ASM}}, & \text{no Transportation constraints} \\ \mathrm{w_T}, & \text{Transportation constraints exist} \end{cases}$$ Equation 4.18

$$L_{ASMT} = \begin{cases} L_{ASM}, & if\ no\ structural\ constraints \\ l_T, & if structural\ constraints\ exists \end{cases}$$ Equation 4.19

Where, w_T and l_T represent panel width and length due to manufacturing constraints and W_{ASMT} and L_{ASMT}, respectively, represent final length and width of panel due to architectural, structural, manufacturing, and transportation constraints.

Figure 4.19: Alignment of panels on trailer

Figure 4.20: Special steel frames on trailer for panel transportation

Figure 4.21: Inclined steel frame for last floor parapet panel transportation

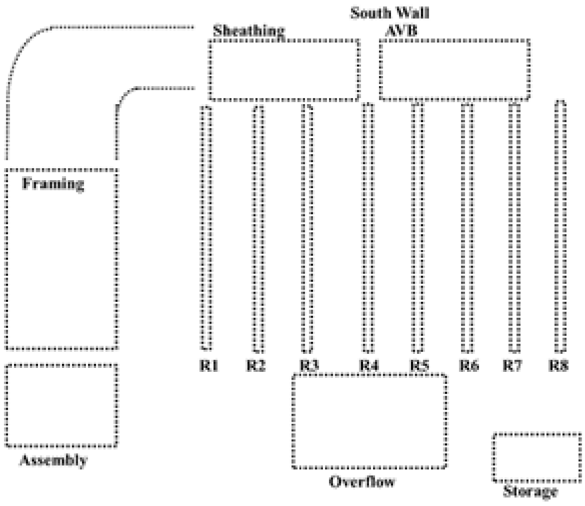


Figure 4.22: Manufacturing facility layout

4.4 Scheduling and buffering model

The proposed method integrates CCPM and LSM; the aggressiveness of CCPM leads to shorter schedules while LSM visualizes repetitive processes and accounts for continuity of resources. The proposed method framework is illustrated in Figure 4.23.

4.4.1 Calculation of aggressive and safe activity durations

Safe activity duration is defined as a duration estimate that includes enough safety to protect activities' execution against contingencies. Aggressive activity duration is the average estimate without safety time (Dilmaghani, 2008). Aggressive activity duration depends on the aggressive productivity rate calculation and the constrained productivity rate CPR at a 50% confidence level of resources availability, as presented in Equation 4.20. Safe activity duration depends on using CPR at a 90% confidence level of resources availability, as presented in Equation 4.21.

Calculation of aggressive and safe durations using CPR leads to identification of the controlling resource for each activity, as presented in Equation 4.22. The controlling resource was defined as the resource that controls the activity duration as follows:

$D_{i,j}$ (AG) = activity quantity / $CPR_{i,j}$ (AG) Equation 4.20

$D_{i,j}$ (CL) = activity quantity / $CPR_{i,j}$ (CL) Equation 4.21

$$CPR\,(CL) = Activity\ \ total\ quantity\ (any\ unit) \times \frac{\text{available resources output /day (CL)}}{\text{Total activity required resources output}}$$

Equation 4.22

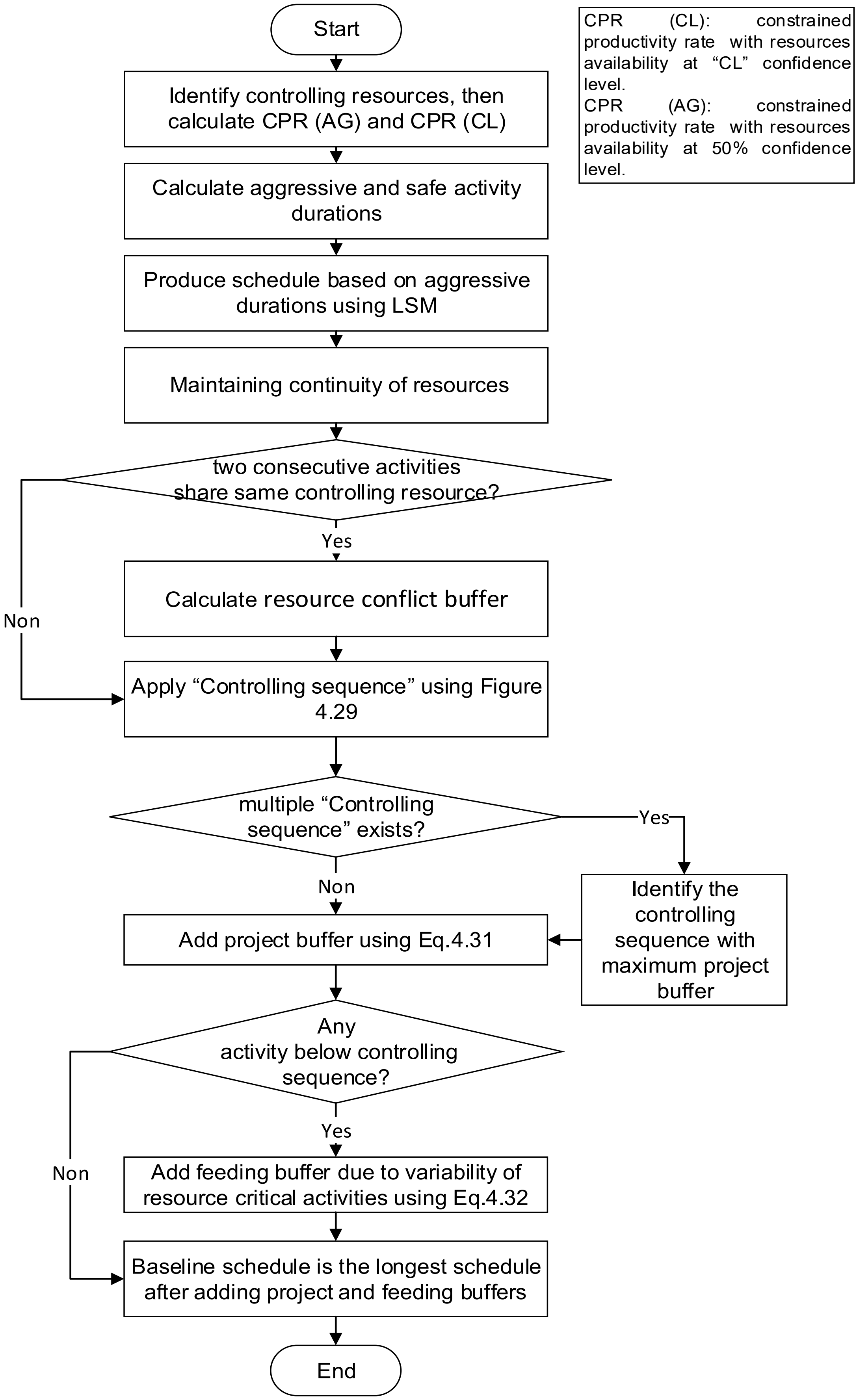


Figure 4.23: The proposed method for integrating LSM and CCPM

Where, $D_{i,j}$ (CL), represents the safe duration of activity "i" in process "j" with given confidence level "CL"; $D_{i,j}$ (AG), represents the aggressive duration of activity "i" in process "j"; CPR_i (CL) represents constrained productivity rate of activity "i" with resources availability at "CL" confidence level; and CPRi (AG), represents constrained productivity rate of activity "i" with resources availability at a 50% confidence level.

4.4.2 Sequencing activities based on aggressive durations (average schedule)

The aggressive schedule was sequenced using Equations 4.23 and 4.24 based on aggressive durations by deducting all safety durations from activities as per the CCPM rule of aggressiveness (Goldratt, 1997):

$$SD_{i,j}(AG) = \text{Max}\,[FD_{i,j-1}\,(AG), FD_{i-1,j}(AG)] \qquad \text{Equation 4.23}$$

$$FD_{i,j}(AG) = SD_{i,j}\,(AG) + D_{i,j}\,(AG) \qquad \text{Equation 4.24}$$

4.4.3 Maintaining aggressive schedule continuity

LSM rules were applied to maintain the continuity of resources for all activities. Figure 4.24 illustrates the developed procedure for maintaining the continuity of resources.

4.4.4 Resolving resources conflicts

An important issue in CCPM scheduling is resources conflicts because solving these conflicts changes the traditional critical path into the critical supply chain constrained by resource limitations, as shown in Figure 4.25 to 4.27. However, the linear scheduling continuity constraint should be respected. If two or more sequential activities share the same controlling resource, then priority is given to predecessor activities to respect the aggressive schedule's continuity constraint. Hence, successor activities start only if there are enough resources to ensure continuity, while the logic relationships between preceding and succeeding activities are respected.

However, if the normal productivity rate of a preceding activity is equal to or larger than the constrained productivity rate of the aggressive activity (CPR_{AG}), then there are no residual resources quantities that could be shared with the succeeding activity. In this case, the start of the first activity of the succeeding process was related to the end of preceding process last activity, as presented in Equation 4.25. However, if the normal productivity rate of the preceding activity (without resources constraints) is lower than aggressive constrained productivity rate (CPR_{AG}), then enough resources are available to start the succeeding activity before the completion of preceding activity. The overlap between the two activities was calculated using Equations 4.26 and 4.27:

$SD_{i,j+1(AG)} = FD_{i+n,j(AG)}$ Equation 4.25

$Q_R = Q_T - Q_C$ Equation 4.26

$O_{RC} = Q_R / \min(CPR_{AG}, PR_{AG})$ for succeeding activity. Equation 4.27

Where, Q_R is the residual quantities in preceding activity; Q_T, the total available quantities according to constrained activity productivity rate in preceding activity; Q_C, resources quantities consumption during normal duration in preceding activity; and O_{RC}, overlap due to resources conflicts.

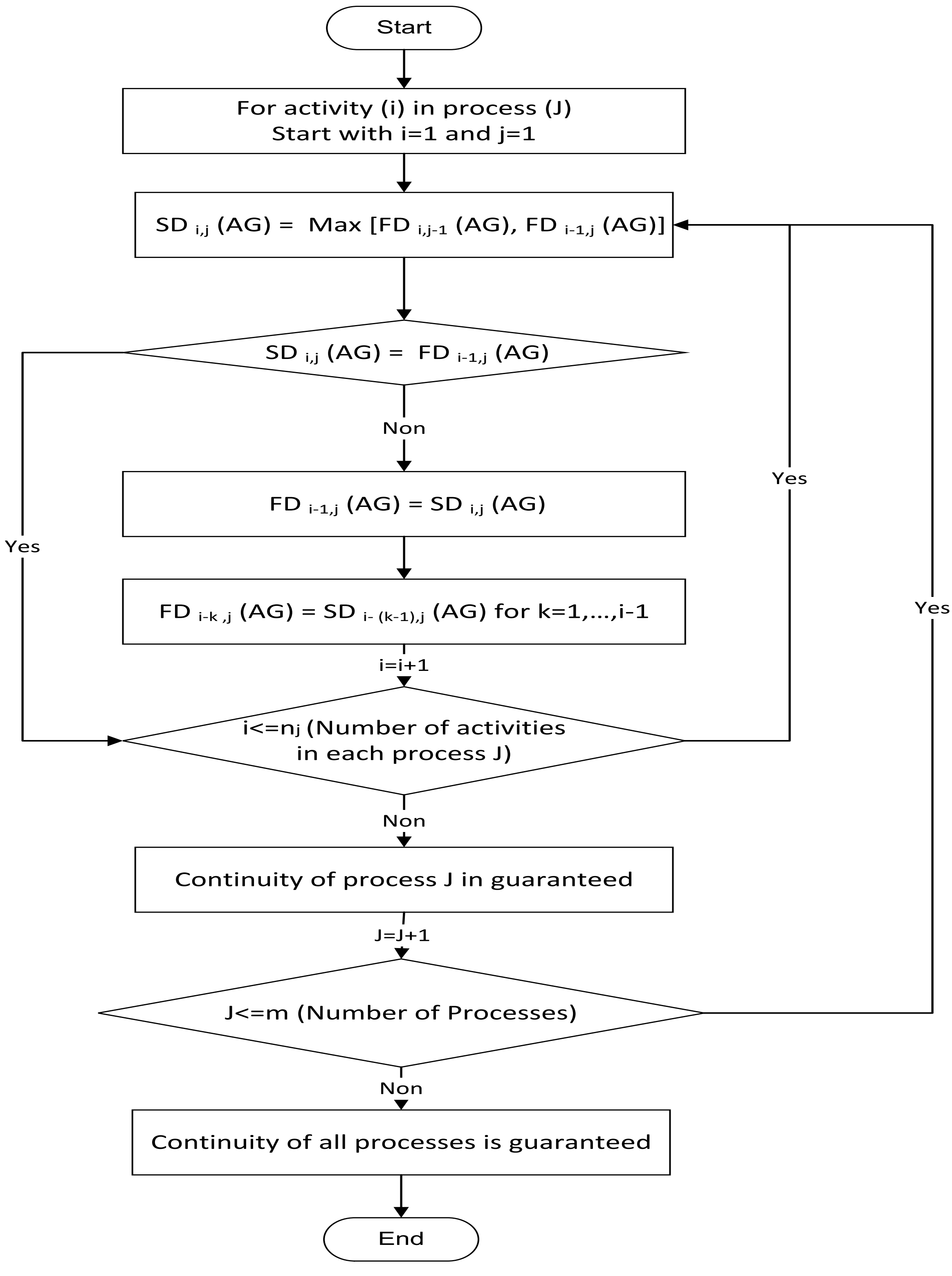


Figure 4.24: Maintaining aggressive schedule continuity

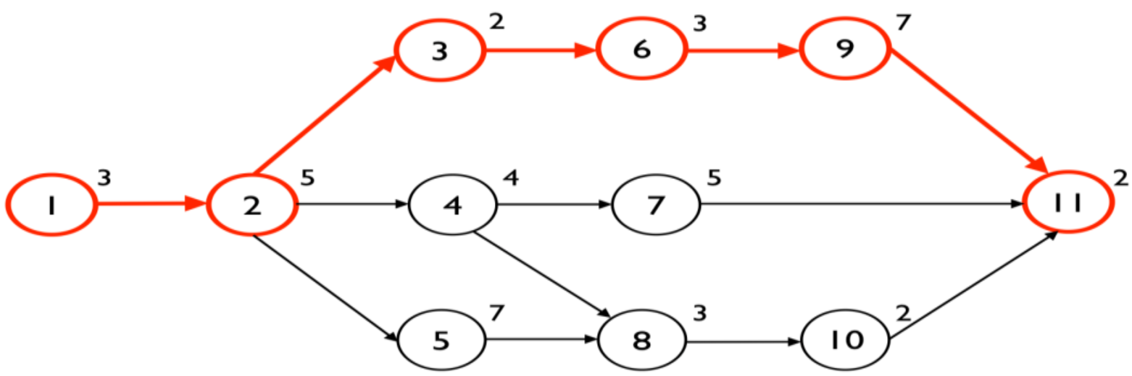


Figure 4.25: Critical path for a network before resolving resources conflict (www.pmknowledgecenter.com)

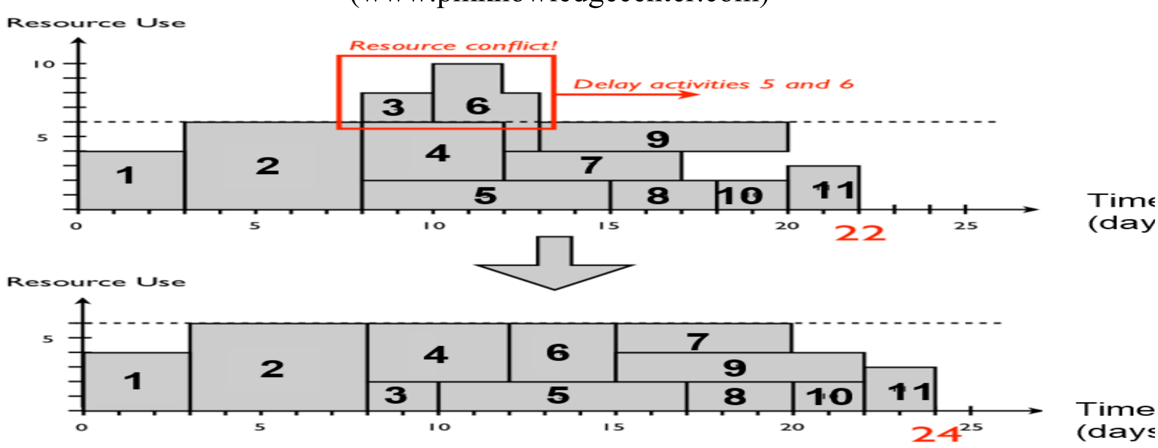


Figure 4.26: Resolving resource conflict (www.pmknowledgecenter.com)

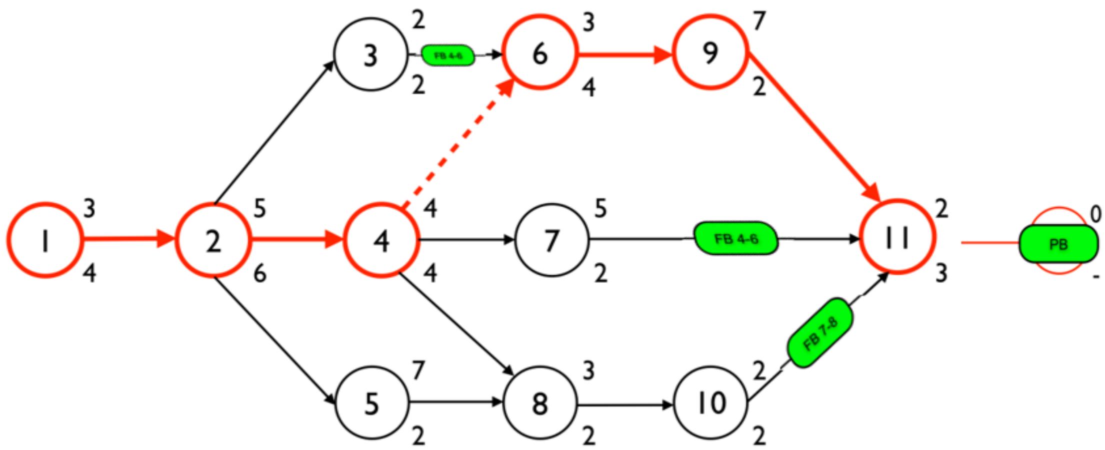


Figure 4.27: Critical supply chain after resolving resource conflict (www.pmknowledgecenter.com)

The resource variability for the preceding activity shifts the start of the succeeding activity by creating another overlap (O $_{VAR}$) between the preceding and succeeding activities. The difference between O $_{RC}$ and O $_{VAR}$ creates a resources conflict buffer (RCB), as illustrated in Equations 4.28 to 4.30:

$O_{VAR} = Q_{50\%} - Q_{90\%} / \min(CPR_{AG}, PR_{AG})$ for succeeding activity Equation 4.28

$RCB = O_{RC} - O_{VAR}$ Equation 4.29

$SD_{i,j+1(AG)} = FD_{i+n,j(AG)} + RCB - O_{RC}$ Equation 4.30

Where, O $_{VAR}$ is the overlap of resources quantities variability for preceding activity;

$Q_{50\%}$ is quantities in preceding activity with 50 % confidence in availability;
$Q_{90\%}$ is quantities in preceding activity with 90 % confidence in availability; and
RCB is the resource conflict buffer.

RCB accounts for conflict in availability of resources for preceding and succeeding activities, as shown in Figure 4.28.

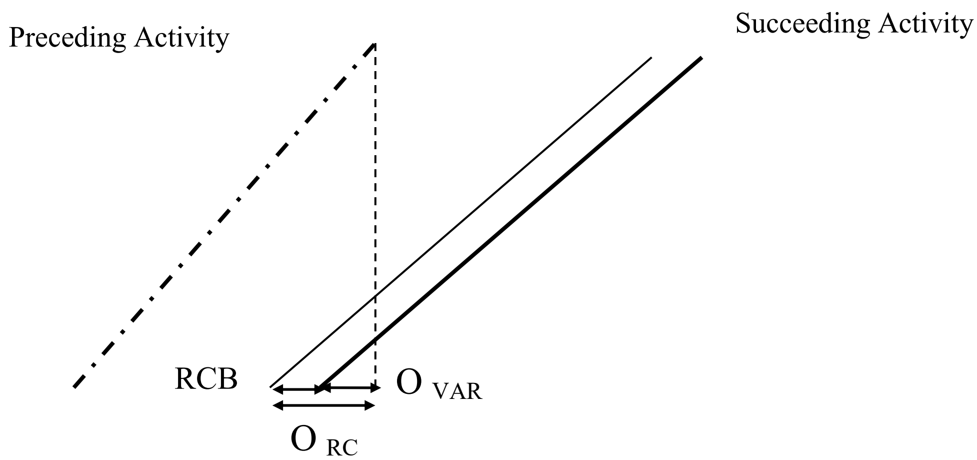


Figure 4.28: Identifying the RCB

4.4.5 Identification of critical sequence

Finding the critical sequence was crucial in integrating CCPM and LSM because CCPM is based on identifying the critical path constrained by resource limitation, while the resources continuity needed to be maintained according to LSM. The critical sequences for the aggressive schedule were identified using the newly developed identification procedure, illustrated in Figure 4.29, which was based on the graphical procedure presented by Harmelink and Rowings (1998) .

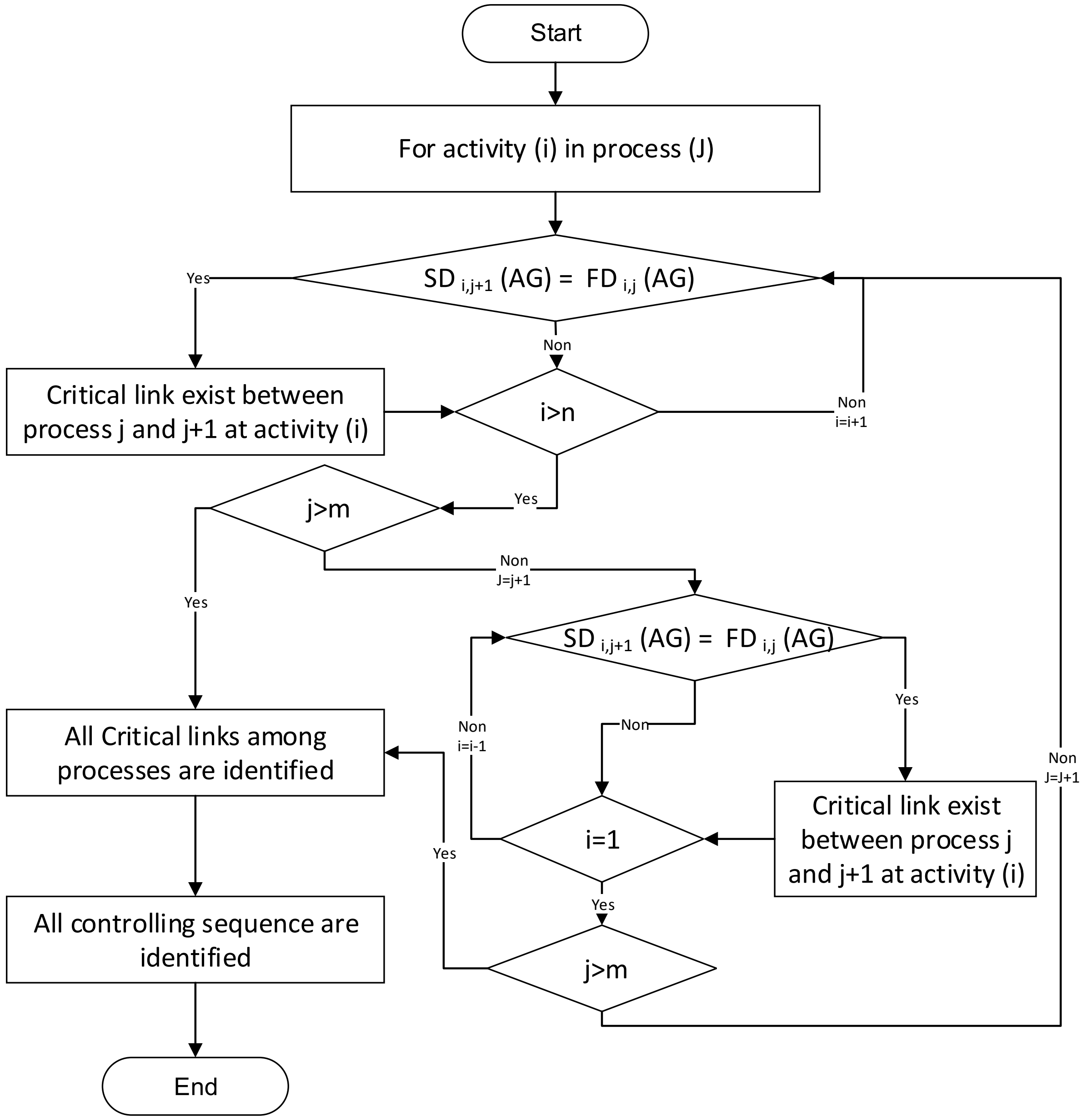


Figure 4.29: The proposed identification process for critical sequence

4.4.6 Adding feeding and project buffers

A project buffer was added at the end of critical sequence as per the CCPM. In case of multiple critical sequences, each critical sequence should have a different project buffer depending on its critical activities variability. In this case, the project buffer was selected as the maximum buffer of all critical sequences and was calculated using Equation 4.31. The feeding buffers were added based on the CCPM to reduce the non-critical chains' delay effects on the critical chains. Feeding buffers in activity-based scheduling were assigned between the critical chain and non-critical chain. This was applied to multiple non-critical chains as well, as shown in Figure 4.30. Included also were the buffers arising from the variability of "resource-critical activities" number D1, 2, 3 and F1, 2, 3, 4, 5, as shown in Figure 4.31 (Harris and Ioannou, 1998). Since the delay of resource-critical activity delays part of the critical controlling sequence and accordingly the project completion date, the feeding buffer needs to be assigned at the end of resource-critical activities and calculated using Equation 4.32. However, this causes activity discontinuity and for this reason, feeding buffers in this research were assigned at the end of activities with a value that accounts for variability of resource-critical activities. For an example, since activities D1, 2, 3 are resource-critical activities, a feeding buffer was assigned after D6 not D3 to respect the continuity of activity D.

$$\text{Project Buffer}=\sqrt{\sum_{P=1}^{P=n}\left(D_P(CL) - D_P(AG)\right)^2} \quad \text{Equation 4.31}$$

$$\text{Feeding Buffer}=\sqrt{\sum_{F=1}^{F=n}\left(D_F(CL) - D_F(AG)\right)^2} \quad \text{Equation 4.32}$$

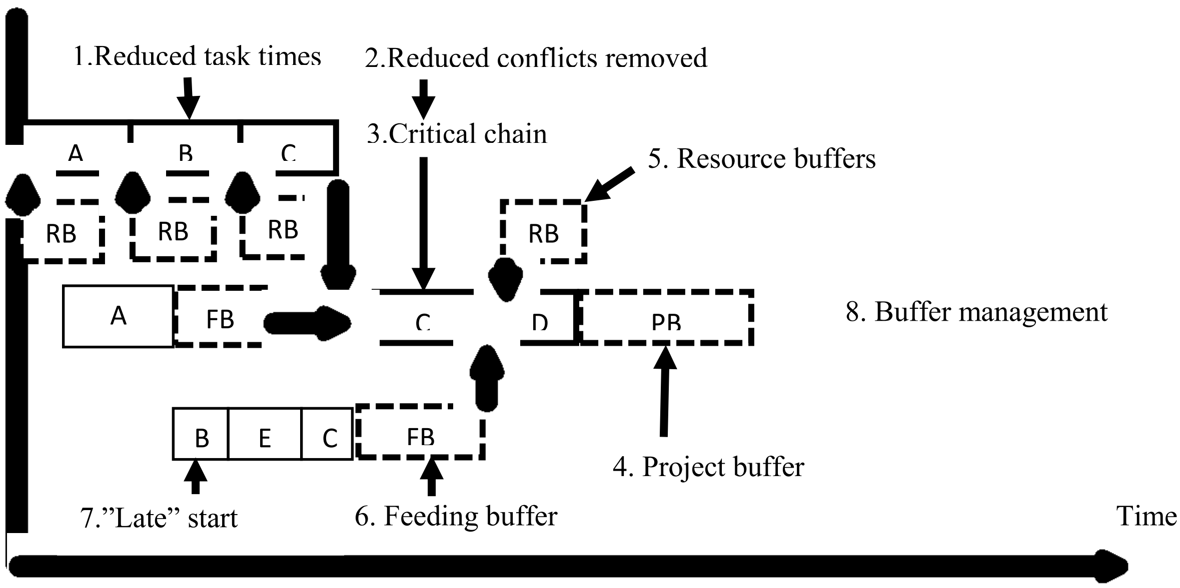


Figure 4.30: Key features of the critical chain project management system requirements (Adapted from Leach, 2000)

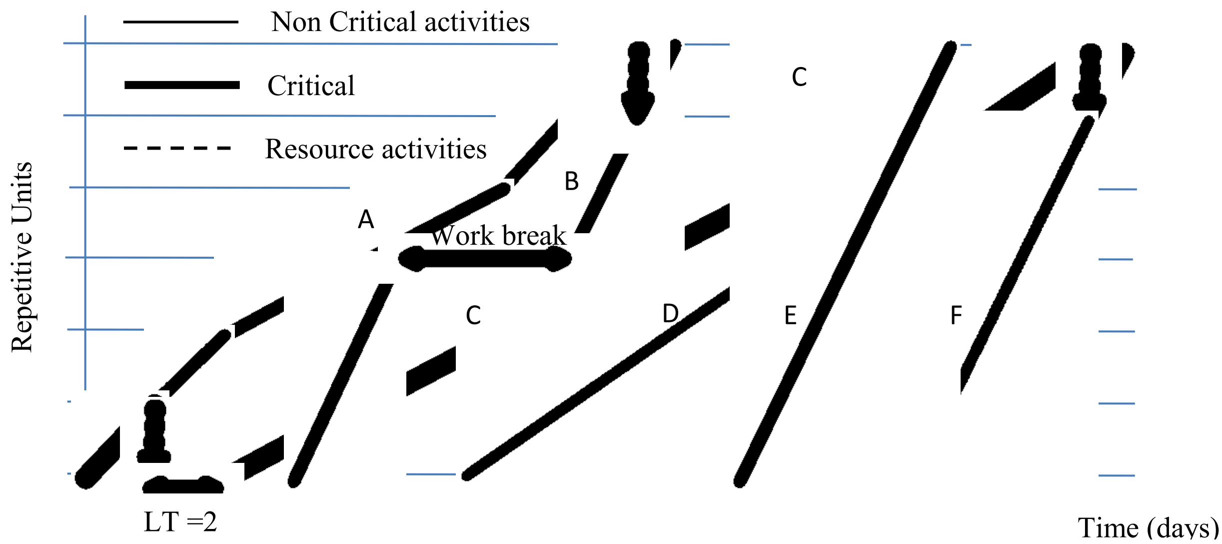


Figure 4.31: Identification of resource-critical activities (Adapted from Harris and Ioannou, 1998)

4.4.7 Integration of offsite and onsite construction

Modular construction enables building delivery as an assembly of a set of modules manufactured offsite in a controlled manufacturing facility environment. Unlike stick-built practices, modular construction enables higher schedule control of construction projects due the inherent concurrency of offsite and onsite construction operations. The literature provides simulation-based scheduling methods that integrate offsite and onsite construction activities. These methods, however, depend largely on the availability of data such as productivity rates for offsite and onsite activities. This research presents an alternative BIM-based framework that integrates linear schedules of onsite and offsite construction operations in a manner that synchronizes the work progress of these operations. The use of BIM provided visualization capabilities for the integrated schedule and allowed for silmutaneously monitoring offsite and onsite activity work progress. The proposed approach was based on a previously presented BIM-based integrated framework for modelling and planning of hybrid construction projects using the integration between LSM and CCPM (Salama et al., 2016) as follows. The proposed framework used BIM for data collection automation. The collected data was then used to generate the linear schedule. A set of assumptions were considered in the proposed methodology as follows:

1- Each of the manufacturing processes (or stations) has one fixed crew with a given productivity rate;
2- Each of the manufacturing processes is considered continuous due to the use of racks that reduce the variability in productivity rates of panels; and
3- The manufacturing of panels follows the sequence of onsite erection.

The project was modelled using BIM software (e.g. Vertex BD Pro 2016 22.0) that facilitated modelling with automatic framing capabilities. The BIM model allowed for the generation of a database which included: property (e.g. dry wall), dimensions, list of components (e.g. openings), and each panel's onsite erection sequence. Figure 4.32 presents the interconnections between the BIM model and project database.

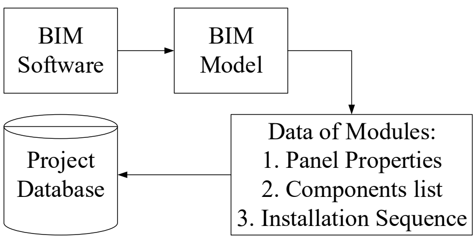


Figure 4.32: The interconnections between the BIM model and the project database

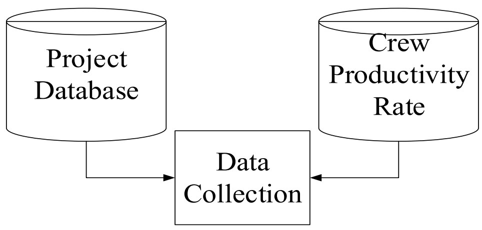


Figure 4.33: The data collection framework

The data collection had two main levels: 1) a project database generated from a BIM model and 2) the productivity rate data for crews involved in the manufacturing processes. The framework of the data collection is presented in Figure 4.33.

This framework depended on all the previously mentioned steps to generate linear schedules by integrating the LSM and CCPM. This included the calculation of aggressive and safe activity durations, sequencing activities based on aggressive durations, maintaining aggressive schedule continuity, resolving resource conflicts, critical sequence identification, and adding feeding and project buffers. The offsite schedule baseline was generated as per the presented framework in Figure 4.34.

Identification of the critical control point CCP between offsite and onsite schedules was crucial because the CCP connects both schedules and any delay in the offsite schedule would affect the CCP and onsite schedule. The CCP is logically constrained by the last manufacturing process for modules/panels and transportation method availability and capacity for modules/panels transportation from offsite manufacturing facility to construction site. For example, two scenarios affected the position of the CCP according to panel transportation as follows:

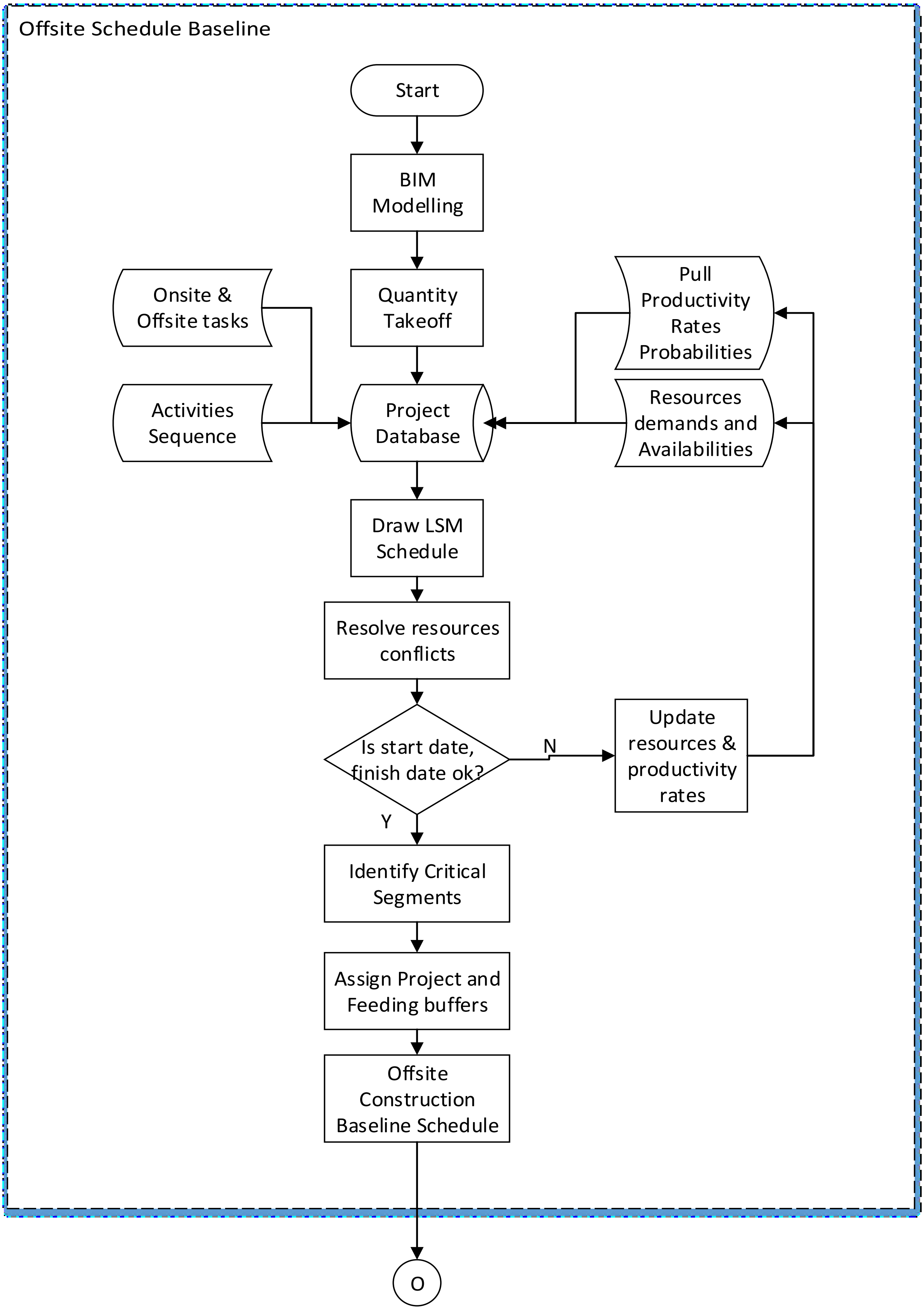


Figure 4.34: Generating offsite schedule baseline

1- In case of transporting panels by batches after each batch was manufactured, the CCP is the start date of first onsite activity for last batch of panels after transportation (i.e. surveying panel location), as shown in Figure 4.35 and calculated using Equation 4.33:

$$SD_{\mathrm{OLB\ (AG)}} = FD_{\mathrm{OLB\ (AG)}} + D_{\mathrm{LBT}} \qquad \text{Equation 4.33}$$

2- In case of transporting panels after all the batches are manufactured, the CCP is the start date of first onsite activity for the first panel after transportation (SD_{OFP}) (i.e. surveying panel location) as shown in Figure 4.36 and using Equation 4.34:

$$SD_{\mathrm{OFP(AG)}} = FD_{\mathrm{OLB\ (AG)}} + D_{\mathrm{LBT}} \qquad \text{Equation 4.34}$$

Where, SD_{OLB} is the start date of the first onsite activity for the last panel batch after transportation at aggressive schedule; FD_{OLB} is the finish date of the last offsite manufacturing process for the last panel at aggressive schedule; and D_{LBT} is the duration for the last batch transported from the offsite manufacturing facility to the construction site. The onsite schedule baseline was sequenced after fixing the CCP between offsite and onsite aggressive schedules, as shown in Figure 4.35, 4.36, and 4.37. The process that contains the critical control point was the first process to be sequenced and the other processes were sequenced using Equations 4.23 and 4.24. Then, the continuity of all processes was maintained using the procedure mentioned in Figure 4.24. Resources conflicts were identified between successive processes and RCBs were calculated using Equations 4.28 to 4.30. Feeding and project buffers for offsite and onsite schedule were calculated using Equations 4.31 and 4.32. However, the overall project schedule (offsite and onsite) has another overall project buffer (OPB) based on variability of onsite and offsite schedules.

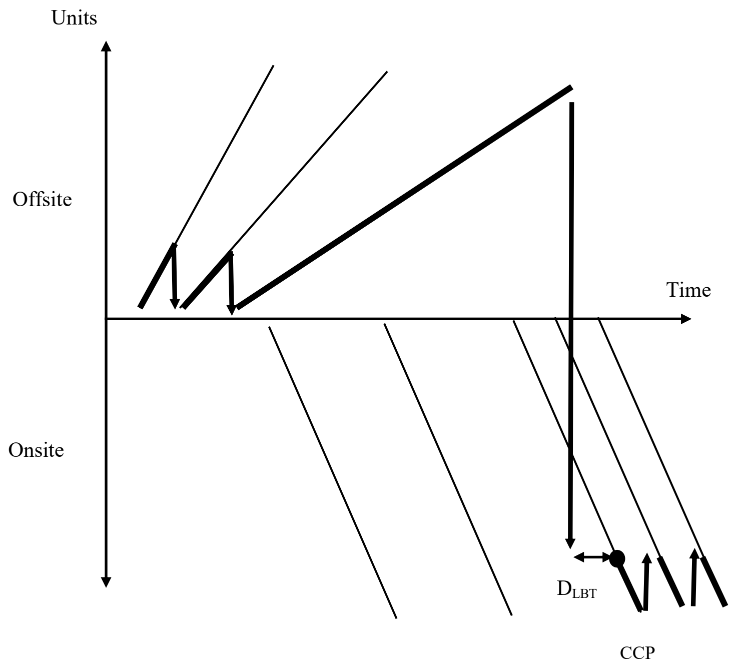


Figure 4.35:Identifying CCP for the scenario of transporting panels by batches

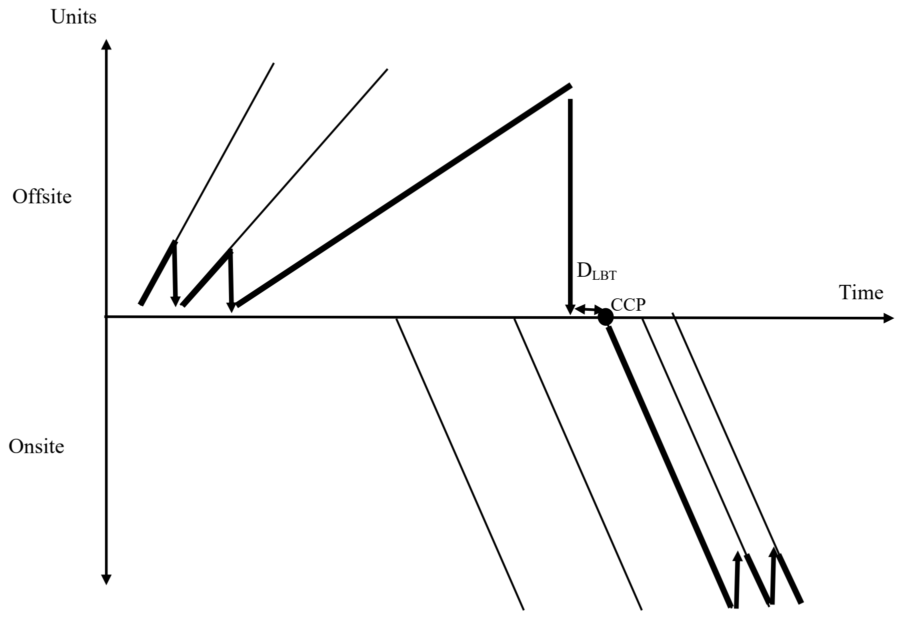


Figure 4.36: Identifying CCP for the scenario of transporting panels after all batches are manufactured

Both schedules are connected at the CCP to create the overall project critical sequence. The OPB was allocated at the end of the overall project critical sequence based on variability of the whole offsite schedule and the onsite schedule after the CCP. The processes before CCP at the onsite schedule were shifted with the amount of its critical sequence variability, as shown in Figure 4.37. The variability of its critical sequence was accumulated in a special buffer named onsite activities buffer (OAB); this procedure protects the overall project critical sequence from delay by allowing onsite processes before CCP to start early, and was done using Equation 4.35:

$$OAB = \sqrt{\sum_{O=1}^{O=n} (D_O(CL) - D_O(AG))^2} \qquad \text{Equation 4.35}$$

Where, D_O (CL) is the onsite activity safe duration with a given confidence level "CL" and D_O (AG) is the onsite acitivty aggressive duration with a 50% confidence level.

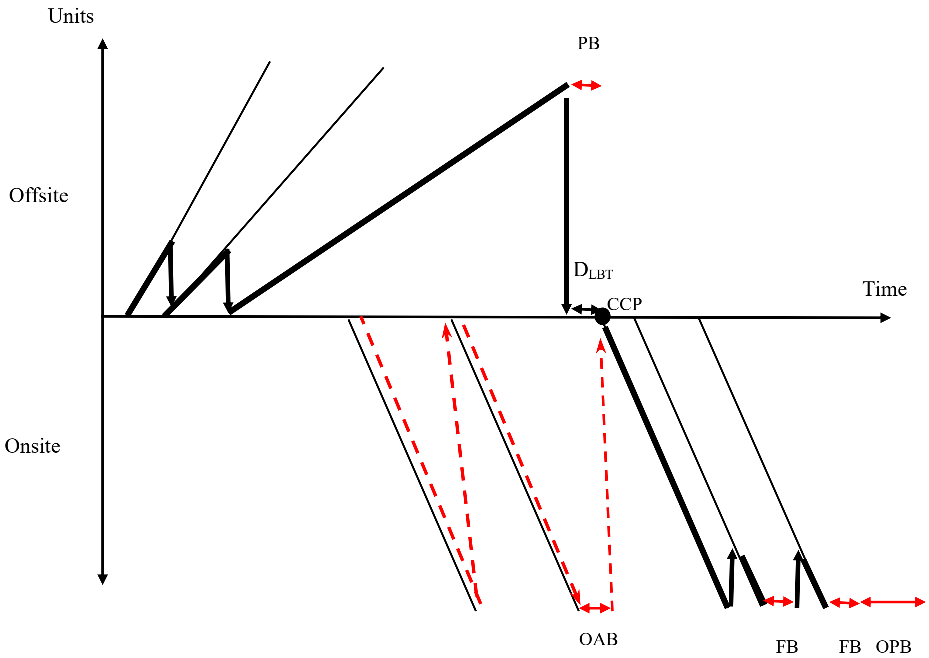


Figure 4.37: Adding feeding and project buffers

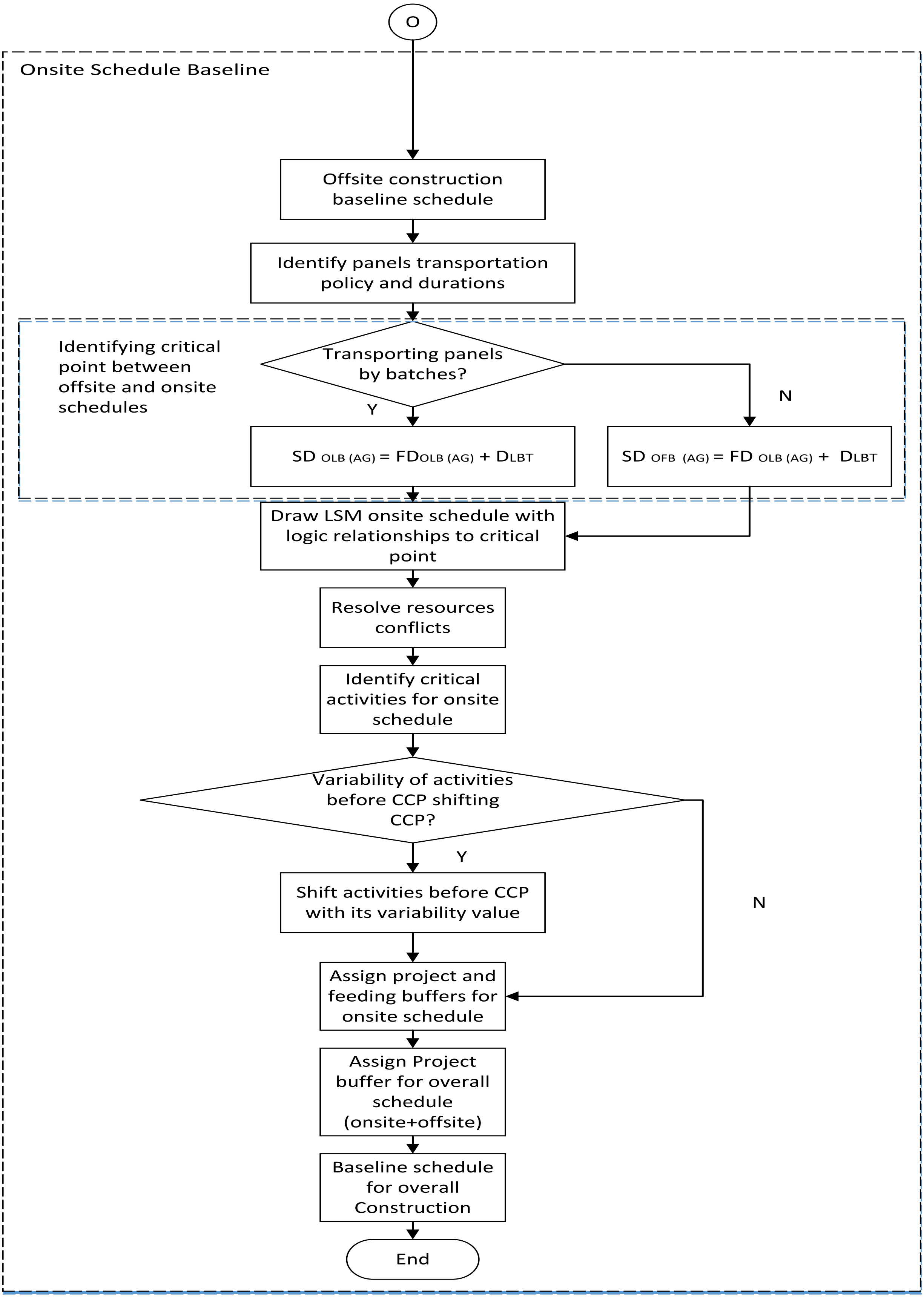


Figure 4.38: Generating onsite schedule baseline

4.5 Optimization Model

Existing optimization methods for repetitive scheduling either do not consider uncertainties associated with schedule input parameters, or do not consider delay penalties or bonus payments, or do not assign buffers to absorb delay or optimize a single objective only. Unlike existing optimization methods, the proposed method was developed to optimize the integration of LSM and CCPM (Salama et al., 2017b) in a systematic procedure. The developed procedure considers uncertainties of schedule inputs, utilizes multi-objective GA function that minimizes project duration, cost, and work interruptions simultaneously, considers delay penalties and bonus payments, identifies all critical sequences in the schedule, and allocates buffers according to CCPM if the generated optimized schedule allows for interruptions or not (Salama and Moselhi, 2018c). The proposed optimization model was developed based on earlier work presented by Bakry et al. (2016) and Salama et al. (2017b). Unlike the single optimization method presented by Bakry et al. (2016), the main contribution of developed method is that it provides multi-objective optimization for the integration of LSM and CCPM. This optimization minimizes project duration, cost, and work interruptions simultaneously while considering uncertainties of productivity rates, quantities, and availability of resources. The method steps used to generate the optimized repetitive schedule are shown in Figure 4.39.

These steps start by utilizing triangular membership functions to account for the uncertainties associated with duration of activities and crew outputs. Then, all inputs are defuzzified using the centre of area (COA) method and durations of activities are calculated as illustrated in the next sections. Activities are sequenced based on the “job logic” which respects their logical relationships. Project deadline, penalty cost, and bonus payments are specified, and the relative weights associated with cost (Wc), time (Wt), and work interruptions (Wi) are assigned as inputs. Then, a choice is made by the project planner to allow for interruption or not. In case project planner decided to allow for interruptions, then the developed algorithm to minimize interruptions is utilized, and if the project planner decided to prevent work interruptions, then an algorithm to align activities is utilized to maintain the continuity of resources for activities by postponing the start date/time of activities until continuous work is guaranteed (Salama et al., 2017). Evolver © software is utilized to optimize objective function using the predefined relative weights assigned to cost, time, and work interruptions to generate the optimum schedule. Then, the critical sequence of optimized project schedule is identified and project, feeding, and resource buffers are assigned as described in next sections. Basic components of the developed method included six modules, as shown in Figure 4.40 as follows: 1) uncertainty and defuzzification module using fuzzy set theory, 2) schedule calculations module using the integration of linear scheduling method and critical chain project management, 3) cost calculations module that considers direct and indirect costs, delay penalty, and work interruptions cost, 4) multi-objective optimization module using Evolver © 7.5.2 as a genetic algorithm software, 5) module for identifying multiple critical sequences and schedule buffers, and 6) reporting module (Salama and Moselhi, 2018c). The first module aimed to model uncertainty using fuzzy set theory and to transform fuzzy input variables into crisp values. Second module aimed to calculate activity durations and sequence activities. This module utilized two different algorithms, which are used based on preference of schedulers to allow for work interruptions while minimizing interruption durations and align activities (prevent work interruptions). The third module calculates direct cost (DC), indirect cost (IC), delay penalty cost (PC), and work interruption cost (WIC). The forth module identified optimum crew formation that satisfies a developed multi-objective function (MOF) that accounts for weighted cost, time, and interruptions simultaneously. Optimum crew formation is the selected combination of crews assigned to project activities that generates the optimized project schedule that satisfies the predefined MOF. For example, if activity A has three crews (A1, A2, and A3) which have different productivity rates and activity B has two crews (B1 and B2). Optimum crew formation for cost is A3B2 if utilizing crews A3 and B2 accomplish the least project cost. Genetic algorithm (GA) is particularly suited for this problem because it operates on a set of solutions rather than a single solution, and this advantage makes GA the most suitable searching engine for complicated multi objective optimization problems (Zheng and Ng, 2005). In the fifth module, optimum schedule was selected from a Pareto graph and the critical sequence was identified. Then, project, feeding, and resource buffers were assigned to provide protection against possible delays according to CCPM. Finally, the sixth module reported the outcome of all the previous modules by drawing the optimized linear schedule after assigning required buffers on spreadsheet.

4.5.1 First module: modelling uncertainty and defuzzification

The developed method utilized fuzzy set theory to model uncertainties for different fuzzy input parameters. Fuzzy inputs are based on experience of users to model inputs using fuzzy numbers if users cannot provide deterministic inputs. A triangular fuzzy number is represented by three numbers a, b and c, with associated membership values of 0, 1 and 0, respectively. The value of "a" represents the least possible value, b represents the most possible value, and c represents the largest possible value. Uncertainty was modeled for production rates of crews, direct and indirect costs, and quantities of work to facilitate comparison with Bakry et al.'s (2016) results. After all the required fuzzy inputs were identified, defuzzification begins using the centre of area (COA) method (Salah and Moselhi, 2016) for all fuzzy inputs.

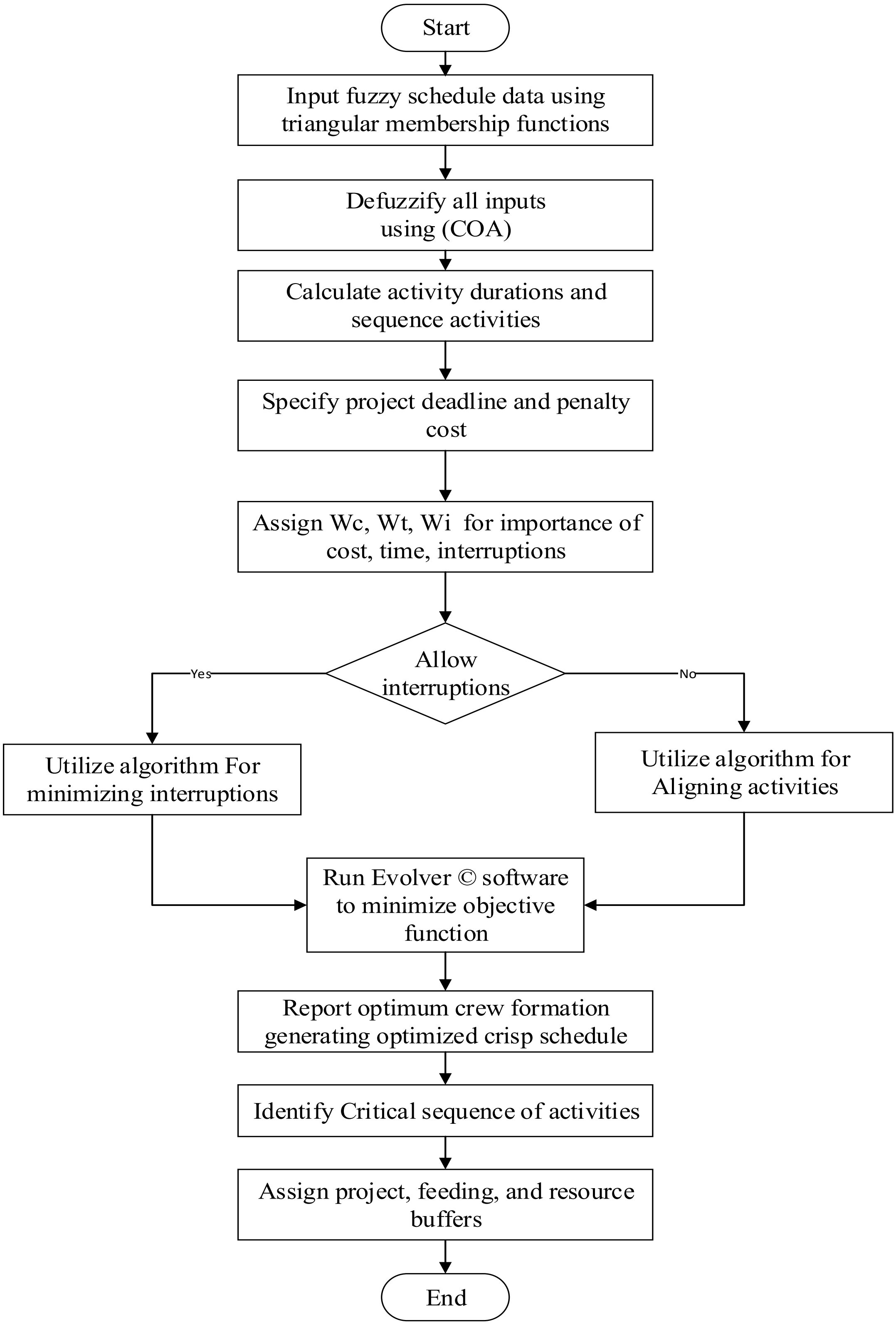


Figure 4.39: GA optimization chart

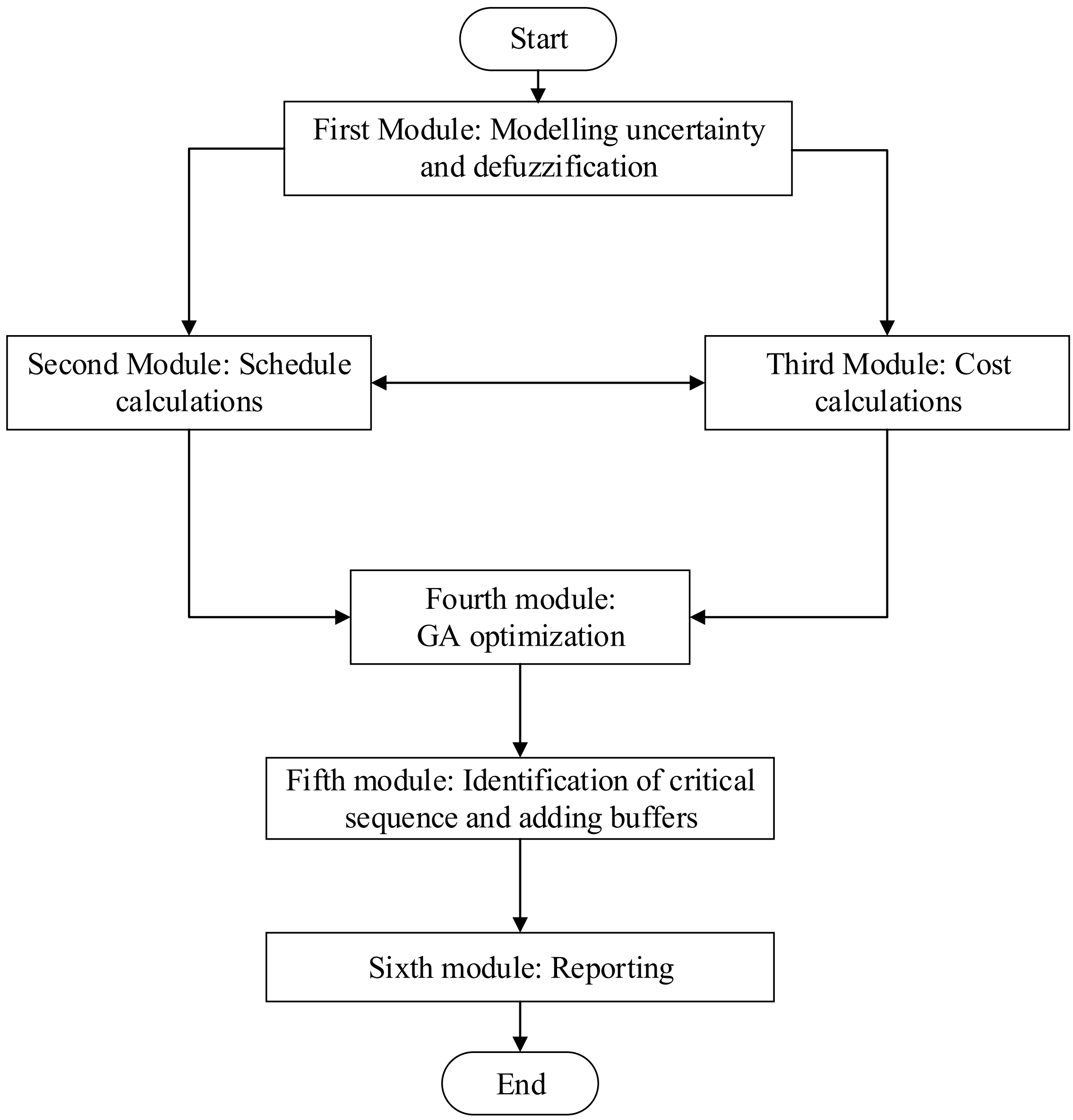


Figure 4.40: Components of developed method

The COA method was utilized to generate the expected value (EV), which matches the probabilistic mean of fuzzy number. The EV of a triangular fuzzy number can be calculated using Equation 4.36 that was utilized by Bakry et al. (2016):

$$EV = \frac{a+b+c}{3} \tag{4.36}$$

4.5.2 Second module – schedule calculations

The developed multi-objective model for optimization minimizes time, cost, and work interruptions simultaneously for repetitive scheduling while allowing for interruptions.

The algorithm developed by Salama et al. (2017b) was automatically formulated in a separate spreadsheet to maintain continuity of schedule if required during optimization. A spreadsheet tool was utilized using Evolver software and the developed model formulation is elaborated on in the following subsections.

Crisp activity durations, which depend on crisp quantities and productivity rates, were calculated using Equation 4.37 for all processes. Crisp value of any input is a representation of a fuzzy number after its defuzzfication, (i.e. it has a single defined value). Schedule was sequenced using Equations 4.38 and 4.39, and project duration was calculated using Equation 4.40 as follows:

Dcr i, j = (Qcr / PR cr) i, j Equation 4.37

SD i,j = Max (FD i, j-1, FD i-1,j) Equation 4.38

FD i, j = SD i, j + Dcr i, j Equation 4.39

PD = FD last “i” in last “j” Equation 4.40

Where, D i, j, represents duration of activity “i” in process “j”; Qcr represents crisp quantity for activity “i” in process “j”; PR cr represents crisp productivity rate for activity “i” in process “j”; SD i, j, is the start of duration for activity “i” in process “j”; and FD i, j end duration for activity “i” in process “j”.

Automatic algorithm shown in Figure 4.41 was formulated into the spreadsheet, and it gives same results of sub procedure (SP1) presented by Long and Ohsato (2009). The objective of this procedure is to start the activities as late as possible without delaying the project. Duration of interruptions (DI) for all activities was calculated after the minimization algorithm was applied using Equation 4.41 as follows:

$$DI = \sum_{A=i,\ P=j}^{A=n,\ P=m} SD_{i+1,\ j} - FD_{i,j} \qquad \text{Equation 4.41}$$

4.5.3 Third module: cost calculations

For this model, total cost (TC) is calculated using Equation 4.42. TC considers direct cost (DC), indirect cost (IC), and delay penalty cost (PC). DC was calculated using Equation 4.43 and includes labour, equipment, and material costs. Labour and equipment costs are functions of activity duration, as shown in Equations 4.44 and 4.45, while material cost is function of material quantity, as shown in Equations 4.46. IC, PC, and WIC costs were calculated using Equations 4.47 to 4.49 as follows:

$$TC = DC + IC + PC + WIC \qquad \text{Equation 4.42}$$

$$DC = \sum_{A=i}^{A=n} LC_{i,\ j} + EC_{i,\ j} + MC_{i,\ j} \qquad \text{Equation 4.43}$$

$$LC_{i,\ j} = (\text{Daily labour cost})_{i,\ j} \times D_{i,\ j} \qquad \text{Equation 4.44}$$

$$EC_{i,\ j} = (\text{Daily equipment cost})_{i,\ j} \times D_{i,\ j} \qquad \text{Equation 4.45}$$

$$MC_{i,\ j} = (\text{Unit material cost})_{i,\ j} \times Qcr_{i,\ j} \qquad \text{Equation 4.46}$$

$$IC = \text{Daily indirect cost} \times \text{project duration} \qquad \text{Equation 4.47}$$

$$PC = \text{Daily penalty cost for delay} \times (\text{project duration} - \text{deadline}) \qquad \text{Equation 4.48}$$

$$WIC = \text{Daily cost for interruption} \times \text{duration of interruptions} \qquad \text{Equation 4.49}$$

Where, DC represents direct cost for all activities from “i” to “n” in processes “j” to “j+m”; LC i, j, represents labour cost of activity “i” in process “j”;EC i, j, represents equipment cost of activity “i” in process “j”; MC i, j, represents material cost of activity “i” in process “j”; and WIC represents work interruption costs.

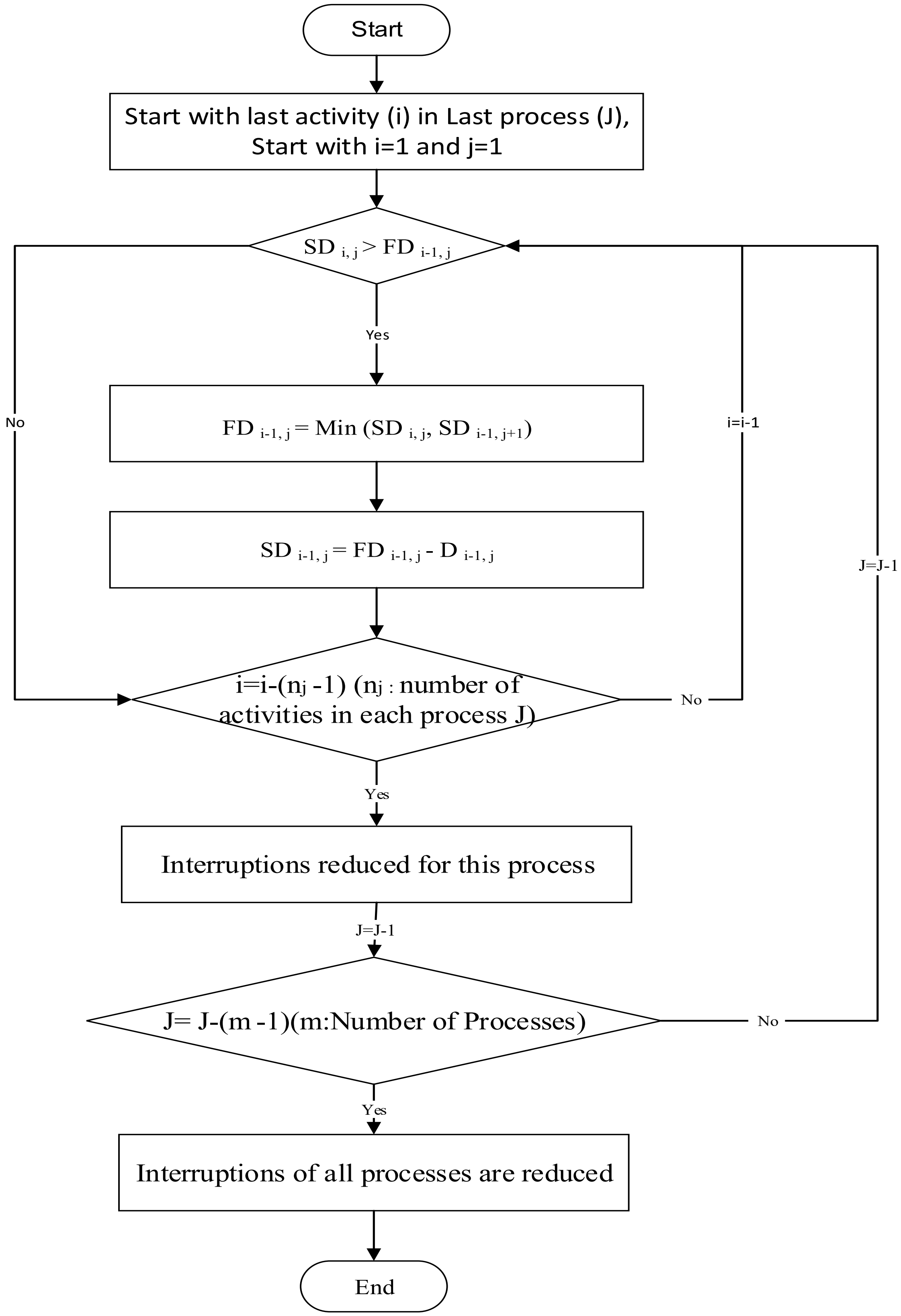


Figure 4.41: Algorithm for minimizing interruption durations

4.5.4 Fourth module: GA optimization

The multi-objective model was formulated into a spreadsheet tool to minimize time, cost, and work interruptions simultaneously for repetitive scheduling using a spreadsheet tool that utilizes Evolver © 7.5.2, a GA optimization software that works as an add-on to Microsoft Excel, as shown in Figure 4.42.

Genetic algorithms (GAs) are search engines that merge genetic operators taken from nature with an artificial survival of the fittest strategy (Hegazy, 1999), to form a procedure that suits many optimization problems. The procedure for application of GAs starts by generating an initial population (collection of random solutions) which are encoded in the form of strings named chromosomes. Each chromosome represents a solution that is worse or, better than other solutions in the population. The fitness of each chromosome is measured on how much its performance satisfies a targeted objective function. When a new offspring gene is generated, two chromosomes are selected from the population. Chromosomes that have high fitness scores are selected as parents. Instead of some genetic algorithm mechanisms that directly select parents for reproduction proportionally to its fitness. Chromosome selection technique utilized by Evolver © 7.5.2 depends on a rank-based mechanism. This mechanism prevents good chromosomes from dominating the evolution from an early stage (Evolver user's guide, 2015), and it offers a smoother probability curve for selection. Instead of chopping the variables list for any scenario at some point (named "single-point" or "double-point" crossover), which bias the search with the irrelevant position of the variables. Evolver © 7.5.2 performs crossover using a uniform crossover routine that forms two groups of variables by selecting items randomly to be in one group or another (Evolver user's guide, 2015). Evolver © 7.5.2 utilizes the order solving method to perform mutation by swapping the positions of some variables in the chromosome. The number of performed swaps is decreased or increased proportionately to the decrease and increase of the mutation rate setting (from 0 to 1) (Evolver user's guide, 2015).

By simulating natural survival of the fittest process, best chromosomes (solutions) exchange information to generate offspring genes which replace less fit members in the population. This process is conducted for many offspring generations, while the best solutions replace unfit solutions (population keeps evolving), until a terminating criterion is reached which means that one solution becomes satisfactory. At the end of this process, the member of the population that has the best performance is considered the optimum solution. To select the optimization engine and its settings, the model was set to the automatic mode in Evolver 7.5.2. This included string size determination while considering independent variables and population size, which is estimated based on string size to improve solution quality. It also included the crossover rate, which represents the probability of swapping bits for two strings to create new offspring strings out of selected parent strings and the mutation rate, which represents the probability of flipping bits within a string to introduce random changes in a solution population.

The spreadsheet model was created by formulating activity durations and sequencing, interruptions and cost calculations, multi-objective normalized function, independent variables, and operating constraints, as shown in the following subsections (Salama and Moselhi, 2018c). The developed multi-objective function (MOF) integrated three objectives linearly using the weighted-sum method (Agrama, 2014), which converts the multi-objective optimization problem into a single optimization to minimize objective function. Each objective was multiplied by the weight identified by the decision maker to reflect relative importance. Weights must have a positive value and its summation equals one. However, each objective has different units; MOF was converted into a normalized fitness function to solve this issue, as shown in Equation 4.50:

1

	Quantity (m3)			
	Section 1	Section 2	Section 3	Section 4
Earthmoving	1147	1434	994	1529
Foundation	1032	1077	943	896
Columns	109.2	90.3	129	106.67
Beams	85	92	101	80
Slabs	0	138	114	145

5

Total Quantity (m3)	Activity	crew	productivity	Labour Cost ($/day)	Equipment Cost ($/day)	Material Cost ($/m3)
5104	Earthmoving	1	93.28	566	340	
3948	Foundation	2	71.81	2853	655	92
435.17	Columns	3	8.03	3000	456	479
358	Beams	3	7.07	2544	204	195
397	Slabs	1	9.02	2230	177	186

3

Duration Section 1	Duration Section 2	Duration Section 3	Duration Section 4	Total Duration (days)
12.3	15.4	10.7	16.4	54.7
14.4	15.0	13.1	12.5	55.0
13.6	11.2	16.1	13.3	54.2
12.0	13.0	14.3	11.3	50.6
0.0	15.3	12.6	16.1	44.0

Section 1		Section 1		Section 1		Section 1	
SD	FD	SD	FD	SD	FD	SD	FD
0.0	12.3	12.3	27.7	27.7	38.3	38.3	54.7
13.3	27.7	27.7	42.7	42.7	55.8	55.8	68.3
31.0	44.6	44.6	55.8	55.8	71.9	71.9	85.1
45.8	57.8	57.8	70.9	71.9	86.1	86.1	97.5
0.0	0.0	70.9	86.1	86.1	98.8	98.8	114.9

2

Activity	Crew	Crew Productivity m3/day	Labour Cost ($/day)	Equipment Cost ($/day)	Material Cost ($/m3)	Labour Cost ($/day)	Material Cost	Equipment Cost ($/day)	Indirect Cost (1000$/d)	Total cost
Earthmoving	1	93.28	566	340		30969.811		18603.774		
Foundation	1	92.76	3,804	874	92	156853.42	363216	36010.862		
	2	71.81	2,853	655	92					
	3	54.76	1,902	436	92					
Columns	1	5.73	1,875	285	479	162579.08	208446.43	24712.02	500608.7	
	2	6.88	2,438	371	479					
	3	8.03	3,000	456	479					
Beams	1	9.9	3,931	315	195	128819.24	69810	10329.844		
	2	8.49	3,238	259	195					
	3	7.07	2,544	204	195					
	4	5.66	1,850	148	195					
Slabs	1	9.02	2,230	177	186	98149.667	73842	7790.3548		
	2	8.14	1,878	149	186					
					∑	577371.21	715314.43	97446.855	115877.2	1506010

4

Wc	1	TC*	1506009.73	MOF	0.9
Wt	0	PD*	142.697536		
Wi	0	DI*	23.0299062		

Figure 4.42. Optimization spreadsheet. (1st red block: input of quantities for activities, 2nd red block: input of different crews for each activity along with its productivity rates and costs, 3rd red block: calculation of durations for activities and start and end dates for all activities, 4th red block: input of relative weights for cost, time, and interruptions and calculations to get minimized MOF, 5th red block: include variables for GA optimization (crew number, productivity, costs).

$$MOF= [W_d \times (PD/PD^*)] +[W_c \times (TC/TC^*)] +[W_i \times (DI/DI^*)] \quad \text{Equation 4.50}$$

Constant values were utilized in this normalization for un-optimized project duration (PD*), total cost (TC*), and duration of interruptions (DI*) suggested by contractor. During each iteration of the GA optimization, the MOF was evaluated using different sets of durations, costs, and interruptions. MOF was utilized to optimize each objective as a single optimization problem by assigning 1 as the weight value for the required objective to be optimized, and 0 for the other two objectives. Of the two above algorithms developed to allow or prevent work interruptions, the user can invoke the one applicable to the case at hand. Independent variables in this model are crew formation that yields the minimum MOF based on optimum crisp productivity rate and assigned weights for objectives, as well as work interruptions. Operating constraints in this model were constraints of precedence among activities, which utilizes “finish to start” relationships that limits activity “i” in each process “j” to start only after completion of its predecessor activity “i-1” in same process “j” and that only one crew can work in each activity.

4.5.5 Fifth module: identification of critical sequence and adding buffers

The main objective of the time–cost-work interruptions trade-off problem is to find non-dominated solutions that form a Pareto front, as shown in Figure 4.43. Optimization objectives conflict with each other (i.e. improvement in one objective may reduce another). Most multi-objective optimization problems do not have one best solution with respect to all objectives. They have a set of solutions known as non-dominated solutions or Pareto front (Ghoddousi et al, 2013). Non-dominated solutions have at least one objective that is better than other solutions. In this case, decision makers select the most suitable solution with respect to project constraints from Pareto front according to their experience. Pareto front is identified by changing the weights of the three objectives and recording the outcome of these trials.

After choosing the optimum solution from Pareto front, the critical sequence of optimum linear schedule was identified using the systematic framework developed by Salama et al. (2017b), as shown in Figure 4.29. This framework identifies the multiple critical sequences using onward and backward procedures to make sure the critical links between activities are utilized at least once. Project, feeding, and resources buffers were assigned at same locations, as suggested by Salama et al. (2017b), to absorb schedule delays due to uncertainty associated with productivity rates in accordance with CCPM rules. According to CCPM, project buffer is the maximum buffer of all identified critical sequences and is assigned at the end of the identified critical sequence. Feeding buffers were added to reduce the effects of delay of non-critical sequences on critical sequences and assigned at the end of resource-critical activities. Resource buffers act as a warning for the controlling resource shortages and cannot be quantified. Resource buffers were assigned before the activities on the critical sequence that required different controlling resources than its preceding activity (Goldratt, 1997). Utilized buffers raise the confidence of meeting project deadlines and milestones, and were calculated using the equations suggested by Salama et al. (2017b).

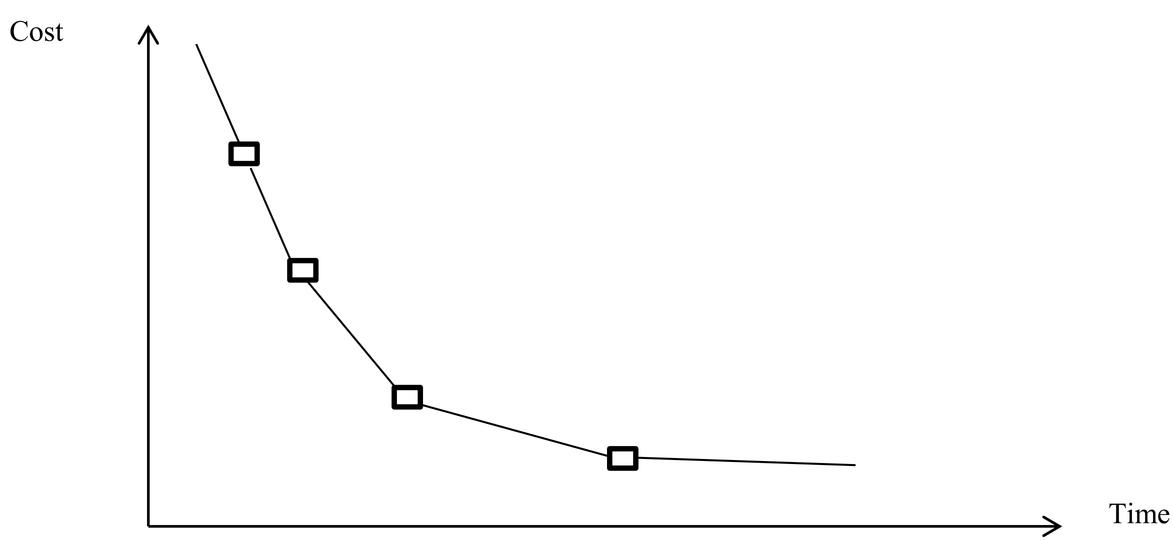


Figure 4.43: Pareto front optimality (adapted from Chen and Weng, 2009)

4.6 Tracking and control model

The main gap found in literature was that the LBMS lacks weekly planning and constraint screening processes and the LPS loses sight of the big picture if not integrated with high level tracking and planning method (Dave et al., 2015). There is also lack of management tools for linear scheduling that account for uncertainties associated with the construction environment such as uncertainties of productivity rates (Bakry et al., 2016). There is a need to develop an integrated framework for tracking and control of activities at strategic and operational levels, while considering uncertainty in productivity rates.

Integrating linear scheduling, LPS, and CCPM generated shorter schedules that consider uncertainty to improve production tracking and control. A comparison shown in Table 4.7 highlights the synergies of the three methods (Salama et al., 2018d). Benefits of the proposed integration are: 1) pulling techniques of LPS fill CCPM gap of cutting 50% of activities durations without justification for this percentage (Herroelen and Leus, 2001); 2) CCPM provides practical features to LPS and LSM by considering uncertainty of durations and by providing time buffers to absorb project delays (Shen and Chua, 2008); 3) combining LPS psychological issues (public promises and public checking of activities completion) and CCPM (student syndrome, what is known as Parkinson‘s law and multi-tasking) enhances reliability of project delivery (Koskela et al., 2010), and 4) LPS, CCPM, and LSM integration provides shorter resource driven schedules because LPS and CCPM resolve schedule constraints (Chua and Shen, 2005).

The proposed method utilizes LPS for monitoring, controlling, and tracking of linear schedules integrated with CCPM. This integration balances between CCPM aggressiveness and LPS reliability (Salama et al., 2018d). This method extends on the work of Seppänen et al. (2010) and Salama et al. (2017b).

Table 4.7: Comparison between LSM, CCPM, and LPS

Criteria	LSM	CCPM	LPS
Method	Non-network	Network	Network
Mode of management	Push	Push	Pull
Utilize buffers	Yes	Yes	No
Consider uncertainty	By integration with Monte Carlo simulation (El-Sayegh 1998) or CCPM (Salama et al. 2017b).	Yes	By integration with CCPM (Shen and Chua 2008).
Consider Concept of flow	Yes	Yes	Yes
Consider psychological issues	No	Yes (Student Syndrome, Parkinson's Law and multi-tasking)	Yes (public promises, public checking of activities completion)
Integration with BIM	Yes (Kenley and Seppänen . 2010)	Yes (Salama et al. 2017a)	Yes (Garrido et al. 2015)

LSM visualizes repetitive activities and respects continuity of resources, CCPM aggressiveness leads to shorter schedules while accounting for uncertainty of productivity rates, and LPS reduces variability of production rates. CCPM is an application of theory of constraints (TOC) (Goldratt, 1997). LPS is a tool of lean production theory which is based on Toyota Production System (TPS) (Ballard, 2000). Detailed processes of LPS are developed to ensure continuous flow of work (Ballard, 2000). CCPM also applies principles of work flow and continuous improvement in project management (Goldratt, 1997). Linear scheduling considers the concept of flow for resources from location to location (Seppänen, 2009). Integrating LPS, LSM and CCPM supports the principles of flow and continuous improvement (Salama et al., 2018d). The proposed method is illustrated in Figure 4.44 and in following steps.

4.6.1 Before project start

BIM software (Vertex BD Pro 2016 22.0) was used to facilitate project modelling. The BIM model helped establish the project database, which included; list of project components (e.g. dry wall) and their respective attributes (e.g. openings), as well as their sequence of onsite erection, productivity rates, resources demands, and availabilities.

The developed method utilized the LPS sequential processes as follows:

1) Master schedule baseline was generated using all previously mentioned steps to integrate LSM and CCPM (Salama et al., 2017a, 2017b). This included calculation of aggressive and safe activity durations, sequencing activities, maintaining continuity of schedule, resolving resources conflicts, identification of critical sequence, and adding feeding and project buffers.

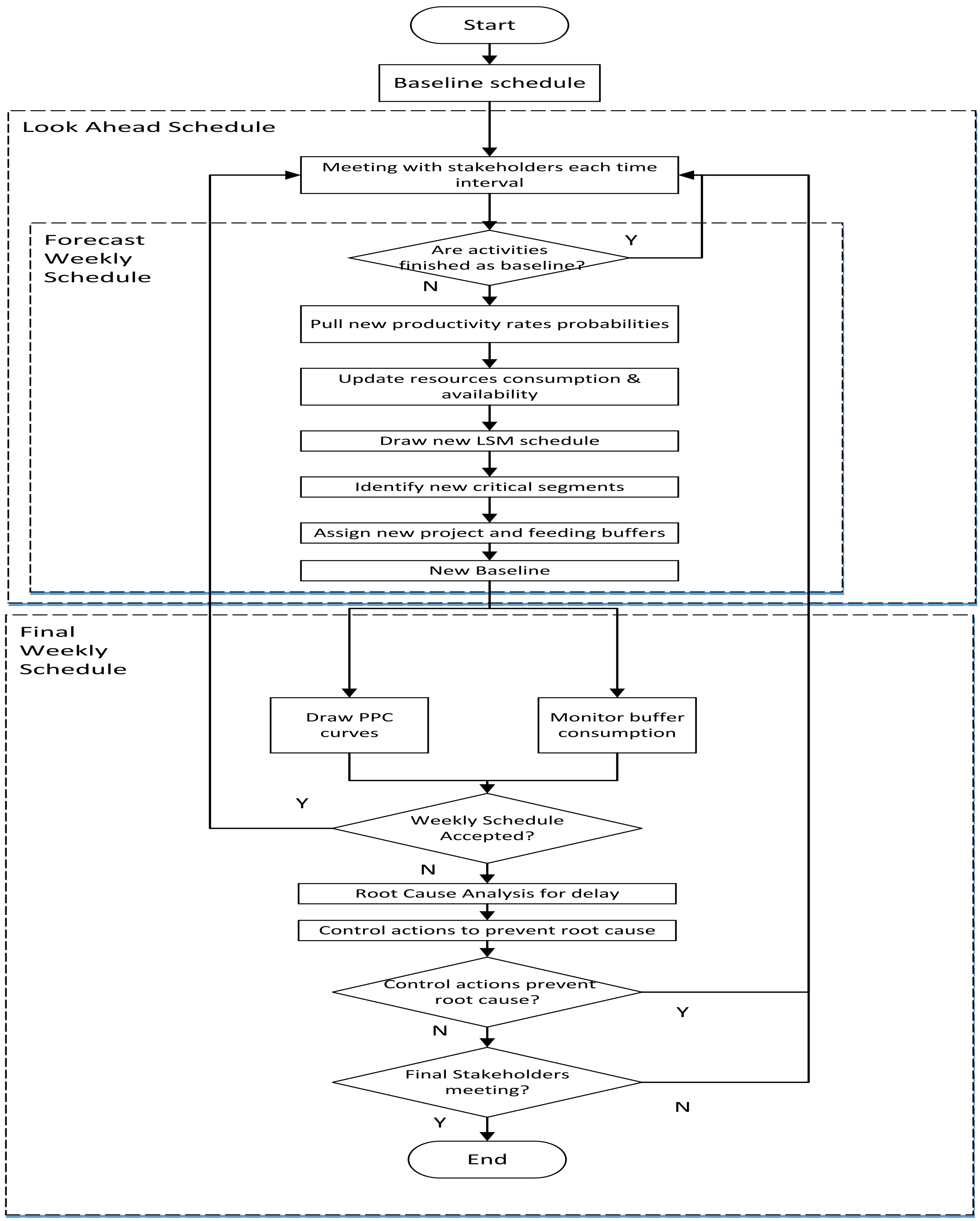


Figure 4.44: The proposed methodology for integrating LSM and CCPM

Project stakeholders organize LPS sessions that provide feedback to generate master schedule baseline using sticky notes by identifying logic of activity sequencing, start and finish timings, expected schedule roadblocks, resources conflicts, and expected productivity rates. According to CCPM, baseline schedule is planned using activity durations with a 50% confidence level using the cut and paste method (C&PM) (Goldratt, 1997). However, this method has been criticized (Herroelen and Leus, 2001; Herroelen, et al. 2002) because it cuts 50 % of activities' durations without justification for this percentage. LPS fills this gap for CCPM because it shields the aggressive schedule against repetitive rescheduling by investigating aggressiveness reliability, while respecting resources continuity by utilizing LSM. LPS is a pull system that specifies due dates and releases information or materials based on project stakeholder feedback. Traditional push systems such as CCPM release information or materials based on targeted completion dates. Pull systems are needed on conditions of variability and uncertainty to provide schedule reliability (Ballard, 2000). Therefore, feedback from project stakeholders changes the aggressive confidence level from 50 % to 60%, 70%, or whatever level they deem appropriate. Aggressive activities durations were calculated based on project stakeholders feedback, considering what can be done instead of what should be done.

Offsite production was planned to follow lean concepts of takt time (TT) and just in time (JIT). TT represents the production speed of an entire production line that satisfies customer requirements, as shown in Equation 4.51 (Yu et al., 2011). Cycle time (CT) is the time required to produce one unit in each process, as shown in Equation 4.52. TT was calculated using Equation 4.51 and indicates the production rate at which products should be produced, while CT was calculated using Equation 4.52 and indicates the actual production rate for each process, as follows:

TT = time according to customer demand for production line / number of units   Equation 4.51

CT = time available for process / number of units   Equation 4.52

Hence, if is CT $\geq$ TT for any process, then this process is conducted according to customer requirements and does not need acceleration. If CT < TT, then the production rate of this process needs to be accelerated (i.e. by adding additional resources) to meet customer requirements. The production line is considered "balanced" when cycle time of each station almost equals the TT, which is the optimum case for production lines (Yu et al., 2011).

JIT is a lean strategy to decrease waste and increase efficiency by receiving resources when needed in production lines (Ko and Chung, 2014);

2) Phase scheduling divided the master schedule baseline into offsite and onsite schedules as separate phases and integrated both schedules by focusing on handoffs between different crews (Salama et al., 2017a);

3) Look-ahead schedules defined the schedule constraints and the roadblocks log was tabled to document resolved and unresolved project constraints; and

4) Weekly work plans (WWP) were produced by breaking down phased integrated schedule (offsite and onsite) to provide a proactive tool in identifying and removing roadblocks.

A quantitative cost analysis of the proposed schedule was developed to monitor project costs as follows:

Direct cost for one crew = (Labour cost + Material cost + Equipment cost) for one crew

Equation 4.53

Average daily direct cost = direct cost for one crew $\times$ average daily productivity for one crew

Equation 4.54

Direct cost for all crews = (Quantities/ Average daily productivity for one crew) × Average daily direct cost Equation 4.55

Indirect cost = project duration (days) × daily indirect cost Equation 4.56

Total cost = Direct cost for all crews + Indirect Cost Equation 4.57

Labour, material, and equipment costs for all activities were utilized to calculate direct cost of each activity for one crew using Equation 4.53. Average daily productivity for one crew was utilized to calculate average daily DC for one crew using Equation 4.54. DC for all crews working in each activity was calculated using Equation 4.55, and IC was calculated using Equation 4.56 based on total project duration and the daily IC for this project. Total project cost is a summation of DC and IC for all crews and was calculated using Equation 4.57.

4.6.2 After project start

According to CCPM, project managers instruct project stakeholders to finish their activities as soon as possible according to the aggressive schedule to avoid psychological problems in project scheduling such as student syndrome and Parkinson's Law. Project progress was tracked to collect actual productivity rates and resources availabilities, as shown in Equation 4.58.

PRi, j (A) = QA / Di, j (A) Equation 4.58

Where, PRi, j (A) represents the actual productivity rate of activity "i" in process "j"; QA represents actual quantity; and Di, j (A) represent actual duration of activity "i" in process "j".

LPS' psychological processes of pulling data from project stakeholders make progress tracking more reliable by acquiring project stakeholders commitment. LPS pull planning brings project stakeholders together to monitor actual project execution by building trust and relationships. It also helps in revealing unexpected problems and opportunities. A big LPS meeting room was prepared with all the tools needed to display the visual outputs for project stakeholders such as PPC trend curves, WWP tables, and Pareto graphs for root causes of variance. These visual outputs needed to be accurate and transparent to facilitate exchanging project information among project stakeholders. The developed BIM model was utilized as a reference during the LPS sessions to increase interoperability among project team, check quantity take-offs, and perform clash detection analysis for the works conducted by different crews.

Project stakeholders meet at the LPS sessions to check if work progress matches schedule baseline, as shown in Figure 4.44. If activities were finished according to schedule baseline, then the plan was considered still valid and project stakeholders meet in the next LPS session. However, if the schedule was delayed, then actual productivity rates were pulled from project stakeholders as well as actual resource consumption and availabilities. LPS ensures continuous flow of work and considers precedence of activities, production efficiency, and future commitments in forecasting. While, EVM does not consider these factors and it cannot be utilized for accurate schedule forecasting because EVM forecasts schedules based on historical progress only (Kenley and Seppänen, 2010). Look-ahead scheduling included in the LPS was forecasted by assuming that actual productivity rates will continue for the rest of the project to generate an updated schedule baseline. Linear regression was utilized to forecast futuristic productivity rates based on actual data from the past for each activity. Unlike the moving average method proposed by Ibrahim and Moselhi (2014), the utilized method considers the whole set of previous productivity rates.

Forecasted productivity rate of activity "i" in process "j" (PRi, j (F)) was calculated using

Equation 4.59 at specific forecasting time (t), after calculating the intercept (a) and slope (b) of linear regression analysis using Equations 4.60 and 4.61, which depends on the productivity rates (PR) of preceding activities at different number (n) of times (t) (Duffy, 2003).

Then, the forecasted activity duration "i" in process "j" at forecasting time t (Di, j (F)) was calculated using Equation 4.62 based on forecasted productivity rate and the remaining quantities of work (Q) that should be accomplished. Equations 4.63 and 4.64 were utilized for the logical sequence of activities:

$$PR_{i,j}(F) = a + bt \qquad \text{Equation 4.59}$$

$$a = \frac{(\sum PR)(\sum t^2) - (\sum t)(\sum[PR \times t])}{n(\sum t^2) - (\sum t)^2} \qquad \text{Equation 4.60}$$

$$b = \frac{n(\sum[PR \times t]) - (\sum t \times \sum PR)}{n(\sum t^2) - (\sum t)^2} \qquad \text{Equation 4.61}$$

$$[D_{i,j}(F)]t = [Q / PR_{i,j}(F)]t \qquad \text{Equation 4.62}$$

$$[SD_{i,j}(F)]t = \text{Max}\,[FD_{i,j-1}(F), FD_{i-1,j}(F)]t \qquad \text{Equation 4.63}$$

$$[FD_{i,j}(F)]t = [SD_{i,j}(F) + D_{i,j}(F)]t \qquad \text{Equation 4.64}$$

Where, t, represent time; a, represent the intercept of linear regression; b represent the line slope of linear regression; [Di, j (F)] t represents forecasted duration of activity "i" in process "j" at forecasting time t; Q represents remaining quantity at forecasting time t; PRi, j (F) represents forecasted productivity rate of activity "i" in process "j", and SDi,j (F) represents forecasted start duration of activity "i" in process "j".

FDi,j (F) represents forecasted finish duration of activity "i" in process "j".

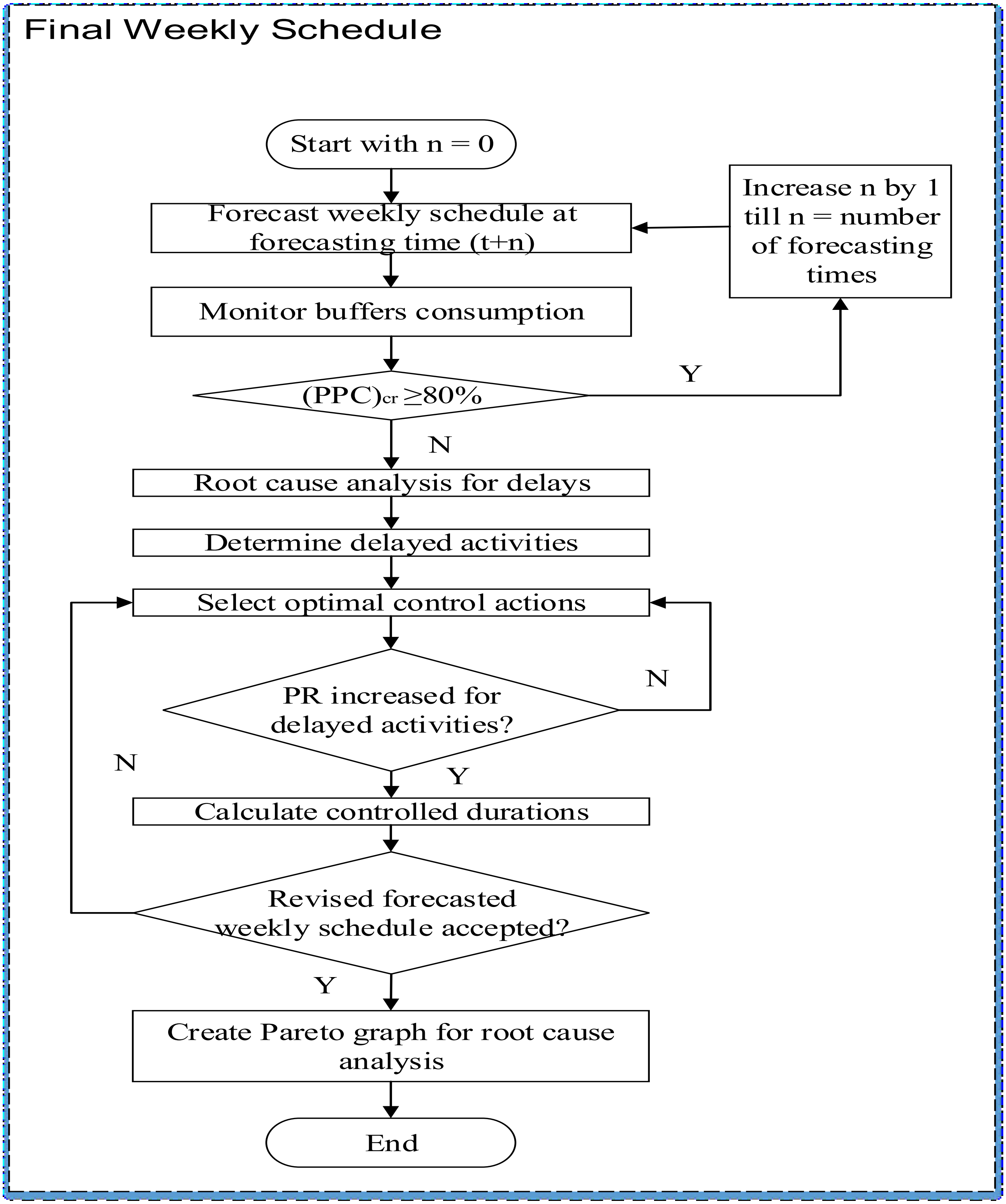


Figure 4.45: Final weekly schedule

A forecasting correction factor Δt (Ibrahim, 2015) was calculated by comparing actual to forecasted productivity rates at time t, as shown in Equation 4.65. To make the forecasting procedure more reliable using historical data by assuming that previous deviation of forecasting is likely to occur again, at forecasting time t+1, the forecasted duration for activity (i+n) was calculated using Equation 4.66:

Δt = (actual productivity rate / forecasted productivity rate) t Equation 4.65

$[D_{i+n,\,j}\,(F)]_{t+1} = [\text{activity quantity} / PR_{i,\,j}\,(F)]_{t+1} \times \Delta t$ Equation 4.66

Then, criticality was calculated for the overall schedule using the updated forecasted durations for all activities using the criticality procedure described earlier (Salama et al., 2017b). The updated forecast for critical activities determines the forecasted duration for overall schedule.

After forecasting WWP, project costs were forecasted during each LPS session using forecasted durations for all activities to ensure that project costs were under control. Each activity's DC was calculated at a specific forecasting time (t) for each LPS session using Equation 4.67. IC was calculated using Equation Equation 4.68 based on forecasted project duration, and total project cost was calculated during each LPS session using Equation Equation 4.69:

(Direct cost) t = [D (A) + D (F)] t × Average daily direct cost. Equation 4.67

(Indirect cost) t = [Forecasted project duration (days)] t × daily indirect cost Equation 4.68

Total cost = (Direct cost) t + (Indirect cost) t Equation 4.69

Where, D (A) is the summation of actual durations for all activities in process "j" before forecasting time (t) and D (F) is the summation of forecasted durations for all activities in process "j" after forecasting time (t).

Monitoring project progress is essential to agreeing upon the final weekly schedule. This procedure included two steps to fulfill LSM, CCPM, and LPS requirements. The first was calculating the percent plan complete (PPC) at the activity level for all processes according to LPS to conclude the reliability of performing each process and performance of each crew according to plan using Equation 4.70. At project level, critical percent plan complete $(PPC)_{cr}$ was calculated only for the critical activities using Equation 4.71 (Salama et al., 2018d). Emdanat and Azambuja (2016) presented a percent required completed or on-going (PRCO) metric to measure the level of completion for critical activities in network scheduling. $(PPC)_{cr}$ measures percentage completion of critical activities in linear scheduling. In the next step, project and feeding buffers were monitored using buffer index (BI) to evaluate the performance of the project using Equation 4.72:

PPC = number of planned activities completed / total number of planned activities Equation 4.70

$$[(PPC)\ cr]_t = \frac{(\text{number of completed critical activities})_t}{(\text{number of planned critical activities})_t}$$

Equation 4.71

(BI) t = (Actual buffer consumption / Planned buffer) t Equation 4.72

If both PPC and BI were found suitable according to the experience of the project manager, and the forecasted baseline schedule and cost adequate, then the weekly forecasted schedule was considered final and project stakeholders meet at the next LPS session to follow up on project progress. If the PPC equaled to 100%, then no delay occurred in the project. If it equaled the targeted percentage by project stakeholders (e.g. 85% or more), then planning was considered reliable, and if it was below the targeted percentage, then a control action was deemed necessary. BI measures consumption of allocated buffers to ensure reliability of schedule. If BI equaled 100%, it meant the whole buffer was consumed. However, when BI was at 0%, then work was accomplished without delay (Salama et al., 2018d).

If the project manager did not approve any of the measured PPCs, BIs, or forecasted weekly schedule and cost, as shown in Figure 4.45, then root cause analysis was performed to identify the main cause of delay. The Five Whys analysis was utilized as a lean tool to solve root causes of the encountered problems by asking the question “why” five times (Ohno, 1988). This analysis separates apparent symptoms from root causes of problems by repeating several questions that start with “why”. The answer to the preceding question is utilized to formulate the next inquiry and sequence of questions. This analysis was performed until no more “why” questions were required to determine root causes (Benjamin et al., 2015). Control actions were suggested to address the root cause of delay by changing quantity of resources, working overtime, changing shift length, reducing non value activities such as materials handling and waiting, etc. Control actions outcome was monitored to investigate their effect on removing root causes of delay. Each root cause of delay (variance) was depicted using Pareto graphs to show statistical trends and determine what needs control actions. Pareto graphs enhance learning curves for activities because they identify reasons for variance.

Chapter 5: Developed Software "Mod-Scheduler"

5.1 Introduction

This chapter explains how the scheduling software prototype named "Mod-Scheduler" was developed to schedule offsite and onsite activities for modular and offsite construction. Calculations for this software were based on the scheduling and buffering model introduced in Chapter 3, which integrated LSM and CCPM to schedule repetitive projects while considering uncertainty of productivity rates. The overall schedule was composed of an upper schedule for offsite activities and lower schedule for onsite activities, as shown in Figure 5.1. This overall schedule was generated after five sequential steps were followed: 1) calculation of aggressive and safe activity durations for offsite and onsite activities, 2) sequencing activities based on aggressive durations, 3) integration of offsite and onsite schedules by identifying the critical controlling link between both schedules (critical controlling link is shown as a green line connecting offsite and onsite schedules, as shown in Figure 5.1, 4) identification of overall critical sequence (shown as the green line in Figure 5.1), and 5) adding feeding and project buffers (shown as yellow and red lines, respectively, in Figure 5.1).

5.2 Design

Software design is explained in the next sections by introducing two levels of technical design. The first is high-level technical design, which discusses the main softwares utilized to build "Mod-Scheduler". The second is low-level technical design which discusses properties of inputs and sequential steps to generate the outputs drawn as the overall schedule for offsite and onsite activities, as shown in Figure 5.1.

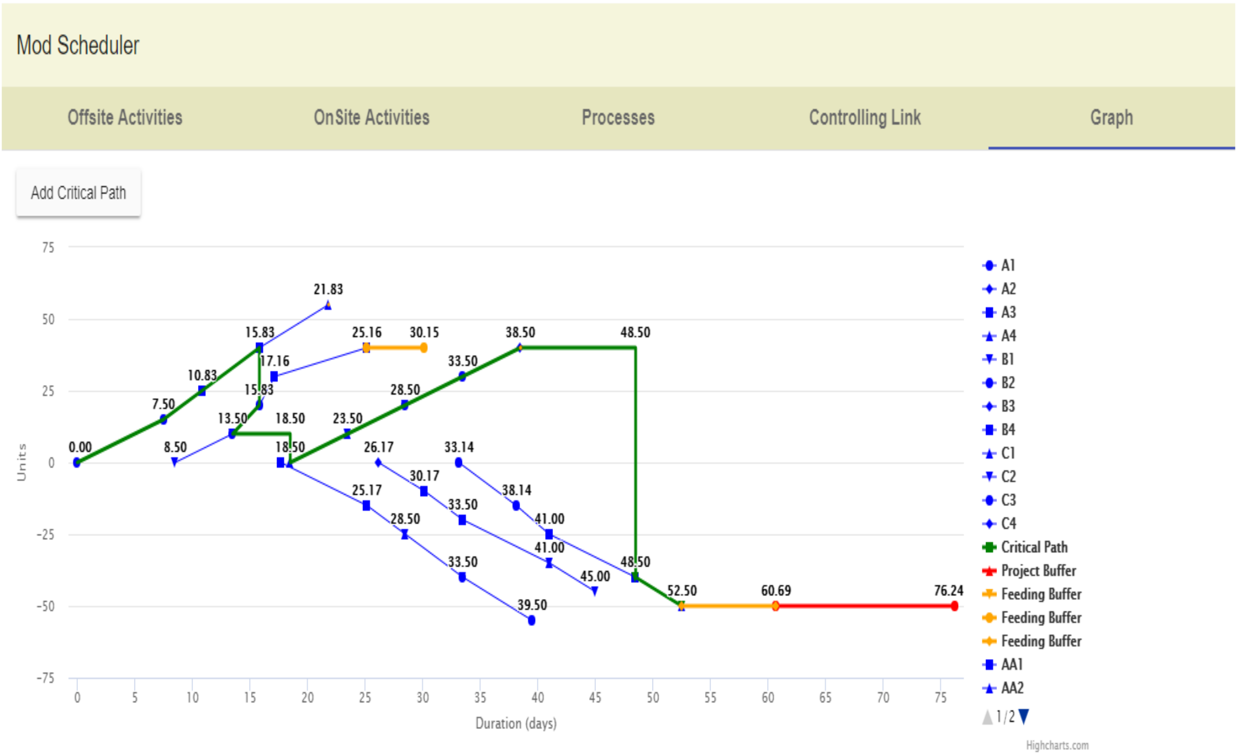


Figure 5.1: Overall schedule (software output)

5.2.1 High-level technical design

“Mod-Scheduler” was programmed as a three-tier application system comprising of: 1) web front-end as the presentation layer coded using Angular, Javascript (JS), hypertext markup (HTML) and cascading style sheets (CSS) languages; 2) ASP.NET core back-end system written in C# to process the information, and 3) SQL server database to store the information.

“Mod-Scheduler” was developed as a web application to benefit from tools and services brought by web technologies, which have became the norm in building software applications. The main advantage of web applications is their ability to be accessed from any computer connected to the internet, without needing to download or install developed software. Web applications are easily deployed and its versions are easily updated. They also benefit from third-party libraries, which draw interactive charts.

The back-end system used the ASP.NET web application programming interface (API), which is a framework that facilitates building hypertext transfer protocol (HTTP) services to reach a broad range of clients, including browsers and mobile devices. “Mod-Scheduler” is currently self-hosted (works without a server to run the application), but can later be hosted on the cloud where it can be accessed over the internet. The front-end application and the back-end system communicate together using messages coded in JavaScript object notation (JSON) data format over an HTTP connection.

The back-end system was structured using a layered architecture that contains the following layers, as shown in Figure 5.2:

- Controller layer: Receives the request coming from the web application, performs authentication and authorization, and passes it on to service layer;
- Service layer: Processes incoming data, performs calculations and in case of data needing to be stored in database, and passes it to the repository layer; and
- Repository layer: Responsible for centralizing database operations.

The repository layer communicates with the database through an object/relation mapping (ORM) framework which is also called entity framework that enables developers to work with relational data as domain-specific objects. Using the entity framework, developers issue queries, using the language integrated query (LINQ) framework, and retrieve and manipulate the data as strongly typed objects.

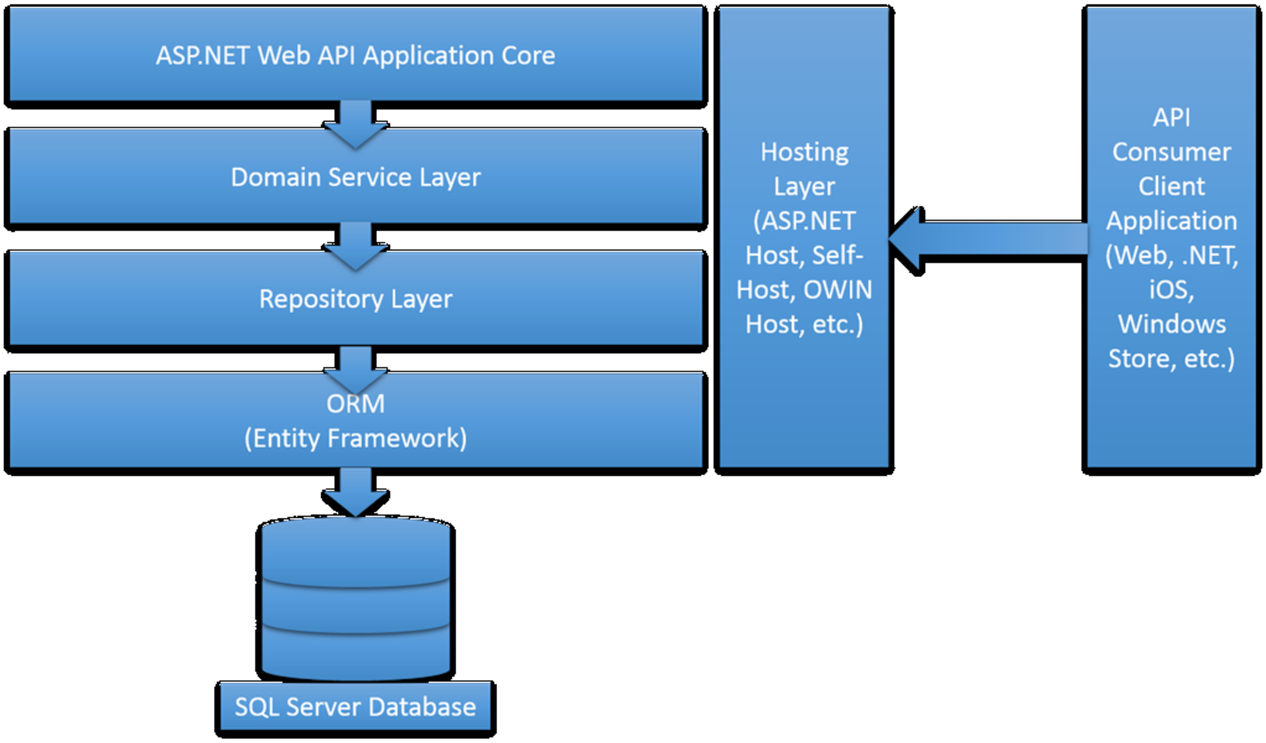


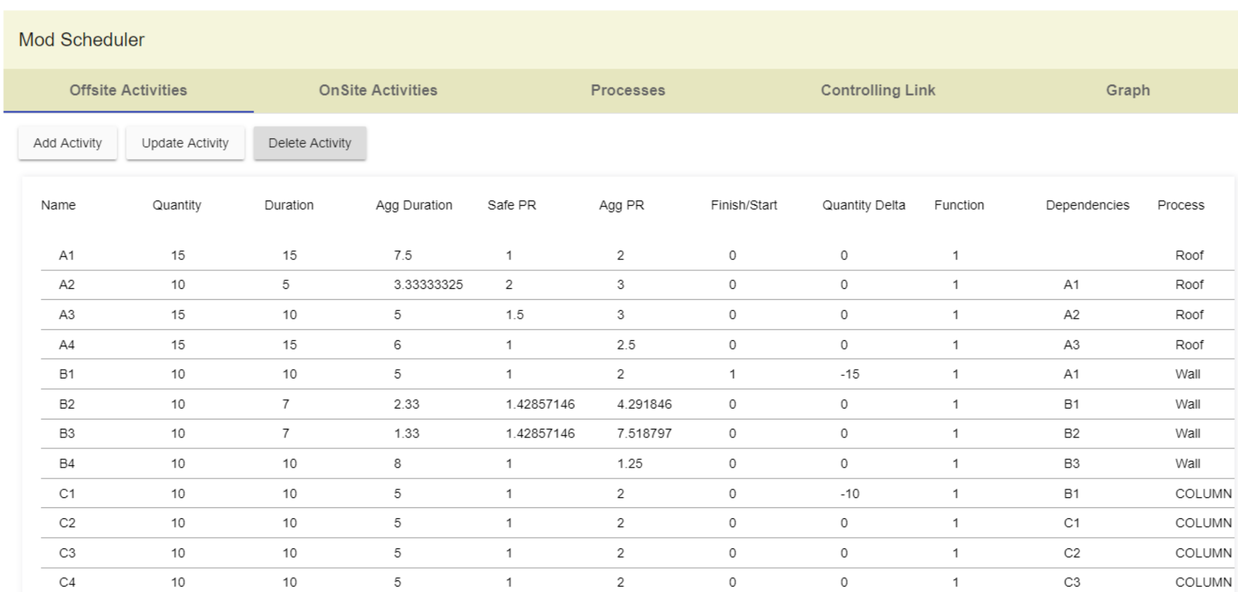
Figure 5.2: Architecture of high-level technical design

5.2.2 Low-level technical design

The first input screen contains basic inputs related to offsite schedule, as shown in Figure 5.3 and Table 5.1, such as process name (process contains several activities), activity name, quantities/units, dependencies between activities, and lag durations. The user has the choice of entering aggressive and safe durations, or entering aggressive and safe productivity rates to calculate safe and aggressive durations using Equations 4.20 and 4.21. After the user completes the first input screen basic inputs, the second input screen is launched to enter the details of the onsite schedule. Toggling between different screens is easy using selected tabs at the top of each window. The third input screen connects offsite and onsite schedules by clarifying the position of the CCP using the finish to start relationship between the end of an activity in offsite schedule and the start of an activity in onsite schedule. The front-end gathers this information for all offsite and onsite activities and displays them, as shown in Figure 5.3.

Table 5.1: Input properties

Name	**Type**	**Description**
Id	int	Technical identifier for activity
Name	string	For example, adding base columns
Units	float	Amount of work needed to complete the activity (quantities)
SafeDuration	float	Duration estimate + safety time
SafeProductivity Rate	float	Set directly or computed based on Units divided by safe duration.
Aggressive Duration	float	Average duration estimate without safety time
Aggressive ProductivityRate	float	Set directly or computed based on Units divided by aggressive duration
Process	Process	Links an activity to a process (example: walls, floor, ceiling)
StartToFinish	Float	Adds a time lag between the start of current activity and the end time of preceeding activity.
Lag / Unit Delta	Float	Adds a unit lag between the start unit of current activity and the end unit of preceeding activity.
Dependencies	List<Activity>	List of activities that depends on current activity. This determines relationship among activities.
Type	Int	Whether it is an offsite or onsite activity



Name	Quantity	Duration	Agg Duration	Safe PR	Agg PR	Finish/Start	Quantity Delta	Function	Dependencies	Process
A1	15	15	7.5	1	2	0	0	1		Roof
A2	10	5	3.33333325	2	3	0	0	1	A1	Roof
A3	15	10	5	1.5	3	0	0	1	A2	Roof
A4	15	15	6	1	2.5	0	0	1	A3	Roof
B1	10	10	5	1	2	1	-15	1	A1	Wall
B2	10	7	2.33	1.42857146	4.291846	0	0	1	B1	Wall
B3	10	7	1.33	1.42857146	7.518797	0	0	1	B2	Wall
B4	10	10	8	1	1.25	0	0	1	B3	Wall
C1	10	10	5	1	2	0	-10	1	B1	COLUMN
C2	10	10	5	1	2	0	0	1	C1	COLUMN
C3	10	10	5	1	2	0	0	1	C2	COLUMN
C4	10	10	5	1	2	0	0	1	C3	COLUMN

Figure 5.3: Properties of activities

5.3 Inputs

Interface of "Mod- Scheduler" includes four input screens for offsite activities, onsite activities, processes, and controlling link between offsite and onsite schedules as shown in Figure 5.3. It also includes one output screen named "graph" which generates the integrated overall schedule as shown in Figure 5.1. Inputs of the first screen for offsite activities are shown in Figure 5.4. Adding an activity to this screen requires ten inputs to be entered to the screen of offsite activities as follows: 1) name of activity, 2) quantity of this activity (e.g. 10 cubic meters of concrete), 3) the choice between inputing aggressive and safe productivity rates to calculate activity durations or inputing durations directly, 4) safe productivity rate or safe activity duration, 5) aggressive productivity rate or aggressive activity duration, 6) lag duration included for the finish to start relationship of this activity and preceeding activity, 7) entering the Y axis coordinates of the start duration for any activity which is related to the Y axis coordinates of the finish duration of its preceeding activity (e.g. if activity B1 is successor to activity A1 with a finish to start relationship, and quantity of activity A1 includes 15 units which means that the Y axis coordinates of its finsih duration is 15 units , then a "quantity delta" of (-15 units) is entered so that the start of activity B1 starts at 0 for its Y axis coordinates), 8) name of process for each activity, 9) input of a duration function which can be either (max or none) to sequence activities that have two predessor activities (e.g. if activity B2 has two predessor activities A1 and B1 which are both related to activity B2 with a finish to start relationship, then the duration function is selected to be (max) so that the start of activity B2 equals the maximum of the finsih duration of activities A1 and B1, and in case activity B2 has only one predessor activity, then the duration function is selected to be (none)) , 10) entering the name of activity that preceeds the current activity.

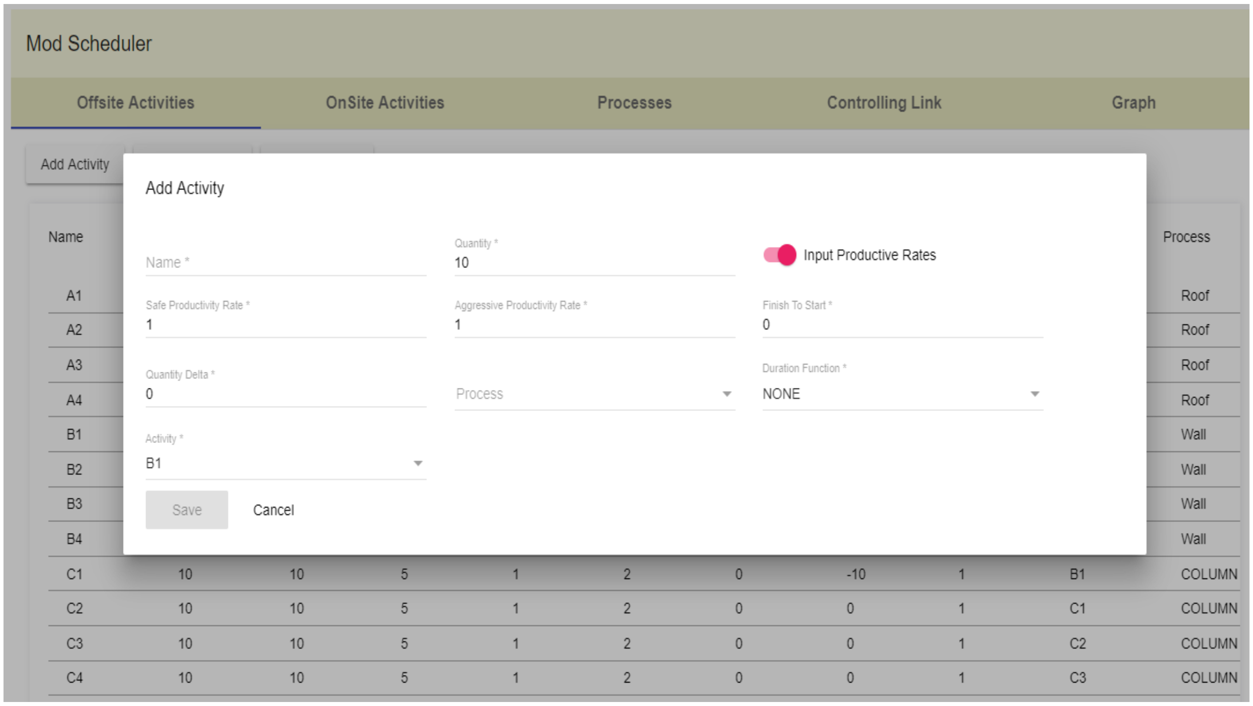


Figure 5.4: Inputs for offsite activities

Inputs for the second screen of onsite activities are shown in Figure II.1 in appendix II, and this screen requires ten inputs to add an activity as the previously explained inputs for offsite activities. Names of work processes for offsite and onsite activities (e.g. floor, columns, etc.) are also inputs in the third screen as shown in Figure II.2. Inputs of the fourth screen for the controlling link between offsite and onsite schedules requires three inputs as follows: 1) name of offsite activity that connects to onsite schedule, 2) name of onsite activity that connects to offsite schedule, 3) transportation duration to trasport panels/modules from offsite manufacturing facility to construction site as shown in Figure II.3. The output screen named " graph" draws both offsite and onsite schedules before identifying the overall critical sequence or adding buffers as shown in Figure II.4. Then by pressing the button named " add critical path" on this screen, the overall critical sequence is idientfied and the feeding and project buffers are identified automatically. The final output screen is shown in Figure 5.1.

“Mod-Scheduler” draws the overall schedule using inputs of activities by applying a set of equations and procedures at different levels according to the following five sequential steps:

- Step 1: Calculation of aggressive and safe activity durations for offsite and onsite activities The overall schedule shows two schedules, an upper one for offsite activities and a lower one for onsite activities. Duration of each activity in both schedules is entered directly, or can be calculated using Equations 4.20 and 4.21 using quantities of each activity and agressive and safe productivity rates.

- Step 2: Sequencing of activities based on aggressive durations. The aggressive schedule is sequenced using Equations 4.23 and 4.24 for each of offsite and onsite schedules separately. Then, the start of any activity is shifted if needed using time or unit lags through the X or Y axis respectively for the developed schedule;

- Step 3: Integration of offsite and onsite schedules.The critical controlling link between offsite and onsite schedules is determined by entering a finish to start relationship between an activity in offsite schedule and an activity in onsite schedule.

- Step 4: Identification of overall critical sequence. The procedure illustrated in Figure 4.29 to calculate multiple critical sequences for repetitive scheduling is coded for each of the offsite and onsite schedules separately. After the two schedules are connected using the critical controlling link, “Mod-Scheduler” determines the overall critical sequence for the overall schedule that generates the longest project duration after adding feeding and project buffers; and

- Step 5: Adding feeding and project buffers. Project and feeding buffers are calculated using Equations 4.31 and 4.32 for the overall critical sequence, represented as red and yellow lines, respectively. Activities and overall critical sequence are represented as blue and green lines, respectively, as shown in Figure 5.1.

Chapter 6: Case Examples

6.1 Introduction

This chapter presents analyzed case studies that were drawn from literature and utilizes collected data from a manufacturing facility for modular construction in Edmonton, Alberta. The purpose is to demonstrate different features and charecteristics of the developed models and to introduce its benefits and limitations. Four different case studies are explained in this chapter in detail. The first case study is introduced to illustrate the use of the proposed indices that accomplish near optimum selection of module configurations for modular construction and then a second real case study is presented to select optimum panel dimensions for hybrid construction based on architectural, structural, manufacturing, and transportation constraints. The third case study, drawn from the literature, is analyzed to demonstrate performance of scheduling and optimization models. The reason behind using this case study is to allow for comparing results with previous methodologies presented by other researchers. The fourth hypothitical case study utilizes real data collected from a manufacturing facility for modular construction, as well as data drawn from literature to showcase the developed tracking and control model for modular and offsite construction. This model embraces BIM and integrates LPS, LSM, and CCPM, while considering uncertainties associated with activity durations.

6.2 Case example for near optimum selection of module configurations

This case study is presented to illustrate the use of proposed indices and to validate the proposed methodology by comparing indices values for the manufacturing of two projects in three different cities (Ottawa, Quebec City, and Kingston) by three different manufacturers. Each manufacturer developed one project as design A and one project as design B, as shown in Figure 4.6, while this project was constructed in Montreal after comparing the three manufacturers cost penalty indices and comparing design A to design B as follows.

6.2.1 Connections Index (CI)

All connections were identified for designs A and B, and then the number of each connection type was multiplied by the assigned cost penalties, as shown in Table 6.1. However, the cost penalty of design A is different from design B due to the difference of loading on each connection type which affect the capacity and sizes of that connection.

Connection penalty costs were calculated, as shown in Table 6.1, as 2015 for design A and 1720 for design B. Then, Equation 4.3 was used to calculate the connection indices for design A and design B as 1.17 and 1, respectively. This indicates that the cost of connections in design A is higher than that of design B because it has a larger number of modules and accordingly, a larger number of connections.

6.2.2 Transportation Dimensions Index (TDI)

This index was calculated using Equation 4.5 after identifying the required number of trucks for designs A and B. Thirteen (13) single-drop deck trailers were needed for design A to transport 18 modules: three trucks for modules 3, 5, 9, 11, 15, and 17 with a rate of two modules per truck, one truck for modules 4, 10, and 16 with a rate of three modules per truck, and nine trucks for modules 1, 2, 6, 7, 8, 12, 13, 14, and 18 with a rate of one module per truck. Eight trucks were required to transport the modules of design B; each module was transported by one single-drop deck truck except the middle module in the first and second floors which shares one truck. The TDI was then calculated as 1.25 for design A and 0.9 for design B, which indicates that module arrangements for transportation is more economical for design B because the area of trailers is used efficiently.

6.2.3 Transportation Shipping Distance Index (TSDI)

The distances between the construction site in Montreal and the three manufacturers in Ottawa, Quebec City, and Kingston were identified from Google Maps, as shown in Figure 6.1. The distances between Montreal and Ottawa, Quebec City, and Kingston were 123, 157 and 179 miles, respectively. These distances were used in Equation 4.6 to identify the transportation value comparing to the practical transportation distance of 125 miles.

Table 6.1: Connections Codes and its Arbitrary Cost Penalty

Connection	**Code**	**(Design A)**			**(Design B)**		
		Arbitrary Cost Penalty	**Number of connections**	**Total cost penalty**	**Arbitrary Cost Penalty**	**Number of connections**	**Total cost penalty**
External connection	1	20	42	840	30	24	720
Internal connection	2	15	39	585	20	0	0
MEP connection	3	10	11	110	10	12	120
Vertical circulation connection	4	20	20	400	30	24	720
Corner connection	5	10	8	80	20	8	160
Total cost penalty				2015			1720

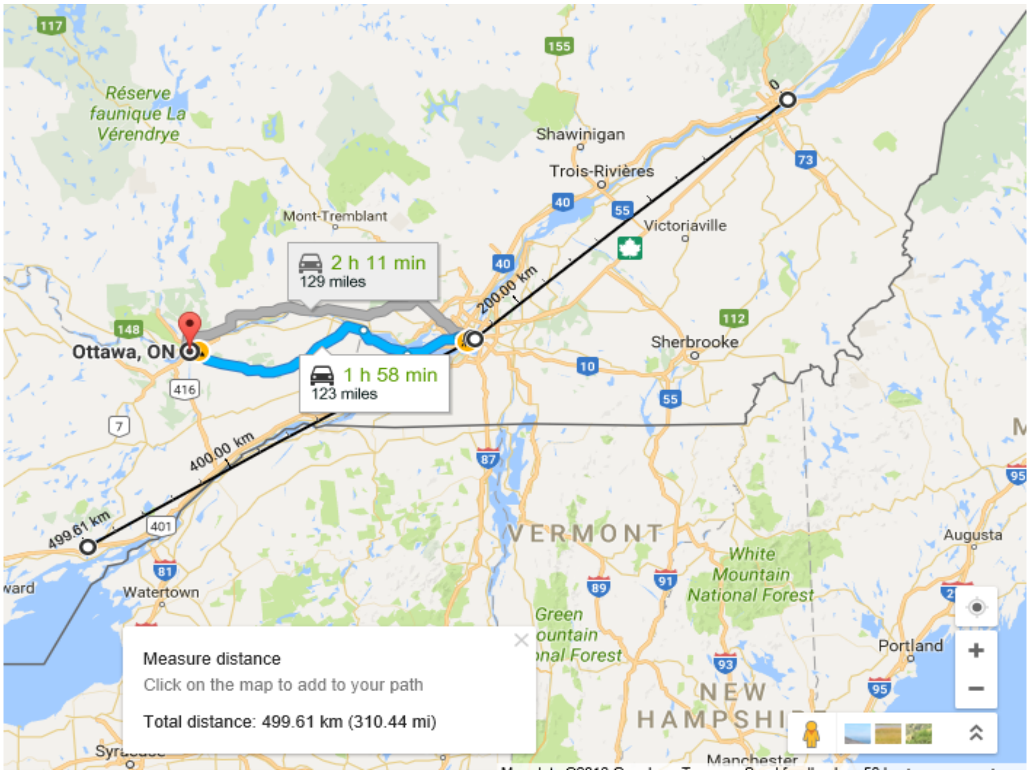


Figure 6.1: Identifying the distance between Montreal, Ottawa, Quebec city, and Kingston

Transportation values were calculated as 0.98, 1.256, and 1.432, for the distance between Montreal and Ottawa, Quebec City, and Kingston, respectively. The single-drop deck truck cost was assumed to be 1500$ for transporting modules with a width of 12-ft or less, and 3000$ for transporting modules with a width more than 12-ft to account for the required permits and escorts on the road. The average cost for transporting modules with a width less than 12-ft was taken as 3.27$/S.F., while the average cost for modules with a width of more than 12-ft was 5 $/S.F. (Smith, 2010). The TSDI was calculated for manufacturing design A and B as 1.13 and 1.06 for Ottawa, 1.45 and 1.36 for Quebec City, and 1.59 and 1.55 for Kingston. This result indicates that design B is more cost efficient than A regarding transportation distance variable because the number of modules is lower in design B than A. It should be noted that design B has higher truck costs than design A due to the need for permits and escorts even though design B remains more efficient than design A.

6.2.4 Crane Cost Penalty Index (CCPI)

CCP was calculated using Equation 4.7 and the assumed variables are included in Table 6.2. Crane daily working hours were assumed to be eight hours, while the hourly placing rate was calculated as the ratio of assumed daily placing rate over daily working hours. The CCPI was calculated using Equation 4.8 by dividing all CCP to the lower cost penalty, which is the cost penalty for design A in Kingston. Design A proved to be more cost efficient than B regarding CCP. This can be attributed to the lower assumed daily placing rate for design A when comparing to design B due to the heavy weight of design B modules, since design B has only nine modules when comparing to design A, which has 18 modules.

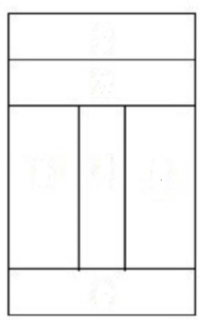
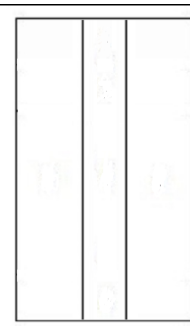
Table 6.2: Crane cost penalty index (CCPI) calculations

City	Design	Crane rental ($/hr)	Number of modules	Daily placing rate	Daily working hours	Hourly placing rate	CCP ($)	CCPI
Ottawa	Design A	437.5	18	10	8	1.25	6300	1.13
	Design B	750	9	6	8	0.75	9000	1.62
Quebec City	Design A	462.5	18	12	8	1.5	5550	1
	Design B	812.5	9	8	8	1	7312.5	1.31
Kingstone	Design A	487.5	18	11	8	1.375	6381.8	1.14
	Design B	875	9	7	8	0.875	9000	1.62

6.2.5 Concrete Volume Index (CVI)

Concrete cost penalty was calculated using Equation 4.9 while considering that the foundation constitutes of strip footings around building perimeter and under modules' connections, as shown in Table 6.3. Strip footing foundation was assumed to have a width of 1-ft and 3-ft of height; hence, concrete foundation volumes of design A and B were 1008 and 864 cubic ft, respectively. By multiplying these volumes to the cost of cubic ft of concrete, which is 14$, the concrete cost penalties were calculated as 14112 and 12096$ for design A and B, respectively. Dividing cost penalty of design A over design B generated the CVI as 1.16 and 1 for design A and B using Equation 4.10. This means that the foundation of design A costs more than that of design B due to the difference in the total number of modules, which require more foundations, as presented in Table 6.3, and accordingly a higher volume of concrete.

Table 6.3: Strip foundation plan lines for design A and B

Design A	Design B
	

6.2.6 Modular Suitability Index (MSI)

The MSI was calculated using Equation 4.11 assuming different values for the relative weights W1 to W5. A sensitivity analysis was performed to investigate the effect of each index on the overall MSI. Relative weight values start at 0.1 for each weight then increase in 0.1 increments until they reach 0.6. For each trial, the specific weight was fixed to a specific value while the rest of the weights for other indices were kept equal. For example, if the relative weight W1 equaled 0.3, then the relative weights W2 to W5 were equal to 0.175.

Figures 6.2 through 6.6 explain the effect of the different indices on the MSI and indicate that, in most cases, design B has a lower MSI though the design of A may be a better option if the relative CCPI weight is higher than 0.3 or TDI is lower than 0.1. Figure 6.7 compares the different cities and designs and indicates that for design B, Kingston is a better manufacturing option because it has the lowest MSI according to the CI.

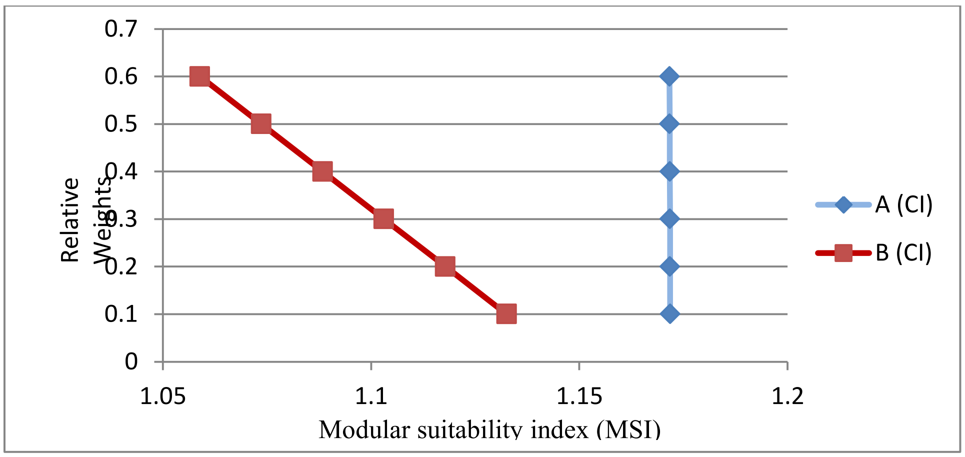


Figure 6.2: Sensitivity analysis for CI effect on modular suitability index while manufacturing design A and B in Ottawa

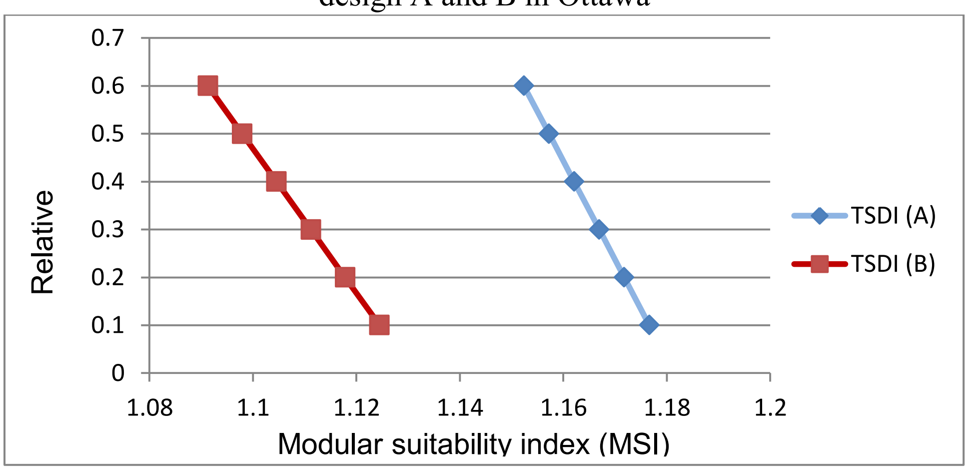


Figure 6.3: Sensitivity analysis for the TSDI effect on MSI while manufacturing design A and B in Ottawa

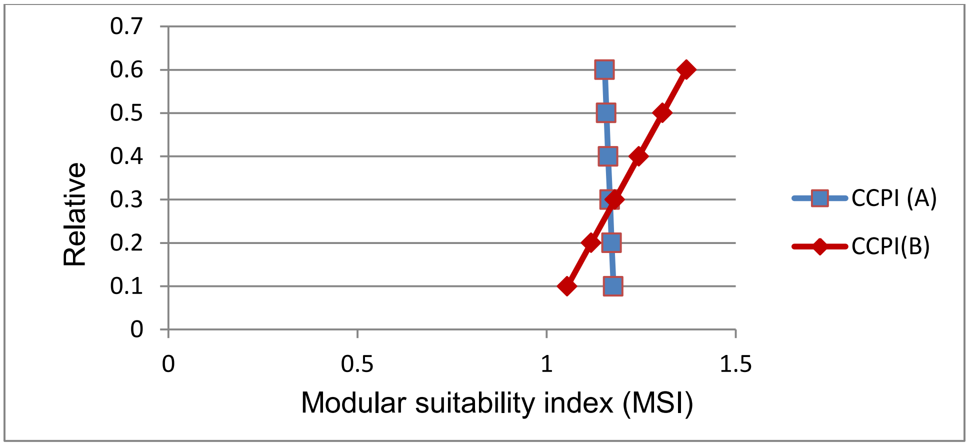


Figure 6.4: Sensitivity analysis for crane the CCPI effect on the MSI while manufacturing design A and B in Ottawa

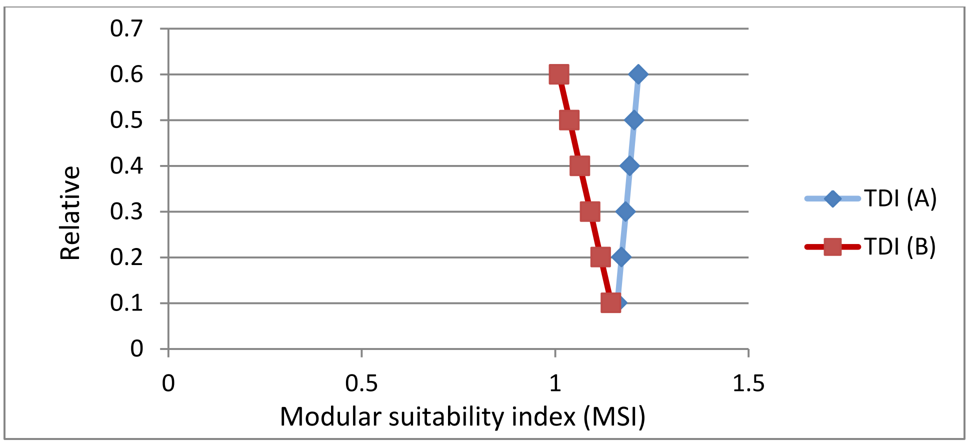


Figure 6.5: Sensitivity analysis for the TDI effect on odular suitability index while manufacturing design A and B in Ottawa

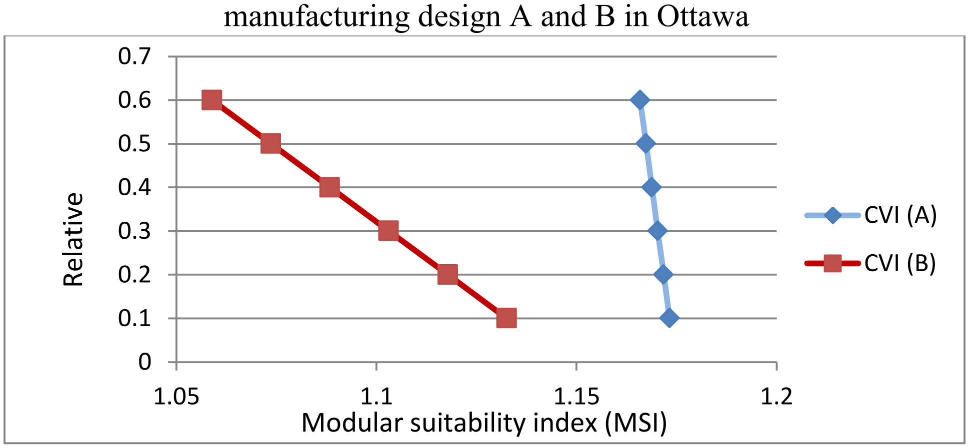


Figure 6.6: Sensitivity analysis for CVI effect on MSI while manufacturing design A and B in Ottawa

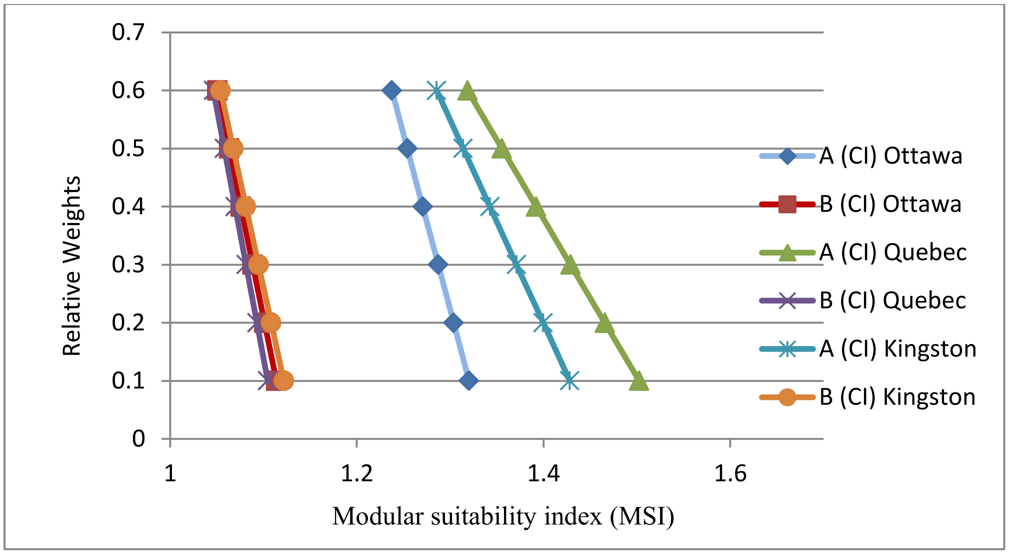


Figure 6.7: Sensitivity analysis for the CI effect on MSI while manufacturing design A and B in for all cities

6.3 Case example for configuration model of hybrid construction

The proposed model was applied on a hybrid construction project in a manufacturing facility in Edmonton, Alberta. This project included fabrication of LGS panels and modular units for residential buildings. This case study is used to demonstrate the applicability of the proposed model and to illustrate its features in selecting the panel dimensions based on architectural, structural, manufacturing, and transportation constraints.

6.3.1 Architectural design

The hybrid residential building was divided into 14 different suites, as shown in Figure 6.8. Each suite has a different plan where the interior panels have different lengths. The most common panel length ranges from 10 to 12-ft because this is the regular practical room width. The red circles shown in Figure 6.9 indicate the panel connections locations where each room has four onsite connections at its four corners and this indicates that the common panel length is dominated architecturally by practical room dimensions.

The studied manufacturing facility manufactured the bathrooms as separate load bearing modules, while the kitchen panels were assembled onsite as a panelized system. The dimensions of the bathroom modules depend on the architectural plan and the number of its accessories. The bathroom dimensions are usually around 9-ft in length by 6-in ft width. Furthermore, the height of the panels in bathroom differs—102” for the ground floors, 120” for the repetitive floors, and 138” for the last floor.

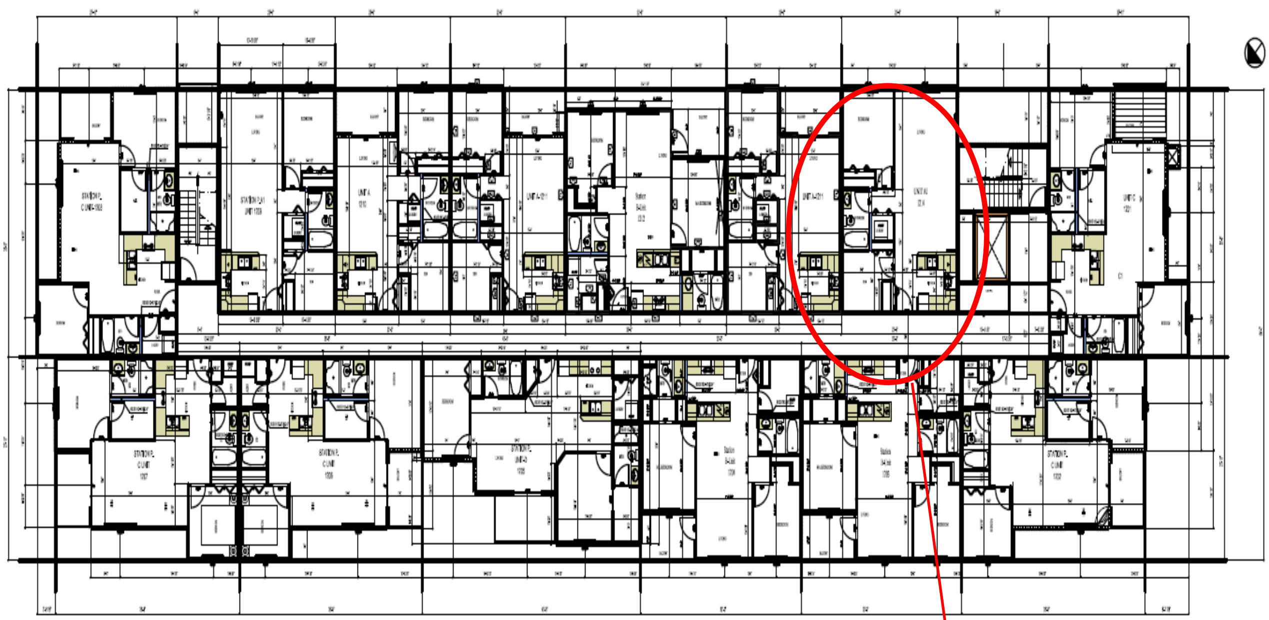


Figure 6.8: Different suits in a hybrid construction project layout

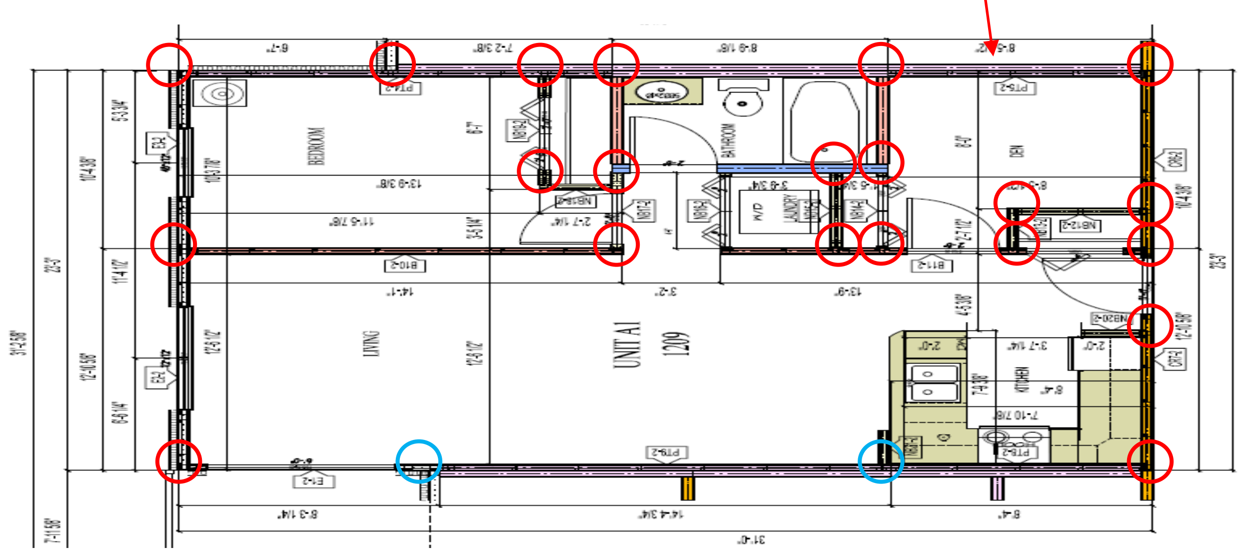


Figure. 6.9: Separate suit layout

6.3.2 The structural design

The manufacturing facility's practice is to manufacture panels of 16-ft in length or less to avoid buckling. However, if the panel length exceeds 16-ft, then the structural design of the panel is changed to introduce a new joint that divides the panel into two panels. If a joint is not possible, then the manufacturing facility considers an increase in panel stud thickness so as to prevent panel buckling. However, increasing the thickness of studs imposes other limitations such as handling on site as well as at the manufacturing facility.

For example, considering a panel that is located on the ground floor having 20-ft in length and 97mm in stud thickness. If the same panel was located on the fifth floor, then the studs of this panel would need to have less thickness because the panel would now sustain less load than when located on the ground floor. In this case, the panel would need to be divided into two panels 10-ft in length and the stud thickness (gauge) lowered so that it would be economical for its sustained load and craned and transported without buckling.

6.3.3 Manufacturing limitations

The manufacturing process in the studied facility integrates static with linear production systems. This process comprises of three manual linear tables, which are the assembly, framing, and sheathing tables. It also comprises eight static racks that allow for performing six sequential processes: waterproofing, foaming, rasping, base coating, priming, and finishing, as shown in Figure 4.22. The main manufacturing limitation in this case study was the framing table that limits the length of panels to 20-ft. This length is actually the maximum length the facility can produce to allow for the framing crew to handle the framing process properly. The facility manager mentioned that the usual panel dimensions on the eight racks was 10-ft in length by 10-ft in height, although the racks can handle any panel length up to the 20-ft limit.

By applying the proposed model on the case study layout shown in Figure 6.9, most of the panel connections were identified based on the architectural design step except for the panel with the blue circles. This panel length was 31-ft; hence, it was divided by the blue left circle that connects this panel to another perpendicular panel. The remaining panel length was 22-ft, as such, it was divided by the right blue circle since the structural design check maximum limit for panel length is 16-ft. As a result, the manufacturing limitations were satisfied since all panels were now less than 20-ft in length.

6.3.4 Transportation limitations

The main transportation limitation for the panels was the trailer height. The transportation limitations in Alberta are 13'7'' for trailer height from the ground level, 8'6'' for trailer width, and 75'3'' for overall maximum trailer length (website of Transportation Alberta, 2017). These transportation limitations are different from province to province and are regulated by the Department of Transporation in each province.

The studied manufacturing facility has three types of trailers according to its dimensions and usage; the trailers dimensions are shown in Table 6.4. The first two trailers dimensions follow transportation limitations of Alberta regarding allowable trailer width, but the trailer's height from ground restricts the panel height to around 10-ft for the first trailer and around 11-ft for the second trailer. Hence, this transportation limitation usually restricts building floor height to about 10-ft.

Given these restrictions, the last floor panel height would reach 15 or 16-ft due to the parapet extension above the same panels, which cannot be transported using the usual trailers dimensions shown in Table 6.4. Hence this facility uses a third truck with an inclined steel frame, as shown in Figure 4.21, to facilitate transportation of panels for the last floor according to stipulated height transportation limitation. However, due to the inclined shape of the panels, the number of panels decreases when compared to trailers 1 and 2. Moreover, it is clear that hybrid and panelized construction are more flexible than modular construction in transportation. Therefore, more manufacturers have started to use hybrid construction to eliminate the dimensional limitations that modular manufacturers currently face (Cameron and Carlo, 2007).

Table.6.4: Trailers Dimensions

Dimensions	**First Trailer**	**Second trailer**
Height from ground level	3’ 5’’	2’ 9’’
Length	35’	24’ 3’’
Width	7’ 9’’	8’

6.4 Case example for scheduling model

The numerical example presented in this section builds upon that of Selinger (1980) for a hypothetical three span reinforced concrete bridge that has four segments (units) with five repetitive processes in each segment, as shown in Figure 6.10. These processes are excavation, foundation, columns, beams, and slabs. This example was used by other researchers deterministically (Russell and Caselton, 1988; Moselhi and El-Rayes, 1993; Nassar, 2005; Liu and Wang, 2007) and stochastically by Bakry (2014). Bakry (2014) included the uncertainty by utilizing fuzzy duration function for activities which is transformed into a deterministic duration (Dur_{EV}), as shown in Table 6.5. Then another duration was assumed based on agreement index (AI) assigned by the user to assess the amount of uncertainty affecting the activity being considered to account for the user desired confidence in the produced schedule.

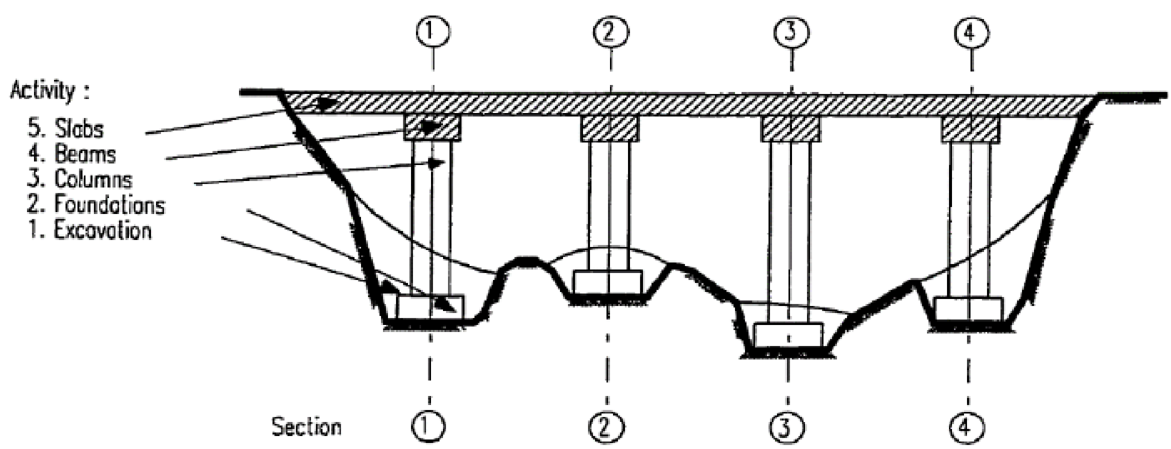


Figure 6.10: Three-span RC bridge (Selinger, 1980)

Table 6.5: DurEV and DurAI for bridge segments (Bakry, 2014)

Activity	Unit 1		Unit 2		Unit 3		Unit 4	
	Dur_{EV}	$Dur_{AI=0.9}$	Dur_{EV}	$Dur_{AI=0.9}$	Dur_{EV}	$Dur_{AI=0.9}$	Dur_{EV}	$Dur_{AI=0.9}$
Earthmoving	12.4	13.2	15.5	16.6	10.8	11.5	16.6	17.7
Foundation	19.5	21.9	20.3	22.9	17.8	20	16.9	19
Columns	19.1	21	15.8	16.9	22.5	25	18.6	20.3
Beams	15	15	16.3	16.3	17.8	17.8	14.1	14.1
Slabs	0	0	17.3	18.7	14.3	15.5	18.1	19.7

The later method was applied, assuming that $D_{i,\ j}$ (AG) = Dur_{EV} and $D_{i,\ j}$ (CL) = $Dur_{AI=0.9}$, to illustrate the differences between the developed method and that of Bakry (2014). Bakry's method adds intermediate buffers at the point of contact of two critical activities, as shown in Figure 6.11. However, the CCPM method emphasizes "safety durations" be removed between activities. Bakry's approach, however, focused on respecting activities' continuity to the maximum by adding intermediate buffers to account for the variability of different activities that may cause unnecessary extended project duration. The proposed method was applied, as shown in Figure 6.12. All the intermediate buffers were removed based on the CCPM, then two feeding buffers were added, as shown in Figure 6.12, after columns and slabs activities. The first equals 2.2 days and accounts for the variability of the first two resources-critical activities for columns process and the second equals 1.8 days and accounts for the variability of the first two resource-critical activities for slabs process, while the first three beam activities do not have a feeding buffer because they have no variability in productivity rates. Then, the project buffer of 5.45 days was added at the end of the critical sequence, which is marked by dotted arrows on Figure 6.12. The project duration in Bakry's study was 163 days with buffers; however, the developed method led to 152.5 days including feeding and project buffers.

The developed method introduces another feature of identifying multiple critical sequences then to add feeding and project buffers. As an illustration of this feature, it was assumed that the duration of the second activity $D_{i,j}$ (AG) of earthmoving was changed from 15.5 to 19.5 days, while $D_{i,j}$ (CL) changed from 16.6 to 20.5. A different critical sequence is shown in Figure 6.13 that includes the second acitvity of earthmoving and excludes the first activity of foundation. Another feeding buffer was added as well at the end of foundation activity to account for the variability of the first activity of foundation with a value of 2.4 days. The project buffer changed as a result from 5.45 to 5.56 days to account for the variability of the new critical sequence and the new project duration changed from 152.5 to 155.16 days. Accordingly, the project total duration was 155.16.

Constraining resources is another feature of the developed method to identify the longest critical sequence constrained by resources while respecting resources continuity constraint. The available output of controlling resources for each activity was assumed, as shown in Table 6.6, with 50% and 90% confidence rates. The total required resources output for all bridge sections were calculated using Equations 6.1 to 6.4.

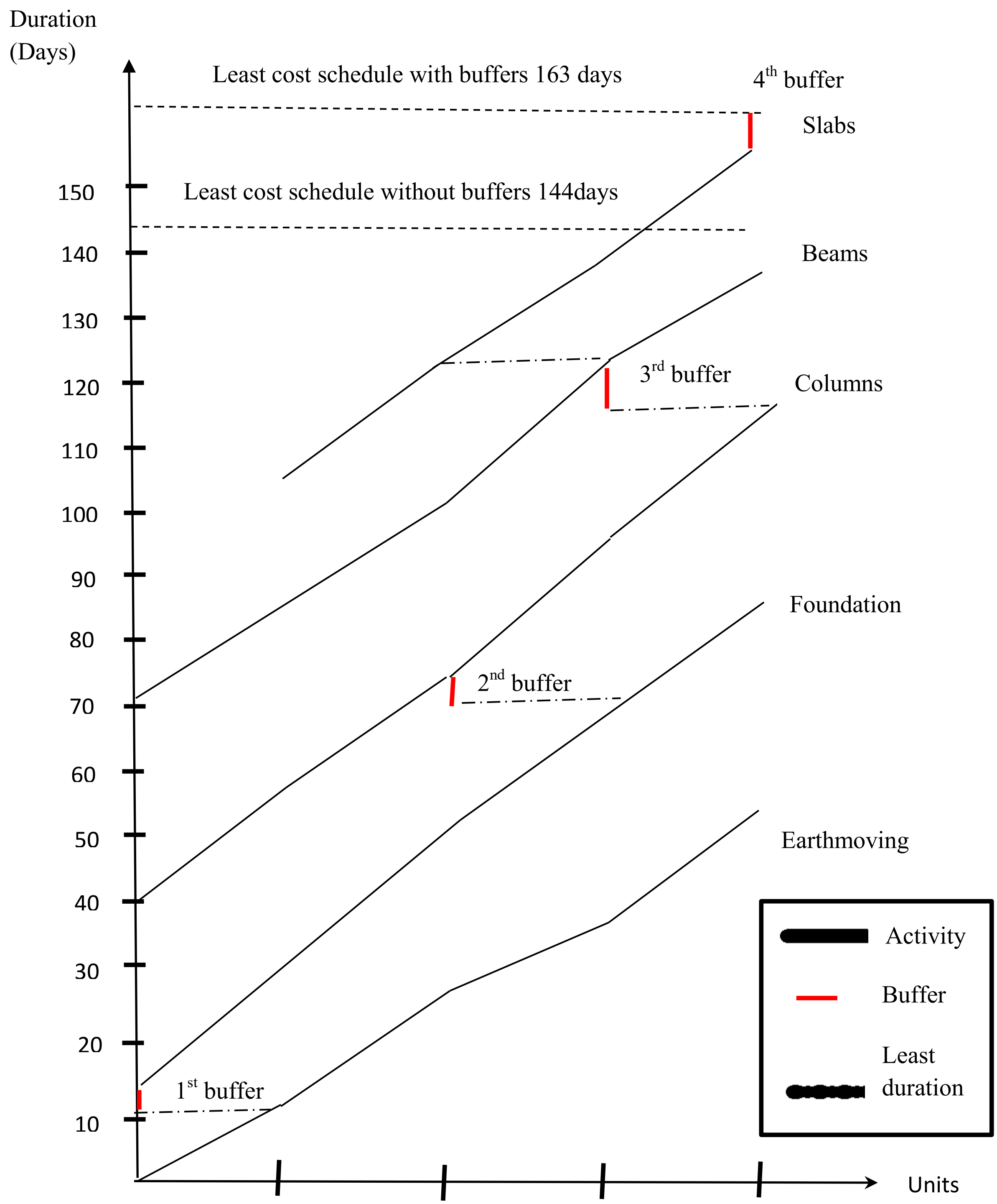


Figure 6.11: Defuzzified schedule with buffers (Adapted from Bakry, 2014)

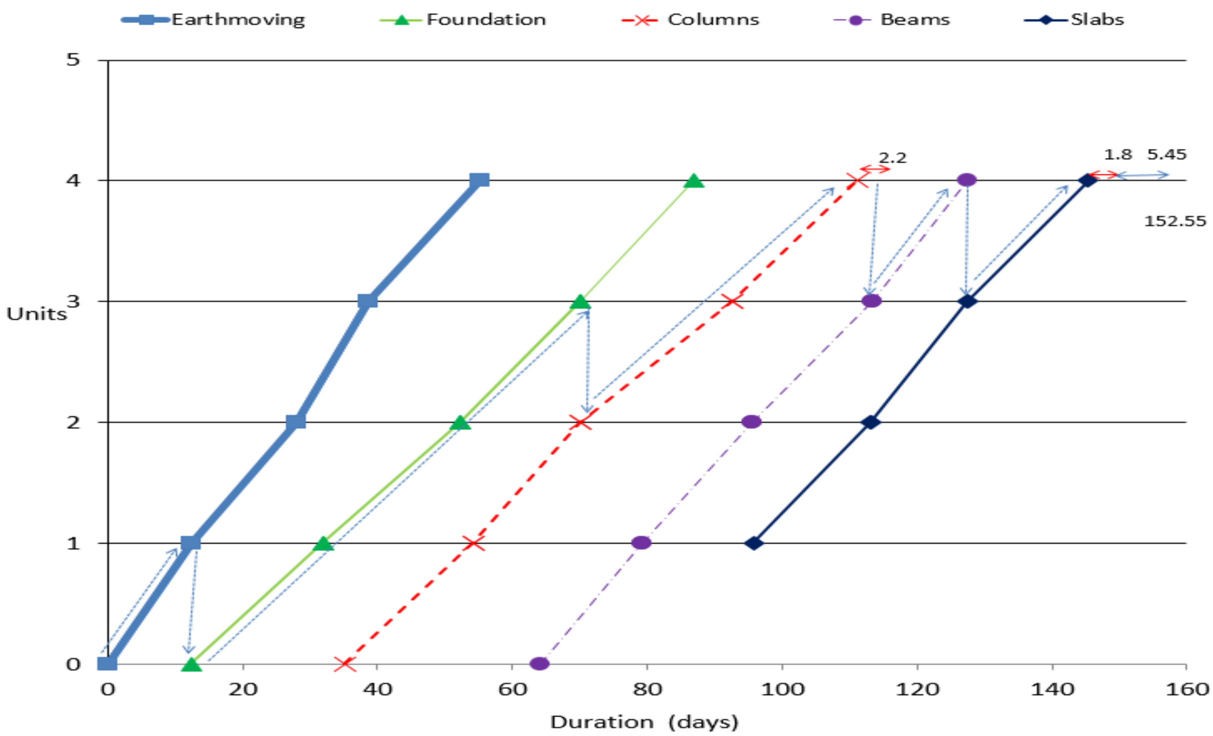


Figure 6.12: Integrated LSM and CCPM schedule

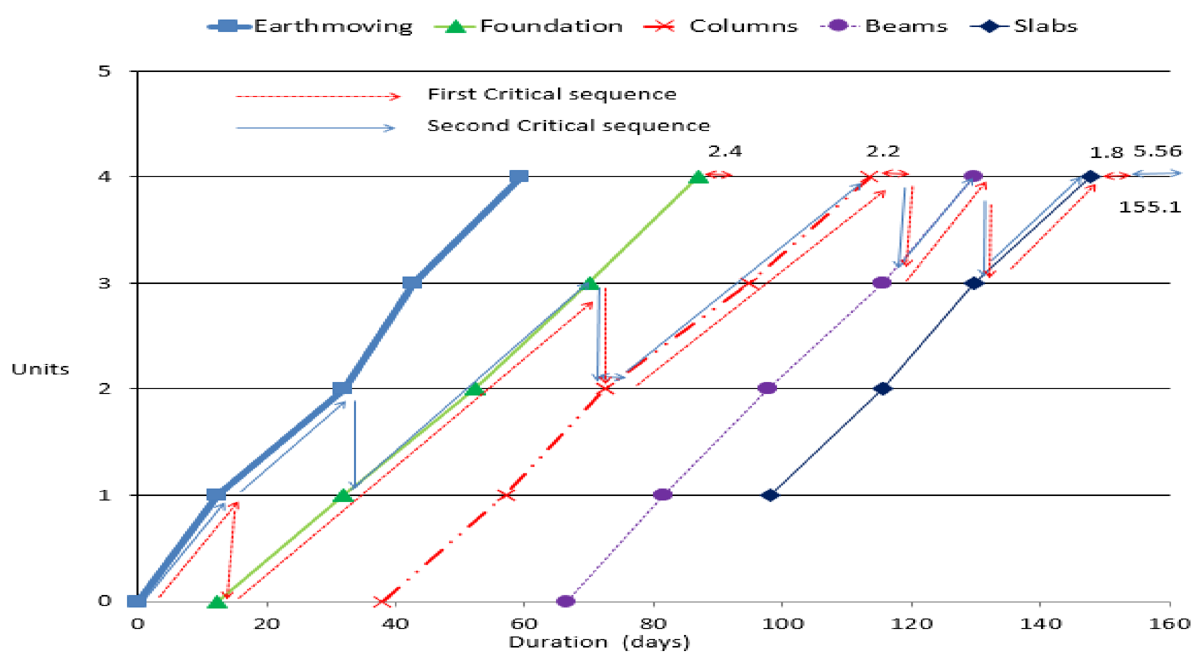


Figure 6.13: Critical sequence

Table 6.6: Controlling resources availability

Activity	Controlling resources	Available Resources output/ (50%) confidence	Available Resources output/ (90%) confidence	Total required resources output			
				Section 1	Section 2	Section 3	Section 4
Excavation	Excavators	3 excavators (23.33 ea. m3/day)	3 excavators (20 ea. m3/day)	1147	1434	994	1529
Foundation (m3/day)	Gravel	27	23.1	794.6	829.3	765.4	689.9
Columns (m3/day)	Sand	2.4	2.3	41.6	34.4	51.6	40
Beams (m3/day)	Sand	2.4	2.3	34	36.8	40.4	32
Slabs (kg/day)	Cement	2100	1750	0	48300	39900	50750

Table 6.7 illustrates the activities quantities as well as the crew output/productivity rates at a 50% and 90% confidence rate (Bakry, 2014). Using CPR of 50% and 90%, the new activities

durations were calculated using equations 4.20 and 4.21, and a new critical sequence was identified using the developed method, as shown in Figure 4.29. Figure 6.12 shows the new critical sequence changed due to resources constraints in foundation, columns, beams, and slabs activities. The project buffer value and the total project duration also changed to 12.8 days and 254.26 days, respectively. The RCB was calculated to be 3.36 days, while the overlap due to resources conflict was 6.73 days and the overlap due to resources quantities variability was 3.36 days. RCB was allocated after the start of beam activity, as shown in Figure 6.14. Resource outputs were assumed and calculated using Equations 6.1 to 6.4 as follows:

Total required gravel outputs = 0.77 × Total foundation quantities. Equation 6.1

Total required sand outputs = 0.4 × Total columns quantities. Equation 6.2

Total required reinforcing steel outputs = 100 kg × Total beams quantities. Equation 6.3

Total required cement outputs = 350 kg × Total slabs quantities. Equation 6.4

Table 6.7: Activities quantities and productivity rates

Activity	Quantities (m3)				Average Crew Output PR (50%) m3/day	Crew Output PR (90%) m3/day	Crew Output due to constraining resources CPR (50%) m3/day	Crew Output due to constraining resources CPR (90%) m3/day
	Section 1	Section 2	Section 3	Section 4				
Excavation	1147	1434	994	1529	92.29	86.52	70	60
Foundation	1032	1077	943	896	52.99	47.12	35	30
Columns	104	86	129	100	5.5	5	6	5.75
Beams	85	92	101	80	5.66	5.66	6	5.75
Slabs	0	138	114	145	7.98	7.36	6	5

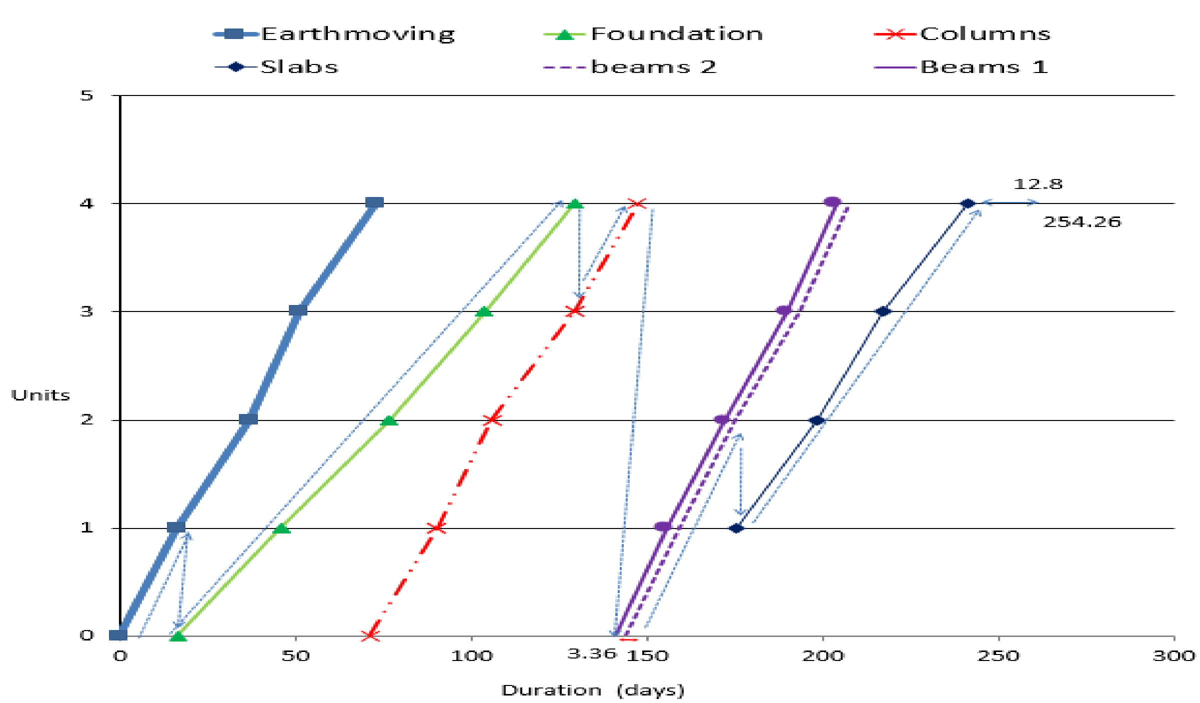


Figure 6.14: Critical sequence based on resources constraints

This case example introduced a newly developed method that integrates LSM and CCPM scheduling methods. The method is capable of (1) respecting the continuity constraint required by LSM, (2) reducing project duration using CCPM aggressiveness, (3) identifying multiple critical sequences which are constrained by controlling resources, and (4) allocating project buffer and feeding buffers at the end of the longest critical chains and between non-critical chains emerging into critical ones based on the CCPM. It also introduced a "resource conflict buffer" to account for delays that may occur due to variability in resource availability. This integration utilised the aggressiveness of CCPM to reduce project durations while respecting the resource continuity as in LSM. Constraining resources changes the critical sequence and project duration. It is important that multiple controlling sequences be identified for they change project duration based on variability of their respective critical chain activities.

6.5 Case example for optimization model

An example project from the literature was analyzed to illustrate capabilities and demonstrate the application of developed GA method. This example was previously analyzed deterministically by other researchers (Selinger, 1980; Russell and Caselton, 1988; El-Rayes, 1997; El-Rayes and Moselhi, 2001; Long and Ohsato, 2009), and stochastically by Bakry et al. (2016). Comparing the results generated by the developed method to those obtained by others provided verification and illustrated the importance of utilizing buffers on final schedule to account for uncertainty (Salama and Moselhi, 2018c). This example is of a reinforced concrete bridge with three spans which has four units (segments), as shown in Figure 6.10. Each unit includes five repetitive processes, also referred to as activities, which are excavation, foundation, columns, beams, and slabs. Figure 4.42 shows the activities quantities for the original case study (Selinger, 1980). Each process is performed by a single crew working from one section to the next, in the assumed order of segments 1 to 4. It is assumed that each crew is able to take up a given segment if its predecessor is accomplished (Selinger, 1980). Project activities are non-typical repetitive activities, (i.e. work quantities of each activity vary from a segment to another). A different number of crews is available to select from for each of the project activities. Each of these crews has its own productivity and cost. Figure 4.42 shows the available crews for each activity of this example project. Each selection of these crews forms a unique crew formation for the project. Clearly each crew formation results in a different project duration and cost. In expressing the uncertainty associated with the input data related to these crews and activities, The same triangular fuzzy numbers used by Bakry et al. (2016) were utilized here to enable comparison. These fuzzy numbers represent the uncertainty associated with the input variables. These variables are possible crew formations, productivity rates, and direct costs. Project indirect cost was considered 1,000$ per day as included in Bakry et al.'s (2016) analysis. The developed model was run eleven times by changing the importance weights of time, cost, and work interruptions to search for optimum crew formation that yields the least normalized MOF as shown in Table 6.8 and to generate the Pareto fronts, as well as to demonstrate features of the developed method.

The purpose of this case example including the number of runs performed is to measure and compare project duration, cost, and work interruptions for the optimized schedule with different cases. The first four runs were optimizing project duration only. The first run is conducted with deterministic inputs while allowing work interruptions to compare results of developed method to other researchers for verification. The second run is conducted to investigate the effect of preventing work interruptions on the first run. Third and fourth runs are conducted to investigate the effect of uncertainty associated with the inputs of first and second runs respectively. The following four runs were optimizing project cost only. The sixth run is conducted with deterministic inputs while preventing work interruptions to compare results of developed method to other researchers for verification. The fifth run is conducted to investigate the effect of allowing work interruptions to the sixth run. Seventh and eighth runs are conducted to investigate the effect of uncertainty for the inputs of fifth and sixth runs respectively. The ninth run is conducted to investigate the effect of imposing project deadline, delay and interruptions penalties, and bonus payments to the seventh run. The tenth run is conducted to utilize different relative weights for time, cost, and work interruptions and for buffering of the optimized schedule while utilizing fuzzy inputs and allowing for work interruptions. The eleventh run is conducted to investigate the effect of uncertainty of resources availability on the eighth run. The results indicate that proposed method provides good optimization performance in comparison to those reported by other researchers because it provides equal or less time and/or cost as demonstrated in the following sections.

Project deadline, delay and interruptions penalties, and bonus payments were only considered in the ninth run. Resource availability was considered only in the eleventh run. First and fifth runs used deterministic inputs utilized by El-Rayes and Moselhi (2001) for the purpose of verification, while allowing for work interruptions. Second and sixth runs utilized the same data as of the first and fifth run, respectively, but interruptions were prevented. Third and seventh runs utilized fuzzy inputs, while for allowing interruptions. Fourth and eighth runs utilized fuzzy inputs, while preventing interruptions. Generated results for different runs that optimize time and cost separately are shown in Table 6.9 and 6.10, respectively, along with a results comparison with other researchers. For the case of duration optimization, the first run identified the optimum crew formation that yields least duration schedule to be E1F1C3B1S1, which is the same crew formation identified by the deterministic model of Long and Ohsato (2009). Least duration was calculated to be 106.8 days, while allowing 13.8 days as work interruption, which is close to the results of El-Rayes and Moselhi (2001) and Long and Ohsato (2009), as shown in Table 6.9. Corresponding project total cost was calculated to equal 1,513,809$. Second run identified optimum crew formation to be E1F2C3B3S1, which is the same crew formation identified by deterministic model of Selinger (1980). The third run identified the least duration to be 105.5 days, with 15.4 days of interruption and a total project cost of 1,516,270$. The fourth run which utilize fuzzy inputs identifies optimum crew formation to be E1F2C3B3S1 as the result of the second run. Duration was calculated to be 115.8 days, with a total project cost of 1,506,009$, and these results were closer to the results of the second run more than the results of Bakry et al. (2016), as shown in Table 6.9. Comparing the results of the fourth and second run shows the effect of uncertainties on the generated optimized schedule. For the case of cost optimization only, fifth and sixth runs identified optimum crew formation to be E1F3C1B4S2, which is the same crew formation identified by El-Rayes and Moselhi (1993) and Bakry et al. (2016). Duration was calculated to be 142.9 days, with a total project cost of 1,460,271$ and these results are close to results of other researchers, as shown in Table 6.10. Seventh and eighth runs identified optimum crew formation to be E1F3C1B4S2, which is same crew formation identified by Bakry et al. (2016), while duration and cost were 141.1 days and 1,463,834$, respectively, which is close to the results of the fifth and sixth runs, as well as the results of Bakry et al. (2016). 2D and 3D Pareto fronts were generated for time, cost, and work interruptions for all runs by changing the weights of the three variables, as shown in Figures 6.15 to 6.18 (Salama and Moselhi, 2018c). In Table 6.9, the results based on fuzzy inputs result in lower duration and higher cost comparing to results based on deterministic inputs. This is attributed to having two fuzzy inputs which are the project quantities and productivity rates of different crews. Both inputs increased in value as fuzzy numbers comparing to detrministic numbers, which means that both project quantities and produtivity rates have increased. Hence, the increase in project quantities increases project cost and the increase in productivity rates decreases project duration comparing to the case of using deterministic numbers.

Table 6.8: Features of different runs											
	Run										
Criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Deterministic inputs	Y	Y	N	N	Y	Y	N	N	N	N	N
Fuzzy inputs	N	N	Y	Y	N	N	Y	Y	Y	Y	Y
Optimize time (Wt)	Y (1)	Y (1)	Y (1)	Y (1)	N (0)	N (0)	N (0)	N (0)	N (0)	Y (0.8)	N (0)
Optimize cost (Wc)	N (0)	N (0)	N (0)	N (0)	Y (1)	Y (1)	Y (1)	Y (1)	Y (1)	Y (0.1)	Y (1)
Optimize interruptions (Wi)	N (0)	N (0)	N (0)	N (0)	N (0)	N (0)	N (0)	N (0)	N (0)	Y (0.1)	N (0)
Allow interruptions	Y	N	Y	N	Y	N	Y	N	Y	Y	N
Consider resources availability	N	N	N	N	N	N	N	N	N	N	Y
Consider project deadline, delay and interruptions penalties, bonus payments	N	N	N	N	N	N	N	N	Y	N	N
Utilize Buffers	N	N	N	N	N	N	N	Y	N	Y	Y
time (days)	106.8	117.8	105.51	115.8	142,9	142,9	141,1	141,1	114.9	109.6	198.4
cost ($)	1,513,809	1,497,574	1,516,270	1,506,009	1,460,271	1,460,271	1,463,834	1,463,834	1,474,918	1,505,960	1,668,016
interruptions (days)	13.8	0	15.4	0	0	0	0	0	0	8.3	0
Optimum crew formation	E1F1C3B1 S1	E1F2C3B3S 1	E1F1C3B1S1	E1F2C3B3S1	E1F3C1B4S2	E1F3C1B4S2	E1F3C1B4S2	E1F3C1B4S2	E1F2C3B3S1	E1F1C3B3S1	E1F3C1B4S 2

Table 6.9 Comparison with results of researchers for duration optimization only

Run	Weights of MOF			Allow interruptions	Inputs	criteria	Developed Method	Selinger (1980)	Russell and Caselton (1988)	El-Rayes and Moselhi (2001)	Long and Ohsato (2009)	Bakry et al. (2016)
	W_c	W_t	W_i									
First Run	0	1	0	Yes	Deterministic	Cost ($)	1,513,809	-	-	-	-	-
						Time (days)	106.8	-	110.4	106.8	106.81	-
						Intrupt (days)	13.8	-	16	15	13.91	-
Second Run	0	1	0	No		Cost ($)	1,497,574	-	-	-	-	-
						Time (days)	117.8	117.9	-	-	-	-
						Intrupt (days)	0	0	-	-	-	-
Third Run	0	1	0	Yes	fuzzy	Cost ($)	1,516,270	-	-	-	-	-
						Time (days)	105.51	-	-	-	-	-
						Intrupt (days)	15.4	-	-	-	-	-
Fourth Run	0	1	0	No		Cost ($)	1,506,009	-	-	-	-	1,511,657
						Time (days)	115.8	-	-	-	-	128
						Intrupt (days)	0	-	-	-	-	0

Table 6.10: Comparison with results of researchers for cost optimization only

Run	Weights of MOF			Allow interruptions	Inputs	criteria	Developed Method	Moselhi and El-Rayes (1993)	Agrama (2015)	Bakry (2014)
	W_c	W_t	W_i							
Fifth Run	1	0	0	Yes	Deterministic	Cost	1,460,271	-	-	-
						Time	142,9	-	-	-
						intrupt	0	-	-	-
Sixth Run	1	0	0	No		Cost	1,460,271	1,458,799		1,460,203
						Time	142,9	142,9	142,9	143
						intrupt	0	0	0	0
Seventh Run	1	0	0	Yes	Fuzzy	Cost	1,463,834	-	-	-
						Time	141,1	-	-	-
						intrupt	0	-	-	-
Eighth Run	1	0	0	No		Cost	1,463,834	-	-	1,476,379
						Time	141,1	-	-	144
						intrupt	0	-	-	0

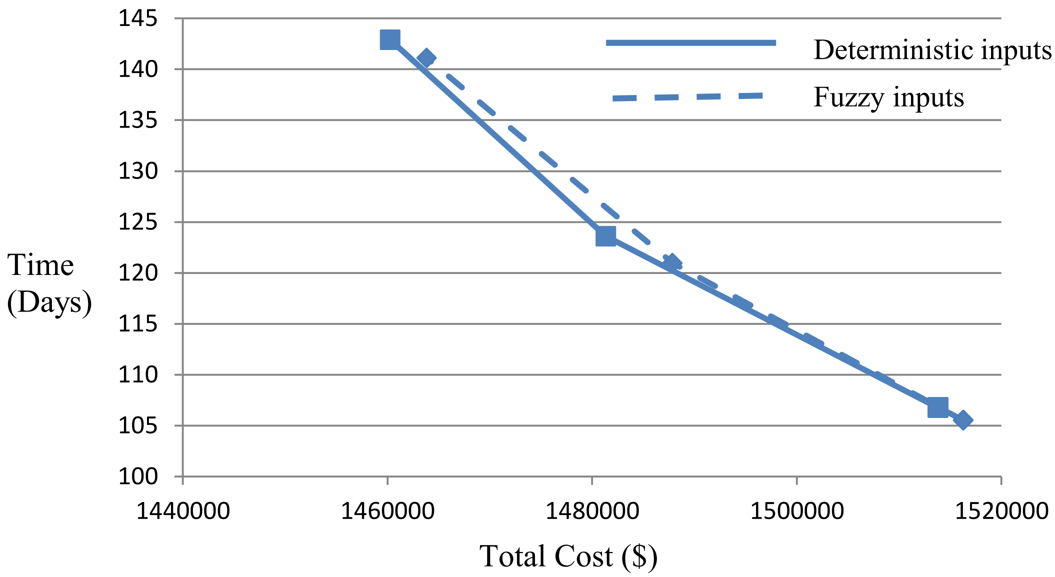


Figure 6.15: Comparison between 2D Pareto fronts of runs allowing interruptions

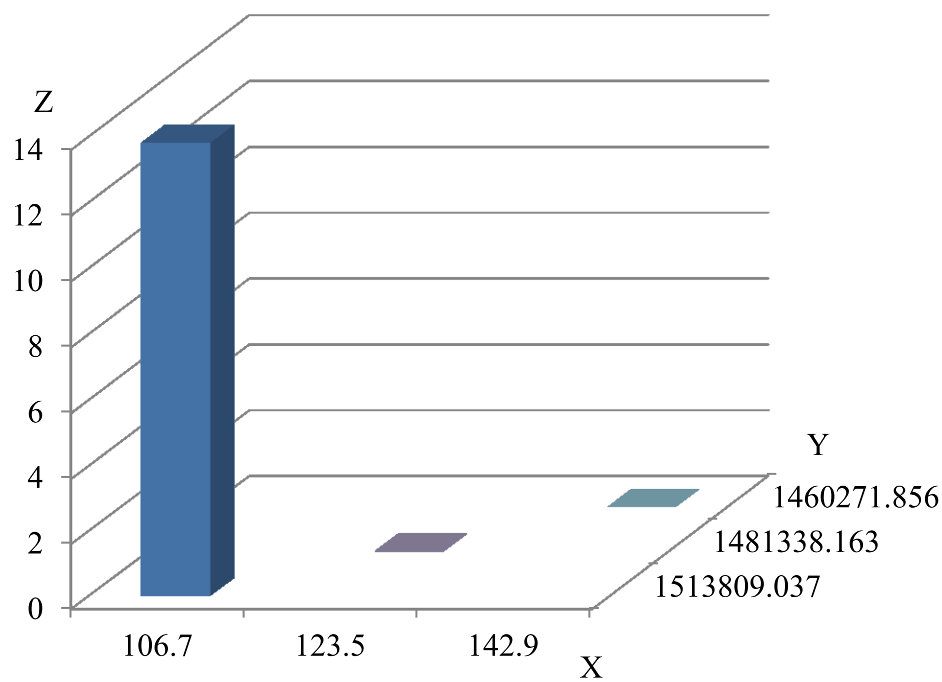


Figure 6.16: 3D Pareto front for first run group (deterministic inputs + interruptions), X:Time (days), Y: Total cost ($), Z: Interruptions (days)

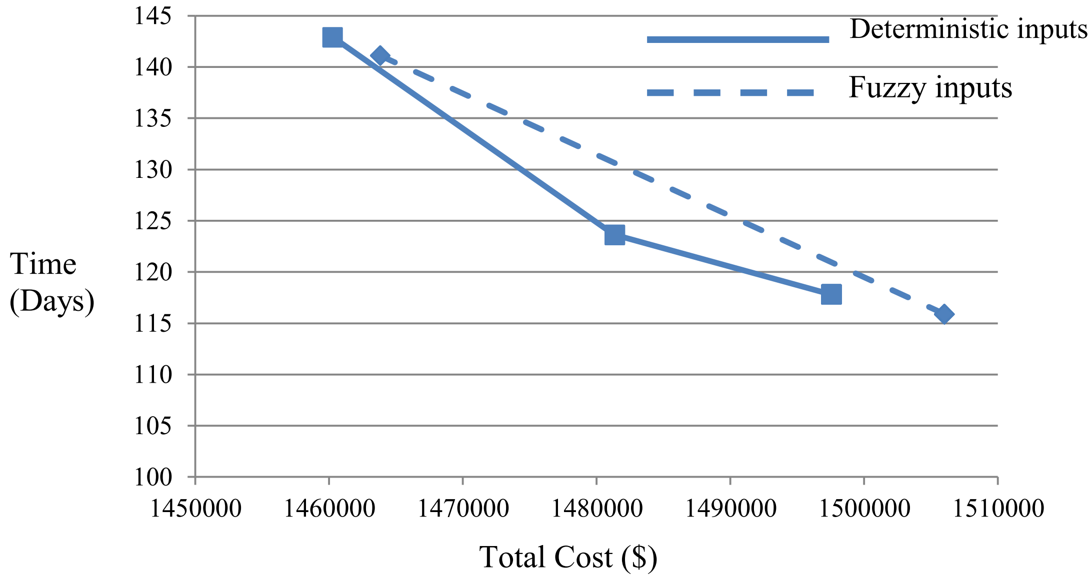


Figure 6.17: Comparison between 2D Pareto fronts of runs preventing interruptions

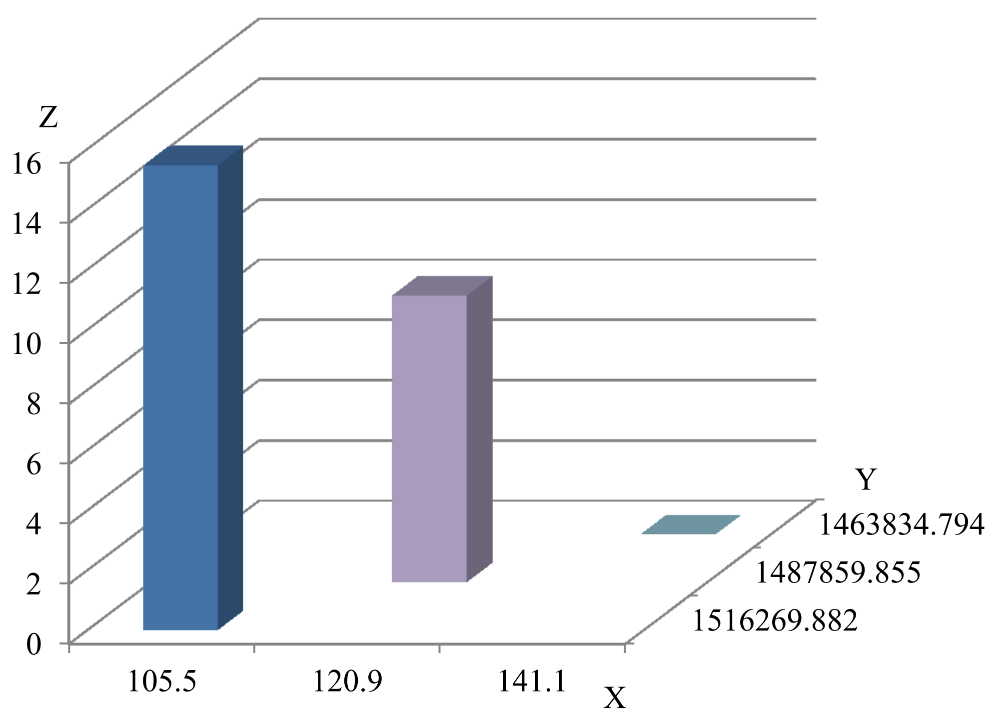


Figure 6.18: 3D Pareto front for third run group (fuzzy inputs + interruptions). X: Time (days), Y: Total cost ($), Z: Interruptions (days)

These Pareto fronts allow project managers to select an optimum solution from a set of non-dominated solutions based on the constraints of their projects. Critical sequence was identified for the optimum cost schedule generated by the eighth run with fuzzy inputs using the framework developed by Salama et al. (2017b) to allow for comparison with the optimum schedule proposed by Bakry (2014). Project and feeding buffers were calculated using equations provided by Salama et al. (2017b), where D(CL) was considered as DurAI, as suggested by Bakry (2014), and D(AG) was crisp durations (Dcr) calculated using crisp productivity rates, as shown in Table 6.11. A project buffer was added at the end of critical sequence and equaled 6.4 days. Two feeding buffers of 2.25 and 1.88 days were assigned at the end of the columns and slabs processes, respectively, at same locations as suggested by Salama et al. (2017b). Resource buffers were not assigned in this case because resources were not included in this run. Project duration was calculated to be 151.6 days after adding buffers, which is close to the duration of 152.5 days in the schedule generated by Salama et al. (2017b). However, this duration was 163 days for the same schedule as that of Bakry (2014), as shown in Figure 6.19. This difference between schedules is attributed to the intermediated buffers assigned by Bakry (2014) to absorb delay that may not happen, which makes intermediate buffers redundant (Salama et al., 2017b).

The ninth run was conducted using fuzzy inputs to illustrate the impact of imposing a project deadline while using a penalty cost and bonus, which were applied after or before this deadline, respectively, as well as interruption cost. Same seventh run inputs were utilized to optimize the schedule while allowing for work interruptions. Project deadline was imposed as 120 days after project start. Penalty cost was assumed to be 10,000$ for every day of delay after deadline and bonus was 10,000$ for every day the project was finalized before deadline. Interruption cost was assumed to be 10,000$ for every day of work interruption. Optimum crew formation changed from E1F3C1B4S2 to E1F2C3B3S1. Optimum cost changed from 1,463,834 to 1,474,918$, while project duration changed from 141.1 days to 114.9 days. The tenth run was conducted to demonstrate the capabilities of the developed method by buffering the optimized schedule while utilizing fuzzy inputs and allowing for work interruptions. This run did not consider project deadline, delay penalty, interruption cost, bonus payments, or resources availability. Importance weights (Wd, Wc, and Wi) for duration, cost, and work interruptions were set to be 0.8, 0.1 and 0.1, respectively. Optimum crew formation was identified to be E1F1C3B3S1. Project duration was calculated to be 109.6 days with a total project cost of $1,505,960 and total work interruption of 8.3 days. Critical sequence was identified for optimized schedule, as shown in Figure 6.20. Project buffer was calculated to be 13.2 days using productivities of critical sequence shown in Table 6.12 and assigned at the end of critical sequence. Four feeding buffers were calculated and equal 1.88, 2.4, 4.2, and 1.7 days due to variability of resource critical activities (Salama et al., 2017b) for foundation, columns, beams, and slabs, respectively. First feeding buffer was not assigned because work interruptions after first activity in foundation process equal 2 days and absorb anticipated delay of 1.88 days. Second and fourth interruptions were assigned in regular positions at columns and slabs processes, as shown in Figure 6.21. However, third interruption was assigned with a value of 0.7 instead of 4.2 days, because work interruption of 3.5 days absorbs part of variability of resource critical activities for beams process. Eleventh run was conducted to optimize linear schedule while preventing work interruptions and considering constrained availability of resources that is assumed, as shown in Table 6.13. Productivity of different crews was considered the minimum of normal crisp productivity rate (PRcr), and resource constrained productivity rate with a 50% confidence rate. Optimum crew that yields least cost schedule was E1F3C1B4S2. Generated schedule duration was 198.4 days, as shown in Figure 6.22, with a total cost of 1,668,016$. However, two sequential processes, which are beams and columns, shared the same controlling resource. Therefore, successor activity, which is "beams", was considered to start when there were enough resources to ensure continuity (Salama et al., 2017b). An RCB was assigned between the two processes to resolve this conflict in availability of resources (Salama et al., 2017b). The RCB equaled 0.26 days and the overlap due to resources conflict (O_{RC}) was calculated to be 3.62 days, while the overlap due to resources quantities variability (O_{VAR}) equaled 3.35 days. The RBC was assigned after the start of the beams process, as shown in Figure 6.23. The critical sequence was identified and project buffer is assigned at the critical sequence end and equaled 12.6 days. One feeding buffer was assigned at the end of the columns process with a value of 3.5 days to absorb variability of resource critical activities in this process. Three resource buffers were assigned without duration as stars, shown in Figure 6.23, when controlling resource changes from preceding to succeeding activities on critical sequence (Salama and Moselhi, 2018c).

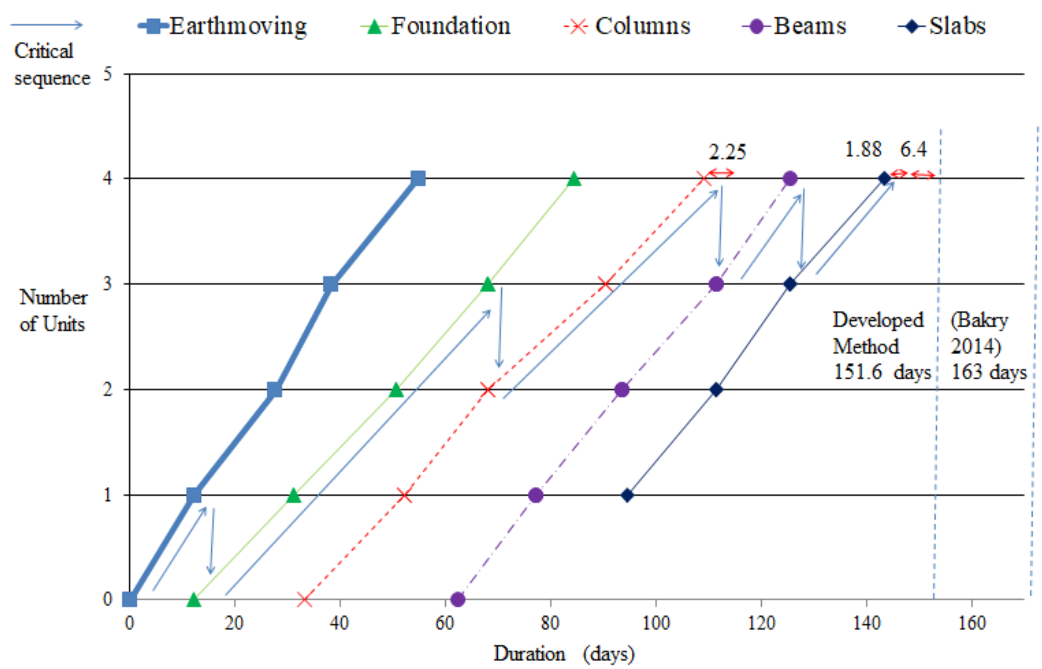


Figure 6.19: Comparison of least cost schedule with results of Bakry (2014) after buffering

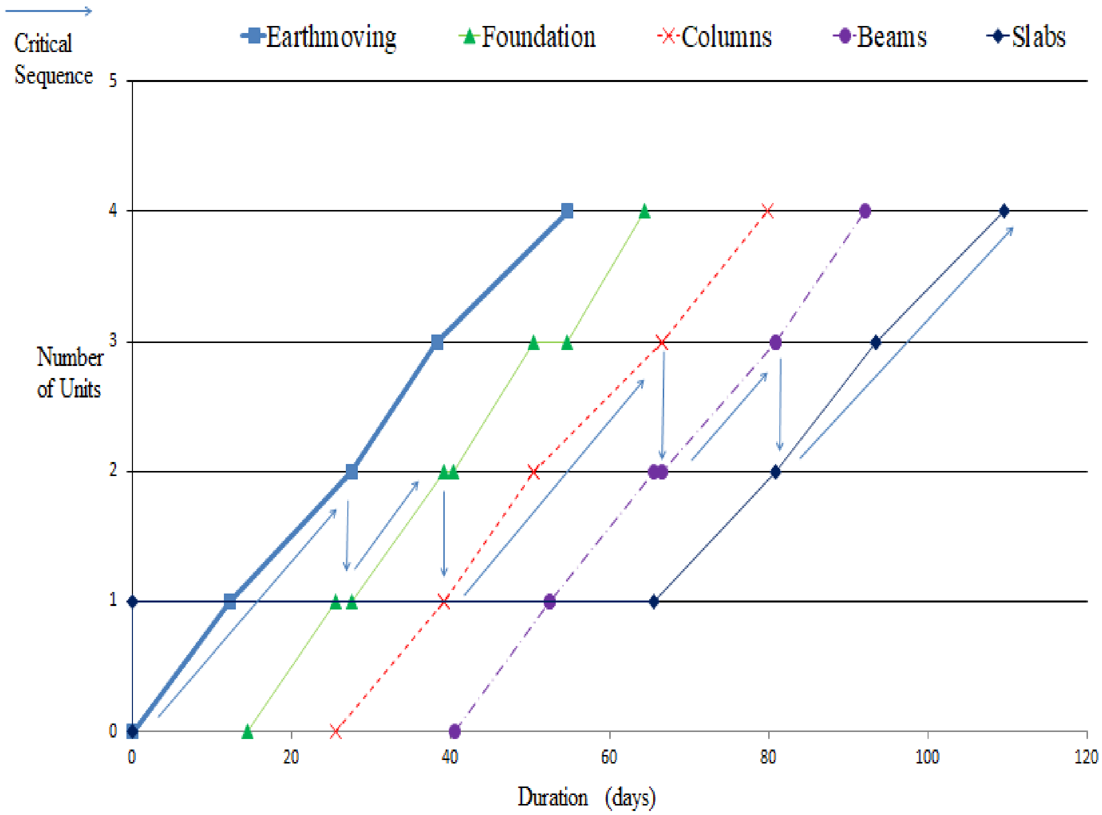


Figure 6.20: Critical sequence of optimized schedule allowing work interruptions

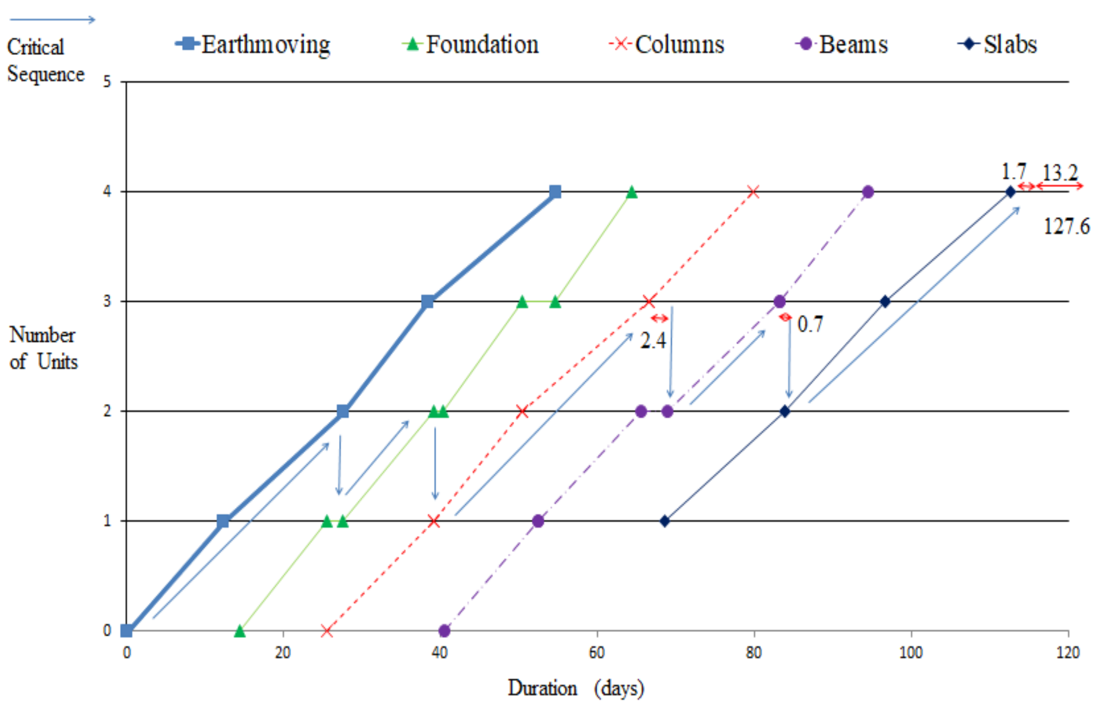


Figure 6.21: Optimized schedule allowing work interruptions after buffering

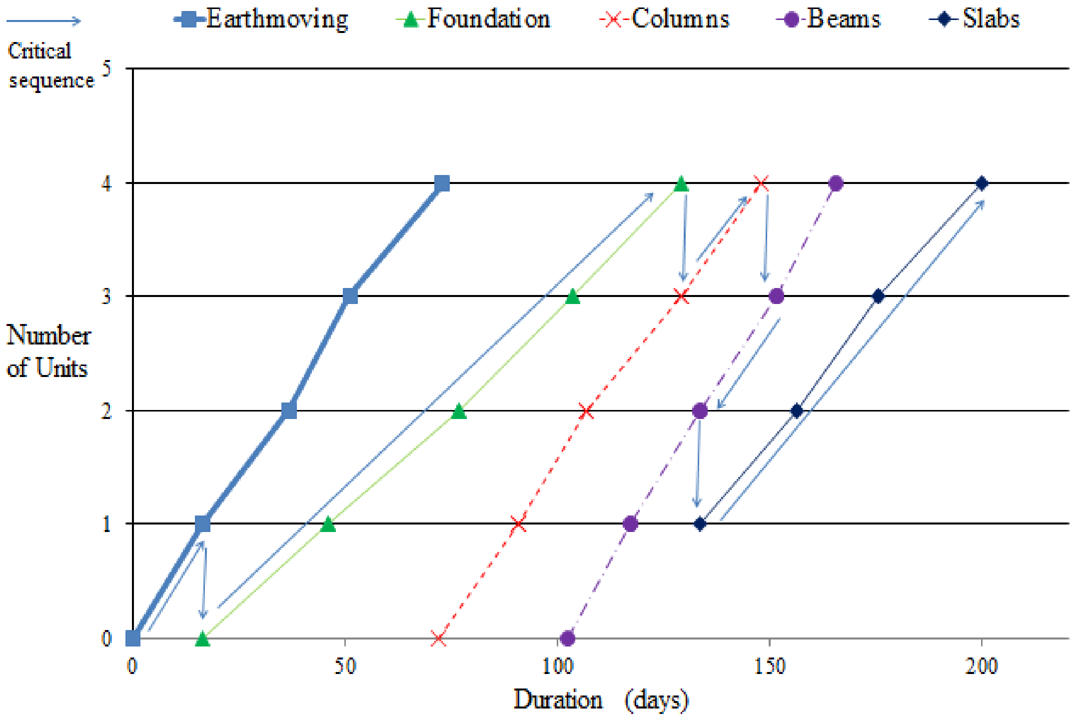


Figure 6.22: Optimized least cost schedule before resolving resources conflict and buffering

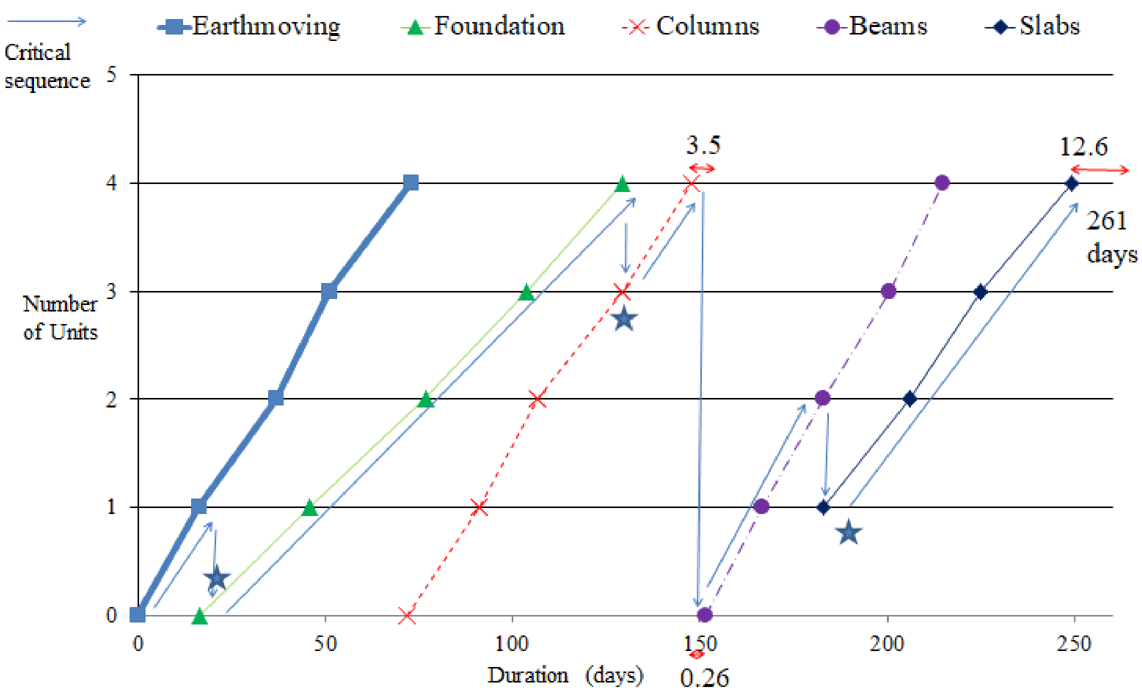


Figure 6.23: Optimized least cost schedule after resolving resources conflict and buffering

Table 6.11: D_{cr} and DurAI for cost optimized schedule preventing interruptions

Activity	**Optimum Crew**	**Q_{cr} (m^3)**				**PR_{cr} (m^3/day)**	**Durations in Days**							
		Section 1	**Section 2**	**Section 3**	**Section 4**		**Unit 1**		**Unit 2**		**Unit 3**		**Unit 4**	
							D_{cr}	**DurAI=0.9**	**D_{cr}**	**DurAI=0.9**	**D_{cr}**	**DurAI=0.9**	**D_{cr}**	**DurAI=0.9**
Excavation	E1	1147	1434	994	1529	93.28	12.29	13.2	15.37	16.6	10.65	11.5	16.39	17.7
Foundation	F3	1032	1077	943	896	54.76	18.84	21.9	19.66	22.9	17.22	20	16.36	19
Columns	C1	109.2	90.3	129	106.67	5.73	19.05	21	15.75	16.9	22.51	25	18.61	20.3
Beams	B4	85	92	101	80	5.66	15	15	16.3	16.3	17.8	17.8	14.1	14.1
Slabs	S2	0	138	114	145	8.14	0	0	16.95	18.7	14	15.5	17.81	19.7

Table 6.12: D_{cr} and DurAI for optimized schedule allowing interruptions

Activity	**Optimum Crew**	**PR_{cr} (m^3/day)**	**Durations in Days**							
			Unit 1		**Unit 2**		**Unit 3**		**Unit 4**	
			D_{cr}	**DurAI=0.9**	**D_{cr}**	**DurAI=0.9**	**D_{cr}**	**DurAI=0.9**	**D_{cr}**	**DurAI=0.9**
Excavation	E1	93.28	12.29	13.2	15.37	16.6	10.65	11.5	16.39	17.7
Foundation	F1	92.76	11.12	13	11.61	14	10.16	13	9.65	12
Columns	C3	8.03	13.6	16	11.24	15	16.06	19	13.28	16
Beams	B3	7.07	12.02	15	13.01	16	14.28	17	11.31	14
Slabs	S1	9.02	0	0	15.29	17	12.63	15	16.07	19

Table 6.13: Controlling resources availability

Activity	Fuzzy Crew Output (m3/day)			Crisp normal Crew Output PR_{cr} (m3/day)	Crew normal Output PR (90%) (m3/day) (Salama et al. 2017b)	Crew Output due to constraining resources CPR (50%) m3/day (Salama et al. 2017b)	Crew Output due to constraining resources CPR (90%) m3/day (Salama et al. 2017b)
	a	b	c				
Excavation	82.58	91.75	105.51	93.28	86.52	70	60
Foundation	43.09	53.86	67.33	54.76	47.12	35	30
Columns	5.73			5.73	5	6	5.75
Beams	5.66			5.66	5.66	6	5.75
Slabs	6.98	7.76	9.70	8.14	7.36	6	5

6.6 Case example for tracking and control model

6.6.1 Generating schedule baseline

A hypothetical case study was used to demonstrate the developed method using real data of a time study conducted for an offsite manufacturing facility in Edmonton, Alberta, Canada (Salama et al., 2018d). Assumed labour, material, and equipment costs for all activities in Table 6.14 were utilized to calculate direct cost of each activity for one crew. Average daily productivity for one crew was assumed, as shown in Table 6.14. Onsite productivity rates for real projects of the same facility were drawn from the literature, as shown in Table 6.15 (Liu et al., 2015). A time study was conducted between July and August 2015 to acquire the productivity rates of different manufacturing stations (Salama et al., 2018d). For each manufacturing process (framing, sheathing, etc.), panels were clustered into three different clusters in respect to the net area of each panel using a software named XLMiner (version 2015-R2) for K means clustering. Time data of assembly and framing stations was clustered into three clusters, as shown in Figures 6.24 and 6.25, where clusters 1, 2 and 3 grouped panels with a net area of 80 to 120, 40 to 80, and 0 to 40 sq-ft, respectively. Sheathing station data was clustered in Figure 6.26 to group panels with the net area of 75 to 120, 40 to 75, and 0 to 40 sq-ft, respectively. Clusters of waterproofing station are shown in Figure 6.27 for three groups of panels with a net area of 60 to 120, 40 to 60, and 0 to 40 sq-ft, respectively. Normal distribution curves were generated for each cluster of data points using Easyfit© software (version 5.5)_to get the 50% and 90% percentiles of productivity rates, as shown in Table 6.16. The case study was modeled using Vertex BD 2016 © for three identical hybrid modular construction units including 45 panels with different dimensions and properties. A hybrid modular unit consists of bathroom modules combined with panelized construction, as shown in Figure 6.28.

Table 6.14: Costs of different activities

	Offsite activities				Onsite activities							
Activity	**Assembly**	**framin g**	**Sheathing**	**Water proofing**	**Formwor k**	**Rebar**	**Pourin g Concre te**	**Curin g**	**Surveyi ng**	**Lifting**	**Insulatio n**	**Drywal l**
Number of crews	1	1	1	1	1	4	2	1	1	1	1	1
Quantities	1428	1428	4286	4286	432	19.5	189	-	1428	1428	4286	4286
Units	L.F.	L.F.	S.F	S.F	S.F	ton	C.Y.	-	L.F.	L.F.	S.F.	S.F.
Average daily productivity (1 crew)	688	414	1147	**427 (959*)**	300	2.1	55	-	1523	2856	22848	4800
Average daily direct cost (1 crew)	9907	5961	3269	589 (1697*)	3255	3706	8499	100	2680	972	83395	7488
Labour cost (1 crew)	8.75	8.75	1.21	0.61 (1)	7.95	825	35.5	100	1.3	972	1.37	1.02
Material cost (1 crew)	5.65	5.65	1.64	0.77	2.9	940	118		0.06	-	2.28	0.54
Equipment cost (1 crew)	-	-	-	-	-	=	1.03	-	0.4	-	-	-
*After adding one worker to water proofing station. (L.F. : Linear feet) , (S.F. : square feet), (C.Y: cubic yard)												

Table 6.15: Onsite activities productivity rates (Liu et al., 2015)

Process	Unit	Number of crews	Productivity rate (50 %)	Productivity rate (90 %)
Erect formwork foundation	S.F./day	1	300	280
Install rebar foundation	ton/day	4	2.1	1.8
Pour concrete foundation	cy3/day	2	55	50
Cure concrete slab	days	-	3	3.5
Survey panel location	1 panel (min)	1	10	12
Lift wall panel + Connect wall panel	1 panel (min)	1	16	19
Place insulation	1 panel (min)	1	2	3
Install drywall	S.F. /min	1	10	6

Table 6.16: Panel groups productivity rates

Process	Panel Group	Panel Net area (S.F)	Productivity rate (50 %) S.F/min	Productivity rate (90 %) S.F/min
Assembly	1	80:120	(4.3)	(2.72)
	2	40:80	(2.35)	(0.31)
	3	0:40	(2.65)	(0.31)
Framing	1	80:120	(2.59)	(1.89)
	2	40:80	(1.59)	(1)
	3	0:40	(2.06)	(1.13)
Sheathing	1	75:120	(2.39)	(1.03)
	2	40:75	(1.99)	(0.46)
	3	0:40	(2.2)	(0.77)
Water Proofing	1	60:120	(0.89)	(0.72)
	2	40:60	(1.05)	(0.8)
	3	0:40	(1.1)	(0.99)

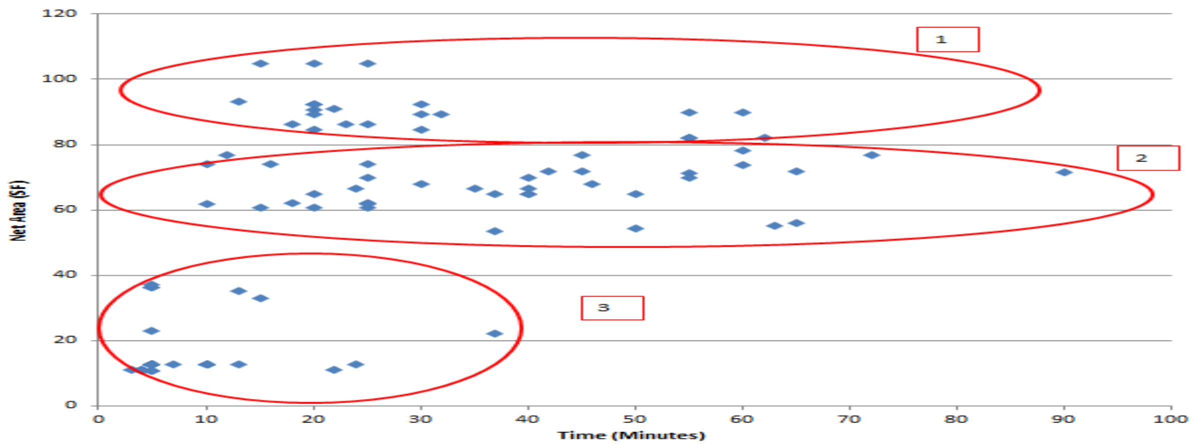


Figure 6.24: Assembly station time study (panel net area/ time)

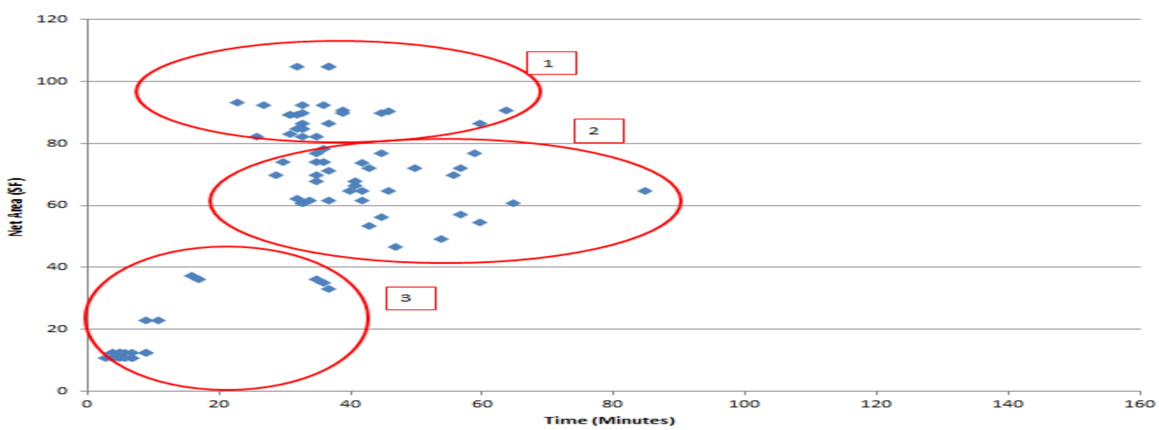


Figure 6.25: Framing station time study (panel net area/ time)

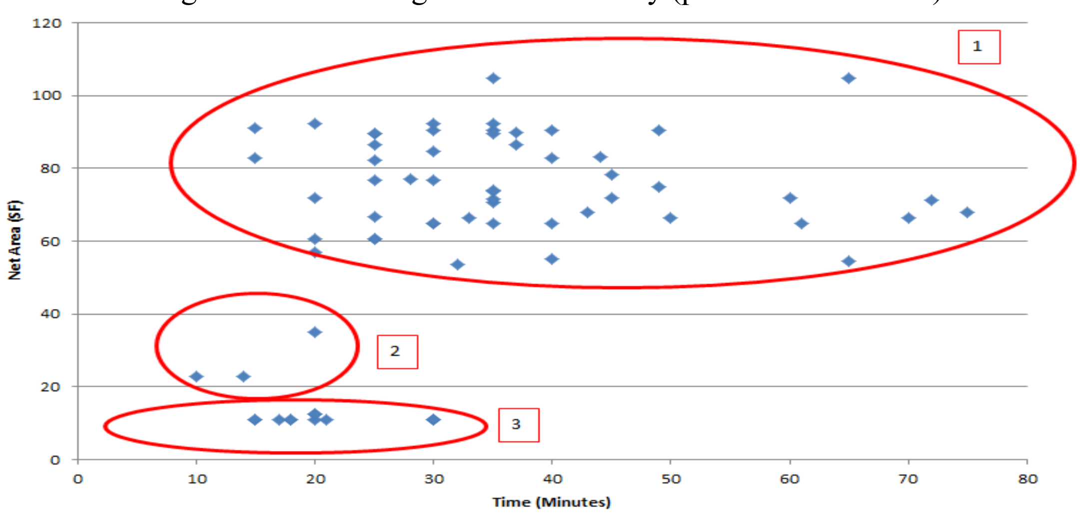


Figure 6.26: Sheathing station time study (panel net area/ time)

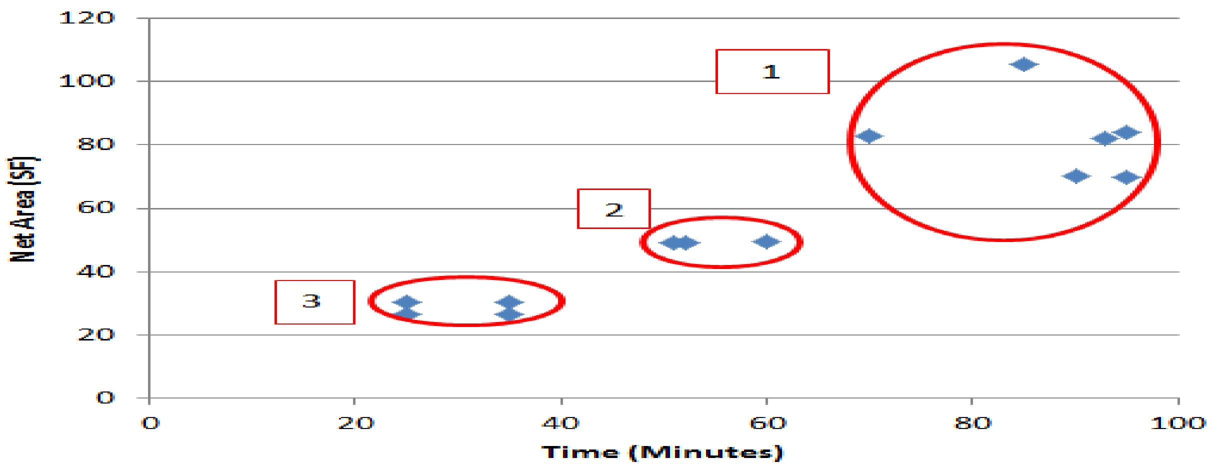


Figure 6.27: Water proofing station time study (panel net area/ time)

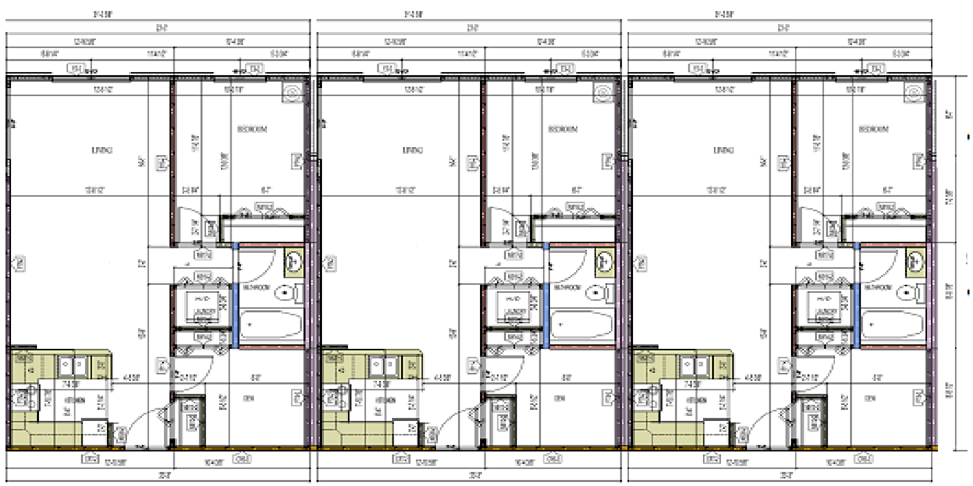


Figure 6.28: BIM model plan view using Vertex BD©

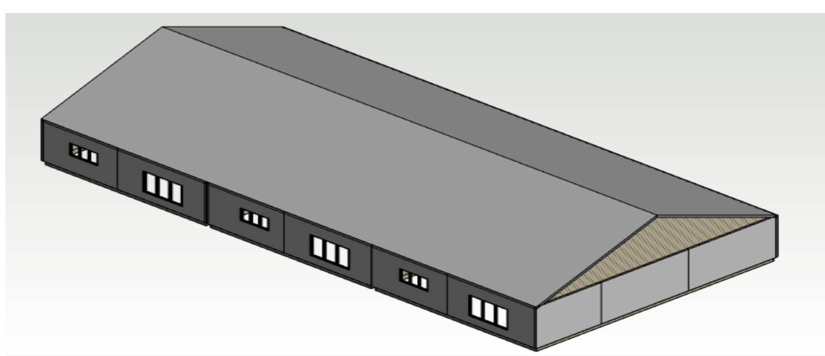


Figure 6.29: Isometric view of the BIM model

The bathrooms were fabricated as separate modules, while the rest of the units were fabricated as panelized construction. Foundation of the three units was assumed to be a reinforced concrete mesh foundation with 73’ of length, 35’ of width and 2’ of height. Foundation reinforcement was assumed to be 135 kg/cubic meter. Vertex BD © was used to generate the BIM model that includes panels of three hybrid units, as shown as an isometric view in Figure 6.29 (Salama et al., 2018d). The net area was calculated based on dimensions generated from the Vertex BD©. Figure 6.30 shows the panel framing generated by Vertex BD© which illustrates the panel dimensions, components, and openings. The productivity rates of four different manufacturing processes (e.g. assembly, framing, etc.) are shown in Table 6.16 for three different groups of panels based on their respective net areas. An EXCEL-based tool was generated to calculate durations, start date, finish date, and time buffers, as shown in Figure 6.31. Linear schedule baseline was generated for offsite manufacturing and onsite construction processes. The critical controlling sequence, shown as the red arrow at Figure 6.32, was identified based on the procedure described earlier (Salama et al, 2017b). It was assumed that panels were transported into the construction site by five separate batches whenever manufacturing processes were completed for each batch. The duration for transporting the last batch from the offsite manufacturing facility to the construction site (D_{LBT}) was assumed to be 180 minutes. The offsite schedule was presented at the top part of the schedule, while the onsite schedule was drawn at the bottom. CCP was identified at the start of the first onsite activity duration for the last batch after transportation.

A feeding buffer was assigned with 18 minutes at the end of the lifting panel process. The OAB equaled 290 minutes due to variability of onsite activities before CCP. OPB equaled 189 minutes due to variability of productivity rates for activities that belong to overall controlling sequence.

These buffers were calculated using equations developed by Salama et al. (2017a). All panels in the last manufacturing process (i.e. waterproofing) were critical because they had the slowest productivity rate among all manufacturing processes. Duration of aggressive overall schedule was calculated to be 5605 minutes and total costs for baseline schedule equaled 166075$, as shown in Table 6.17, after assuming that the daily indirect cost is 1000$.

Before starting the project, aggressive schedule (baseline) in Figure 6.32 was discussed with the customer and different crews to pull feedback on schedule reliability according to LPS. The production line of the manufacturing facility was clearly not optimized. Assembly, framing, and sheathing processes were faster than waterproofing (bottleneck). From a lean perspective, unnecessary inventory was produced offsite, which means a waste of overproduction that violates JIT strategy. Upstream processes of the manufacturing facility started early because the waterproofing process needs improvement.

Customer requested that the the four manufacturing processes be completed in 2200 minutes. TT of the manufacturing facility was calculated to be 49 minutes, while actual cycle times of assembly, framing, sheathing, and waterproofing processes were 22, 36, 39, and 107 minutes, respectively. A worker was added to the waterproofing station to increase average daily productivity from 427 to 959 S.F., as shown in Table 6.14, so that the cycle time of waterproofing station would become 47 minutes. Onsite activities before OAB were aligned to improve the overall production system. Start of offsite manufacturing shifted 595 minutes after start of onsite activities according to the JIT strategy.

Aggressive schedule baseline was changed, as shown in Figure 6.33. Accordingly, aggressive overall schedule changed from 5605 to 3527 minutes, while OPB changed from 189 to 344 minutes.

Total costs decreased from 166075 to 163417$, as shown in Table 6.17, because indirect cost decreased from 11677 to 7347$ due to decrease of duration for aggressive overall schedule, while direct cost increased from 154398 to 156070$ due to addition of an extra worker to the waterproofing station.

A Monte Carlo simulation model was developed using @Risk© software to assess the duration of the overall schedule (Salama et al., 2018d). Uncertainty of productivity rates for all onsite and offsite processes was fitted using triangular distributions. The 50% productivity rates shown in Tables 6.13 and 6.14 were considered the mean of triangular distributions. The simulation output for the baseline schedule is shown in Figure 6.34. A comparison between obtained durations from developed overall schedule and Monte Carlo simulation model is presented in Table 6.18.

6.6.2 Starting the project

After the project start, time interval for LPS sessions (stakeholders meetings) was set to be every two working days (960 minutes) instead of the usual weekly planning meeting. This is because project duration was short (seven working days). Depending on one weekly meeting only for this project would not show the features of the proposed method, while having a two day cycle generated 4 LPS sessions to show the PPCcr curve properly.

At first the LPS session with project crews, actual productivity rates were pulled and it was found that offsite work of assembly, framing, sheathing stations, and erecting formwork onsite were being conducted according to plan. However, the productivity of the waterproofing station decreased from 2 to 1.8 S.F/min. Survey, insulation, lifting, and dry wall processes at onsite schedule were shifted due to delay in manufacturing. OAB increased from 290 to 528 minutes because other onsite processes did not shift. As a result, the BI of OAB equaled -82% due to this increase. WWP was forecasted, as shown in Figure 6.35.

Table 6.17: Forecasting and monitoring costs

	Offsite activities				**Onsite activities**								**Overall Direct Costs**	**Overall Indirect Costs**	**Total Costs**
Activity	**Direct Costs**														
	Assembly	framing	Sheathing	Water proofing	Formwork	Rebar	Pouring Concrete	Curing	Surveying	Lifting	Insulation	Drywall			
Baseline costs (Before TAKT)	20562	20562	12215	5912	4687	34412	29205	300	2512	972	16373	6686	154398	11677	166075
Baseline costs (After TAKT)	20562	20562	12215	7584	4687	34412	29205	300	2512	972	16373	6686	156070	7347	163417
First LPS session costs	20562	20562	12215	8417	4687	34412	29205	300	2512	972	16373	6686	156903	7843	164746
Second LPS session costs	20562	20562	12215	9131	4687	34412	29205	300	2512	972	16373	6686	157617	8264	165881
Third LPS session costs	20562	20562	12215	9185	4687	34412	29205	300	2512	972	16373	6686	157671	8295	165966
Fourth LPS session costs	20562	20562	12215	9185	4687	34412	29205	300	2512	972	16373	8003	158988	8472	167460

Table 6.18: Comparison between developed overall schedule and Monte Carlo simulation model

	Duration of developed schedule (min) 50%	**Duration of developed schedule (min) 90%**	**Duration of Monte Carlo simulation model (min) 50%**	**Duration of Monte Carlo simulation model (min) 90%**	**Monte Carlo simulation /Developed method 50%**	**Monte Carlo simulation /Developed method 90%**
Baseline	3526	3866	3945	4272	1.12	1.10
First LPS session	3764	4068	3982	4247	1.05	1.04
Second LPS session	3966	4244	4007	4263	1.01	1.00
Third LPS session	3981	4256	3996	4260	1.00	0.99
Fourth LPS session	4067	4256	4040	4343	0.99	1.02

Table 6.19: Monitoring indices

	LPS Session Timing (min)	**$(PPC)_{cr}$ Actual**	**BI (OPB)**	**BI (FB)**	**BI (OAB)**	**Forecasted overall schedule duration (min)**	**Δ_t**
Baseline	-	-	-	-	-	3527	-
First LPS session	960	88%	69%	0%	-82%	3765	-
Second LPS session	1920	**85 %**	127%	0%	-151 %	3967	-
Third LPS session	2880	86%	132%	0%	-156%	3982	0.98
Fourth LPS session	3840	**0.83**	156%	0%	-156%	4067	-

Table 6.20: Monitoring PPC at activity level

	Onsite activities				Offsite activities							
Activity	Asse mbly	framing	Sheathi ng	Waterproofing	Formwork	Rebar	Pouring Concrete	Curing	Surveyin g	Lifting	Insulation	Drywall
First LPS session	100%	100%	100%	**<u>88%</u>**	100%	100%	100%	100%	-	-	-	-
Second LPS session	100%	100%	100%	**<u>85%</u>**	100%	100%	100%	100%	-	-	-	-
Third LPS session	100 %	100 %	100 %	**<u>86%</u>**	100 %	100 %	100 %	100 %	-	-	-	-
Fourth LPS session	100 %	100 %	100 %	**<u>100%</u>**	100 %	100 %	100 %	100 %	100 %	100 %	100 %	51%

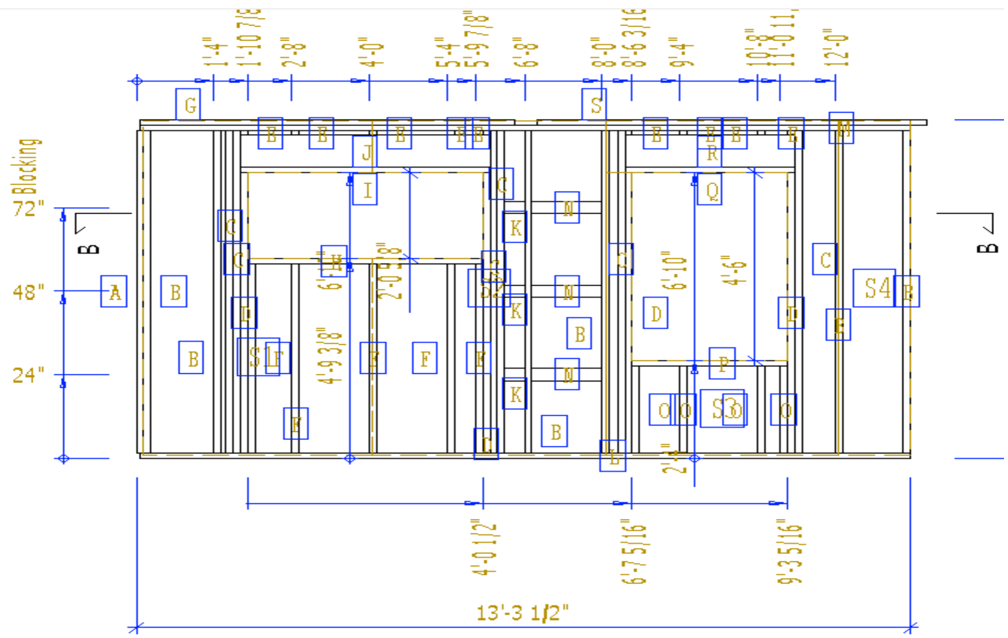


Figure 6.30: Panel layouts generated by Vertex BD

Panel#	PanelName	Aggressive Productivity rate 50 %				Safe Productivity rate 90 %				Aggressive Duration				Safe Duration			
		Assembly	Framing	Sheathing	AVB	Assembly	Framing	Sheathing	AVB	Assembly	Framing	Sheathing	AVB	Assembly	Framing	Sheathing	AVB
1	bath	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	21.0271	34.90991	37.83124	101.5918	33.2414	47.8395	87.7832	125.579
2		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	13.9806	23.21107	25.15342	67.54682	22.1017	31.8078	58.3657	83.4954
3		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	12.0155	19.94852	21.61785	58.05243	18.9951	27.3369	50.1618	71.7593
4		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	12.0155	19.94852	21.61785	58.05243	18.9951	27.3369	50.1618	71.7593
5	bath	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	21.0271	34.90991	37.83124	101.5918	33.2414	47.8395	87.7832	125.579
6		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	13.9806	23.21107	25.15342	67.54682	22.1017	31.8078	58.3657	83.4954
7		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	12.0155	19.94852	21.61785	58.05243	18.9951	27.3369	50.1618	71.7593
8		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	12.0155	19.94852	21.61785	58.05243	18.9951	27.3369	50.1618	71.7593
9	bath	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	21.0271	34.90991	37.83124	101.5918	33.2414	47.8395	87.7832	125.579
10		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	13.9806	23.21107	25.15342	67.54682	22.1017	31.8078	58.3657	83.4954
11		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	12.0155	19.94852	21.61785	58.05243	18.9951	27.3369	50.1618	71.7593
12		4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	12.0155	19.94852	21.61785	58.05243	18.9951	27.3369	50.1618	71.7593
13	PT4 B	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	33.0426	54.85843	59.44909	159.6442	52.2365	75.1764	137.945	197.338
14	PT5 B	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	20.2261	33.58001	36.39005	97.7216	31.9751	46.017	84.4391	120.795
15	B10	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	33.8437	56.18833	60.89028	163.5144	53.5029	76.9988	141.289	202.122
16	B11	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	18.7124	31.06692	33.66667	90.40824	29.5821	42.5732	78.1197	111.755
17	PT4 B	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	33.0426	54.85843	59.44909	159.6442	52.2365	75.1764	137.945	197.338
18	PT5 B	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	20.2261	33.58001	36.39005	97.7216	31.9751	46.017	84.4391	120.795
19	B10	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	33.8437	56.18833	60.89028	163.5144	53.5029	76.9988	141.289	202.122
20	B11	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	18.7124	31.06692	33.66667	90.40824	29.5821	42.5732	78.1197	111.755
21	PT8	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	20.0258	33.24753	36.02975	96.75406	31.6585	45.5614	83.603	119.599
22	PT9	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	34.4444	57.18576	61.97118	166.417	54.4526	78.3657	143.797	205.71
23	E1	4.3	2.59	2.39	0.89	2.72	1.89	1.03	0.72	19.8256	32.91506	35.66946	95.78652	31.3419	45.1058	82.767	118.403

Figure 6.31: The calculations for panel durations and buffers

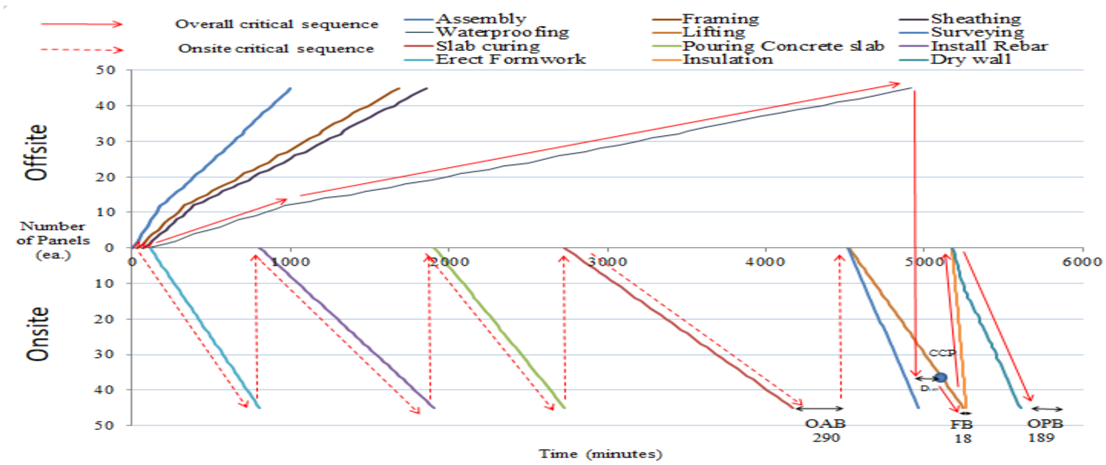


Figure 6.32: Integration of offsite and onsite construction

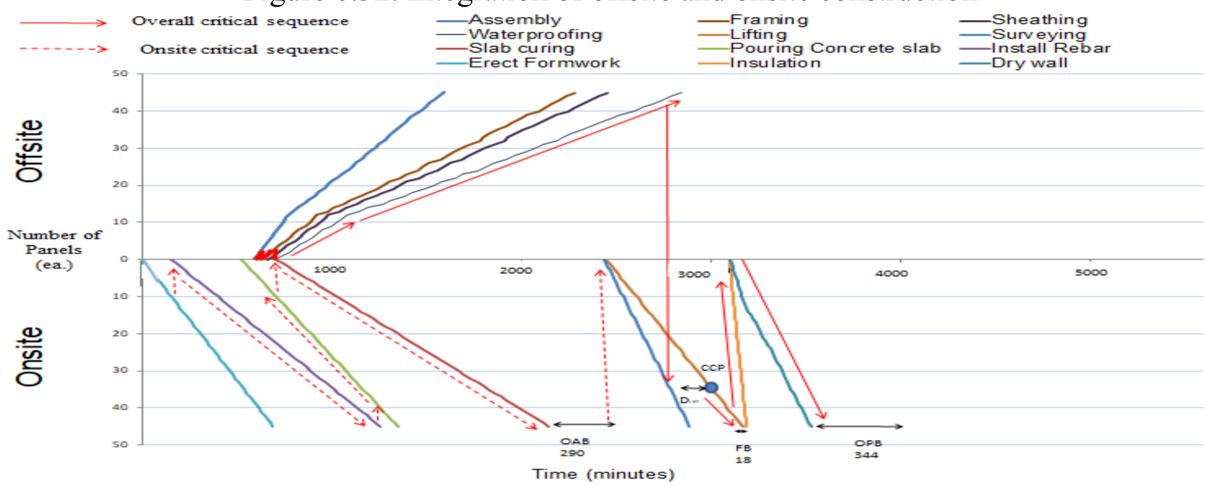


Figure 6.33: Integration after pulling stakeholders productivity rates

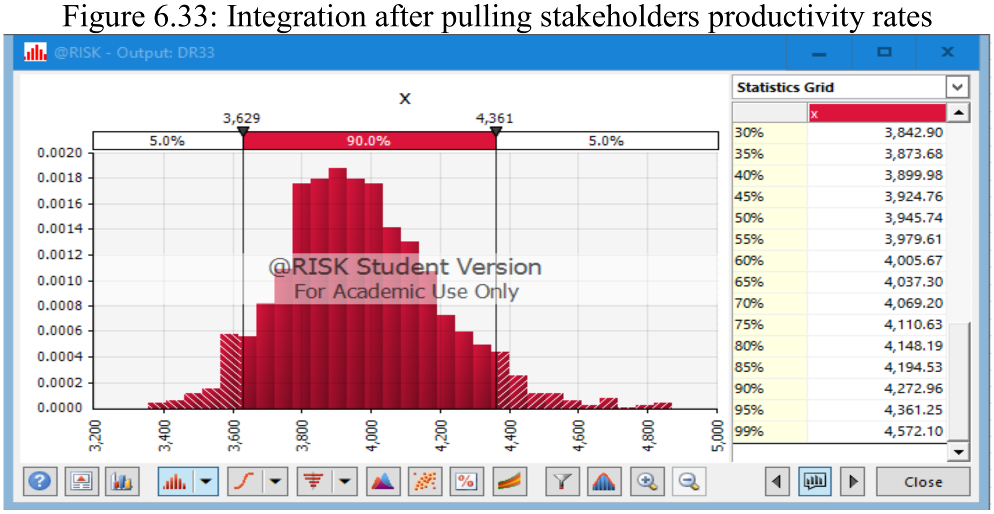


Figure 6.34: Simulation output for baseline schedule

Forecasted overall schedule changed from 3527 to 3765 minutes, while PPC_{cr} equaled 88%, which did not require a delay root cause analysis because it was higher than the allowable limit of 85% set by project stakeholders. BI for OPB and FB was 69 and 0%, respectively. Total cost was forecasted to increase from 163417 to 164746$, as shown in Table 6.17, because both direct and indirect costs increased due to the waterproofing station productivity reduction. At the second LPS session, the forecasted WWP, as shown in Figure 6.36, the productivity of the waterproofing station decreased from 1.8 to 1.3 S.F/min and reduced the PPCcr to 85%. Root cause analysis was conducted using the 5 Whys analysis to investigate the main reason(s) behind delay. Materials required for waterproofing were located at some distance from waterproofing station and it this was identified as the root cause for the encountered delay. This problem was solved by allowing material storage besides the waterproofing station. Total cost was forecasted to increase from 164746 to 165881$, as shown in Table 6.17, because both direct and indirect costs increased due to the reduction in productivity of the waterproofing station. At the third LPS session, shown in Figure 6.37, waterproofing station productivity increased from 1.3 to 1.78 S.F/min and the (PPC)cr increased to 86%, which did not require root cause analysis. Total cost was forecasted to increase slightly from 165881 to 165966$, as shown in Table 6.17, due to the increase in both direct and indirect costs because productivity of waterproofing station increased to 1.78 S.F./min without reaching the productivity of 1.8 S.F/min that occured before the material distance problem.

At the fourth LPS session, shown in Figure 6.38, productivity of drywall at onsite schedule was 7 S.F./min, which reduced the (PPC)cr to 83%, as shown in Figure 6.39. Root cause analysis was conducted and the main reason for the delay was found to be the slow reading of production drawings by worker at the drywall station. Total cost was forecasted to increase slightly from

165966 to 167460$, as shown in Table 6.17, due to productivity reduction of drywall station. This worker was replaced and the project was finalized at 4067 minutes, with a total cost of 167460$, as forecasted at the fourth LPS session.

All project indices were monitored, as shown in Table 6.19 at project level, and in Table 6.20 at activity level (Salama et al., 2018d). A pareto graph was created, as shown in Figure 6.40, to illustrate the root cause analysis findings. The three causes of project delay were variability of productivity rates, distance of material storage, and slow reading of production drawings. These causes were responsible for 45.3, 38.5, and 16.2% of the delay, respectively.

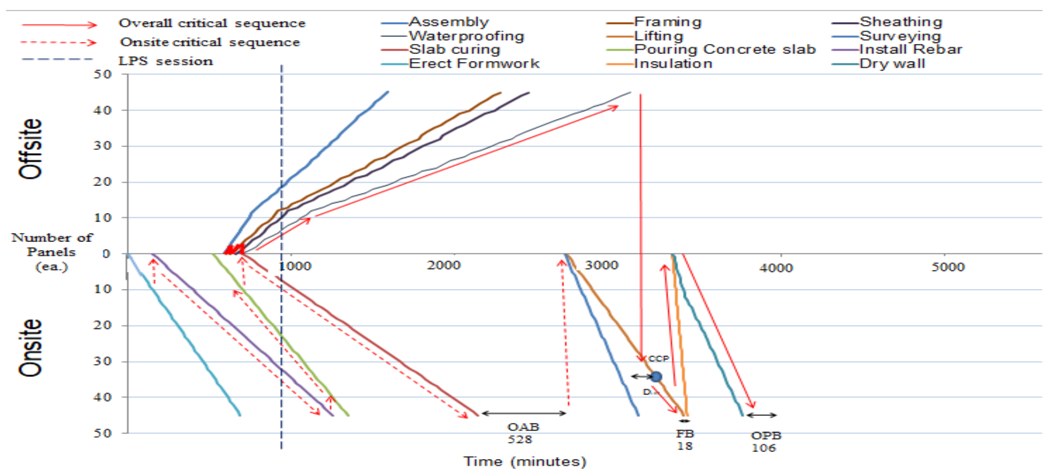


Figure 6.35: First LPS session

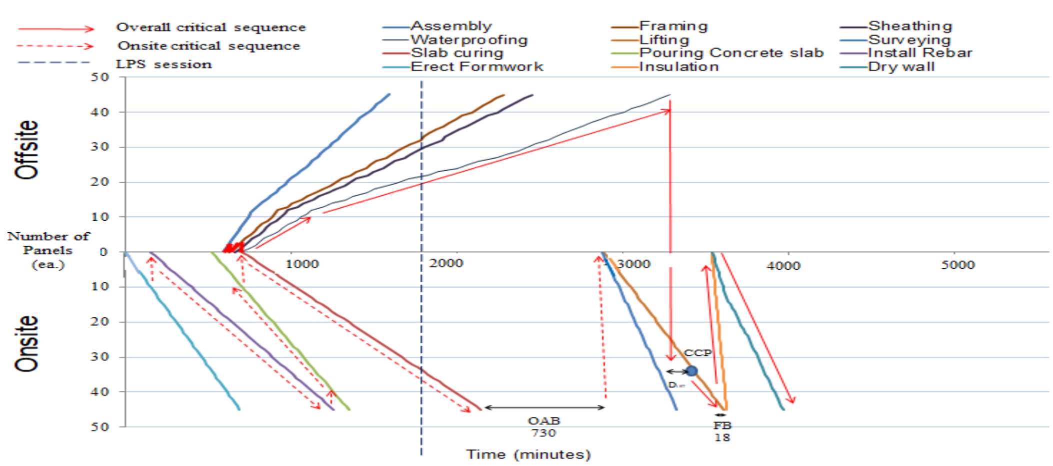


Figure 6.36: Second LPS session

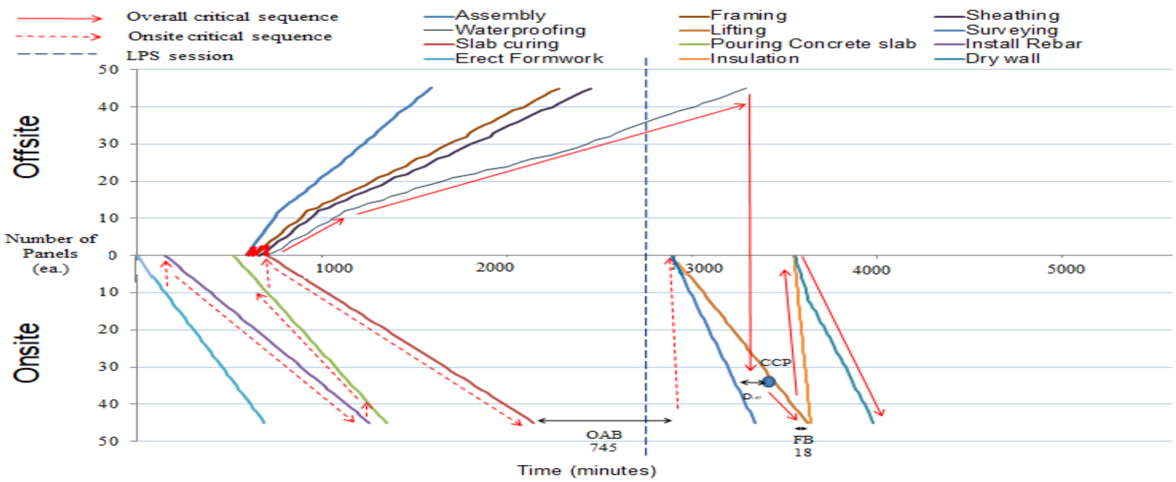


Figure 6.37: Third LPS session

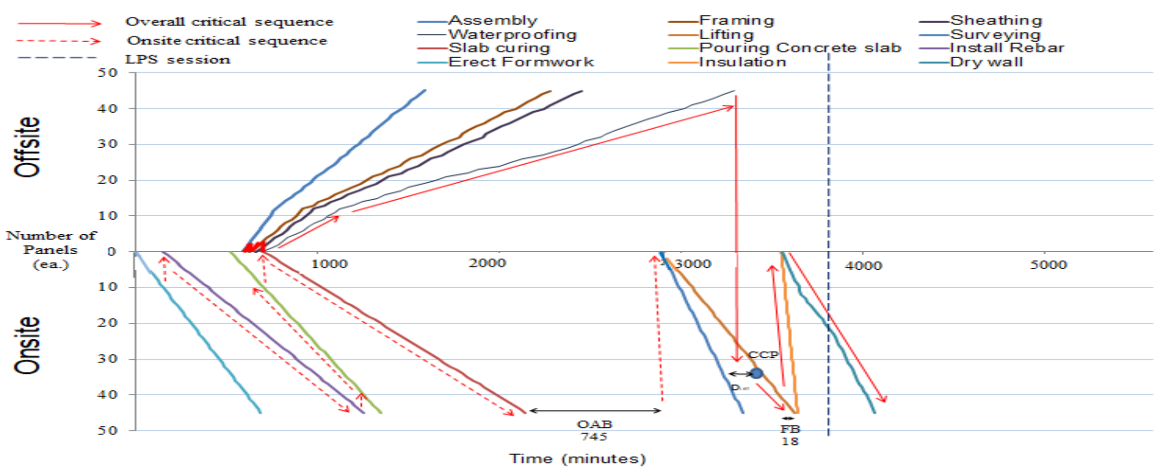


Figure 6.38: Fourth LPS session

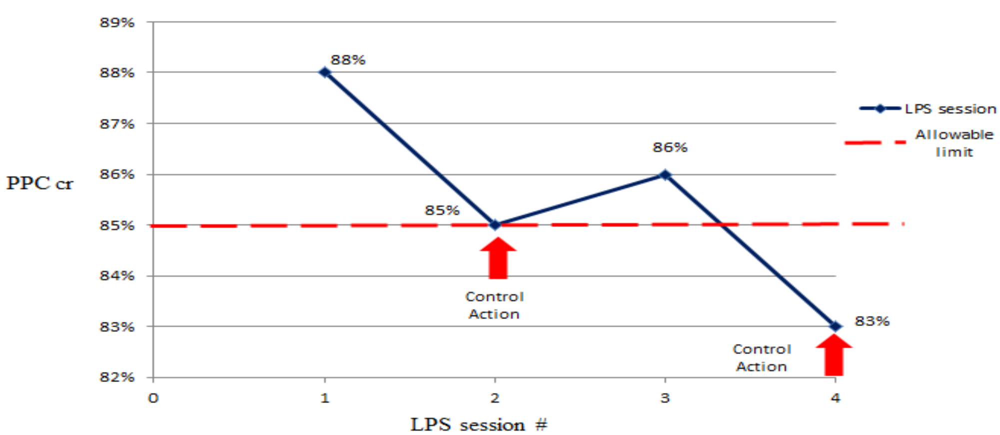


Figure 6.39: Monitoring PPCcr

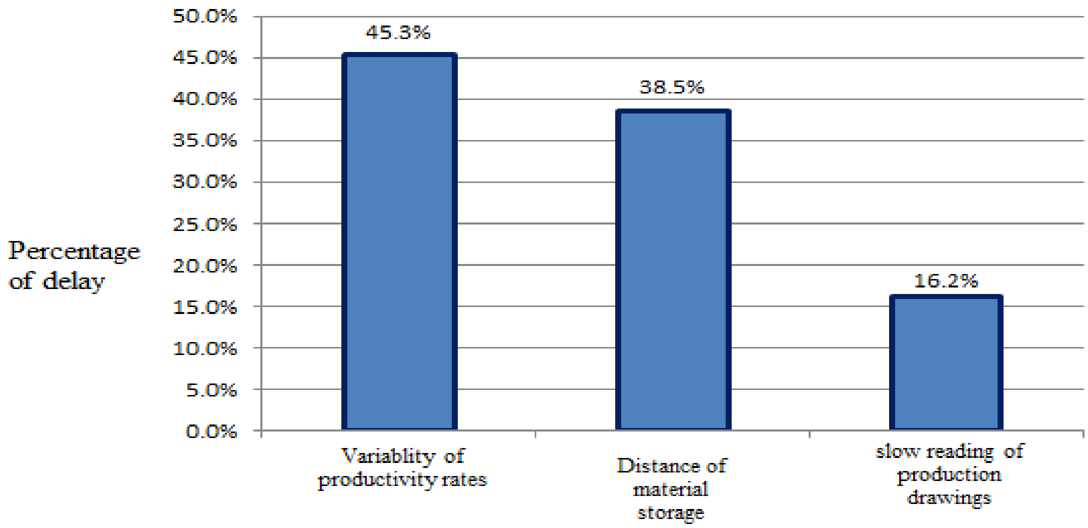


Figure 6.40: Pareto graph for root cause analysis

Chapter 7: Conclusion

7.1 Summary and Concluding Remarks

This chapter summarizes the contributions of this research to the body of knowledge related to planning and scheduling of modular and offsite construction. The literature review and the conducted questionnaire survey revealed number of findings, which are 1) the lack of studies that investigate some practices in modular and offsite construction and barriers to its increased market share, 2) the lack of methodoligies that allow project stakeholders to compare and select near optimum module configuration for modular construction, 3) the lack of models that help in identifying most suitable configurations for hybrid construction, 4) the suitability of LSM-based tools for the optimized scheduling of modular construction, 5) the lack of tools for repetitive scheduling that account for uncertainty of productivity rates, 6) most planning and scheduling techniques for modular and offsite construction utilize simulation tools for optimization and integration of offsite and onsite schedules, 7) the suitability of LPS for tracking and control based on schedules generated using LSM and CCPM, and finally, 8) the lack of multi-objective optimization methods based on schedules that integrate LSM and CCPM.

The questionnaire investigated two main issues; 1) the characteristics of the modular and offsite construction industry, and 2) detected barriers to the increased market share of this industry. Key findings show that DB is the common project delivery system for modular construction, while IPD is emerging and DBB is declining. Nearly half of the responses utilized BIM in their operations while Revit is the common BIM software. More than half of respondents agreed that there is negative stigma associated with modular construction and suggested that social networks and online courses be utilized to promote modular construction. Key findings of this questionnaire include requests for use of separate code of modular construction design, innovative financing and insurance solutions, standards that consider procurement regulations and lending institutions that partner with financial houses to create special lending programs for modular construction. Full questionnaire findings can be found as a separate report at the official MBI website (Salama et al., 2018b). The first model presented a novel methodology for near optimum selection of module configuration. The developed methodology utilized five indices, which accounts for connections of modules onsite (CI), transportation of fabricated modules to construction jobsite (TDI and TSDI), crane operating condition and related cost (CCPI), and project concrete foundation (CVI) (Salama et al., 2017c). The second model identified the optimal module/panel configuration for hybrid construction based on architectural, structural, manufacturing, and transportation constraints. It was concluded that architectural designs dominate the length and width of panels. However, structural, transportation, and manufacturing constraints influence the length and width that exceed the length and width stipulated by regulations and standards (Salama et al., 2017d).

The third model introduced a new scheduling method for repetitive projects that integrates LSM and CCPM to be utilized in modular and offsite construction (Salama et al., 2017b). The proposed method considered constraints of resources continuity and uncertainties associated with activity durations. It was concluded that the developed method is capable of; 1) respecting the continuity constraint required by LSM, 2) reducing project duration using CCPM aggressiveness, 3) identifying multiple critical sequences that are constrained by controlling resources which may change the project duration based on variability of its productivity rates, and 4) allocating project buffer and feeding buffers at the end of the longest critical chains and between non-critical chains emerging into critical ones based on CCPM. Case examples' project duration was reduced from 163 to 152.5 days by utilizing the developed method when comparing to the results of other researcher. The fourth model introduced a new multi-objective optimization method to minimize time, cost, and work interruptions for repetitive scheduling while considering uncertainties associated with different input parameters. The design of the developed method was based on integrating six modules: 1) uncertainty and defuzzification module, 2) schedule calculations module, 3) cost calculations module, 4) optimization module using genetic algorithms, 5) module for identifying multiple critical sequences and schedule buffers, and 6) reporting module (Salama and moselhi, 2018c). It was concluded that for duration optimization that utilizes fuzzy inputs without interruptions or adding buffers, duration and cost generated by the developed method are found to be 90 and 99% of those reported in literature, respectively. For cost optimization that utilizes fuzzy inputs without interruptions, project duration generated by developed method was found to be 93% of that reported in the literature after adding buffers. It was found that the developed method accelerates generation of optimum schedules. The fifth model introduced a new method for project tracking and control of integrated offsite and onsite activities in modular construction that considers practical characteristics associates with this industry. This model embraces BIM and utilizes LPS for tracking and control of the integration between LSM and CCPM (Salama et al., 2018d). Features of the proposed method were illustrated in a case example using real data of productivity rates for offsite activities collected from a manufacturing facility in Edmonton, Alberta. A comparison between the developed schedule and Monte Carlo simulation showed that baseline duration generated from simulation exceeds that produced by developed method by 12 and 10% for schedules with 50 and 90% confidence level, respectively. These percentages decrease based on interventions of members of project team in the LPS sessions. The case example results indicate that the project is delayed 5% and experiences cost overrun of 2.5 %.

7.2 Research Contributions

Several original contributions were introduced during the course of this research, embracing integration of LSM, CCPM and LPS for any type of repetitive projects. The main contributions of this research are:

- Developing a model for near optimum selection of module configuration for efficient modular construction. This model utilizes five indices which are CI, TDI, TSDI, CCPI, CVI and integrates them into one index named the modular suitability index (MSI). MSI allows for comparing different modular designs to reach near optimum modular configuration;
- Developing a systematic model to identify the most suitable configuration for each type of modules (i.e. panels) for hybrid construction. This procedure depends on checking four constraining factors which are architectural, structural, manufacturing and transportation constraints.
- Developing a generic model that embraces BIM for scheduling, tracking and control of repetitive projects by integrating LSM, CCPM and LPS;
- Developing a method for integrating offsite and onsite construction schedules utilizing integration of LSM and CCPM;
- Providing a comparison between scheduling results of Monte Carlo simulation and integration of LSM and CCPM for the overall schedule (offsite and onsite schedules), while considering uncertainity of productivity rates;

- Developing a scheduling software named “Mod–scheduler”, programmed specifically for modular and offsite construction using ASP.NET system coded with C# programming language. This software integrates offsite and onsite schedules while considering uncertainity of productivity rates for both schedules; and
- Developing a new GA multi-objective optimization model to minimize time, cost, and work interruptions for repetitive scheduling while considering uncertainties associated with different input parameters.

7.3 Research limitations

The main limitations of this research are as follows:

- The model for near optimum selection of module configuration does not consider the structural differences of designs or customer satisfaction. If two different modular designs were conducted for a building and both of them apply the required design specifications. Then, the different number of modules for both buildings affects the weight of steel and the cost of the structural system. This change in cost makes one structural design preferable than the other. Customer satisfaction is acquired by investigating customer needs for the area of different rooms and locations of bathrooms and kitchens.
- The proposed model for identifying the most suitable configuration for hybrid construction considers technical aspects but not economic aspects, which may affect further the dimensions of panels;
- The developed scheduling, tracking, and control models do not consider customer satisfaction;

- The comparison between the developed schedule and Monte Carlo simulation showed that the duration generated from the simulation exceeds that of the one produced by the developed method at 12 and 10% for the 50 and 90% schedules, respectively. This can be attributed to the utilized buffer; and finally,
- The developed multi-objective optimization model does not consider or quantify the impact of resources utilization on the quality of activities.

7.4 Opportunities for Future Work

Based on the research conducted, future work may consider:

- Expanding the developed model for configuration of modular construction to account for customer satisfaction and structural preferences. This model can also be expanded to include a commissioning index to its MSI, particularly for industrial projects. The analytic network process (ANP) or the analytic hierarchy process (AHP) can also be used to calculate the relative weight assigned to the indices in the developed method. Both methods create a decision problem as a hierarchy or a network with a goal, decision criteria, and alternatives. Then they use pairwise comparisons to measure the weights, and finally ranking the alternatives of the required decision;
- The integration of technical and economic aspects to determine optimum configuration of hybrid construction. This can be achieved by investigating the options of increasing panel length with higher thickness and comparing it to the options of decreasing the panel length with a lower thickness to sustain the structural loads for all project's panels and comparing the costs of both scenarios ;
- Refining the buffer formulation used to improve the accuracy of developed model;

- Considering integration of LSM, CCPM and agile scheduling or lean-agile concept to focus on customer satisfaction in scheduling, tracking, and control of modular and offsite construction.
- Expanding the developed software "Mod-Scheduler" to account for tracking and control of modular and offsite construction; and
- Developing a time-cost-quality trade-off analysis that allows for work interruption, while considering and quantifying the impact of resources utilization on the quality of activities (El-Rayes and Kandil, 2005), as well as considering uncertainities of different inputs.

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APPENDIX I

Questionnaire Results

First part (Industry characteristics)

The questions and responses of the questionnaire for this part are as follows:

1- What type of material used in fabrication and production of modules?

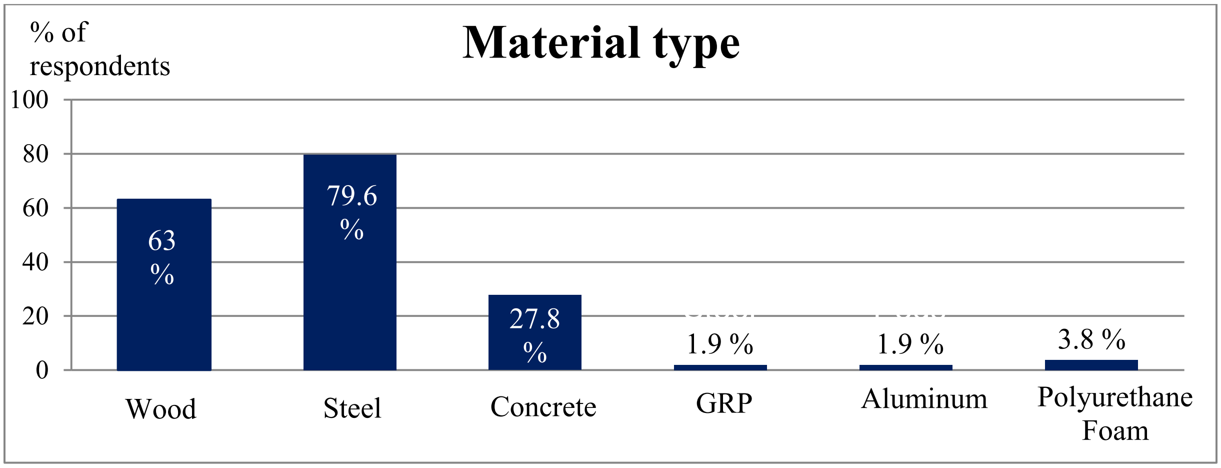


Figure I.1 : Material type of modules

2- What type of modules you produce?

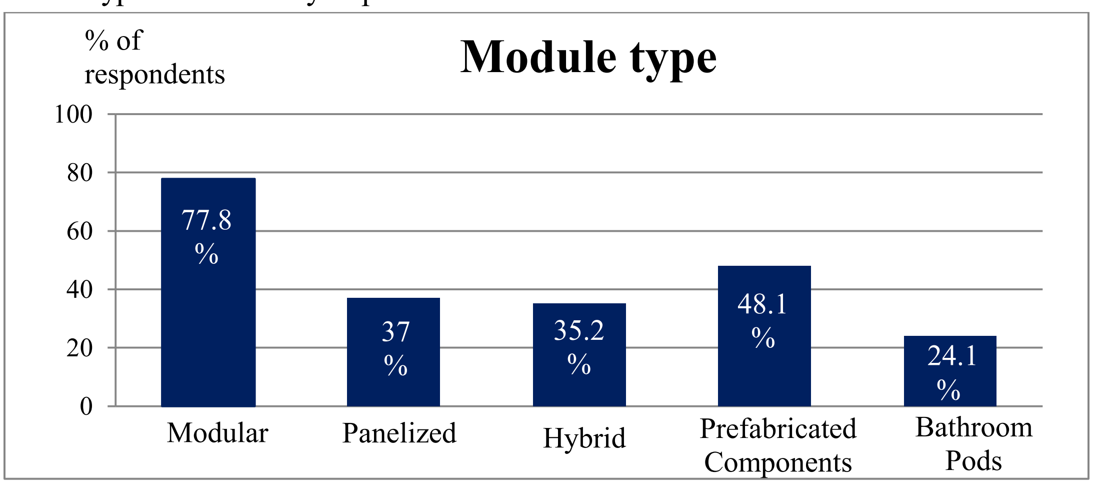
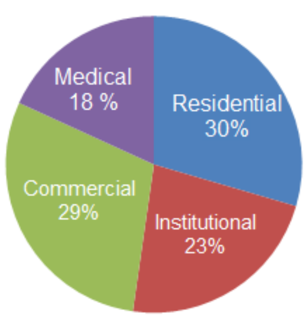
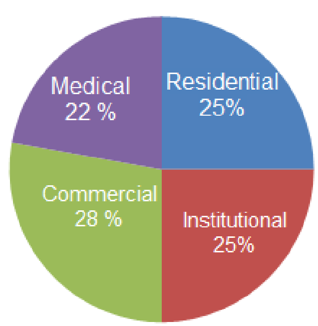


Figure I.2 : Modules type

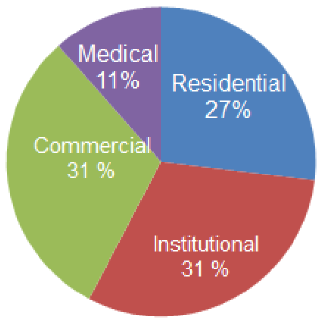
3- What type of modular construction project?



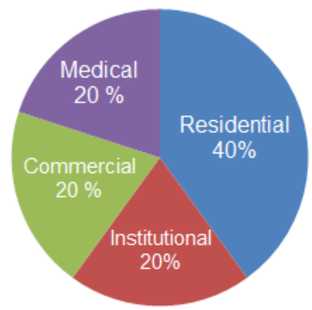
IPD & Project type



DB & Project type



DBB & Project type



CMAR & Project type

Figure I.3 : Type of modular construction project

4- What is the volume of sales (dollar value of business) for modular construction of your company over last 5 years (Please write the value of each year separately from 2012 to 2016)?

It is clear that the percentage of responses that incur an increase in sales is descending from 2012 to 2016.

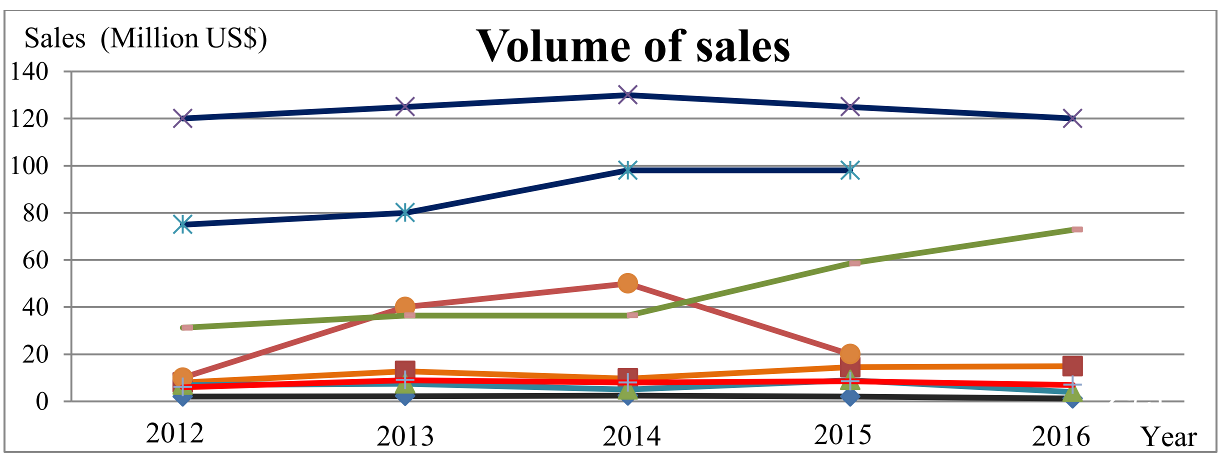


Figure I.4: Volume of sales for modular construction companies

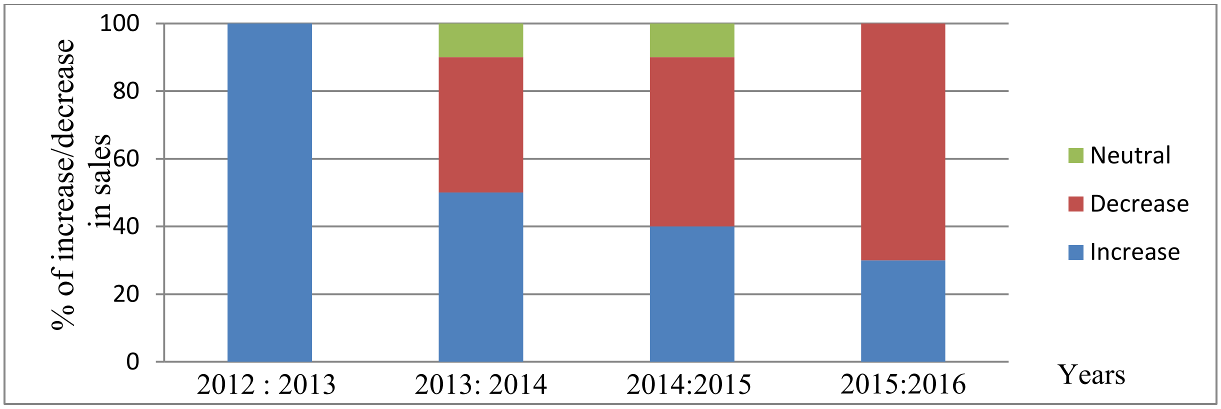


Figure I.5: Percentage of increase or decrease in sales

5- Which party is responsible for the following activities in your modular projects?

(MC: Modular Company (manufacturer), GC: General contractor (onsite), DF: Design firm.

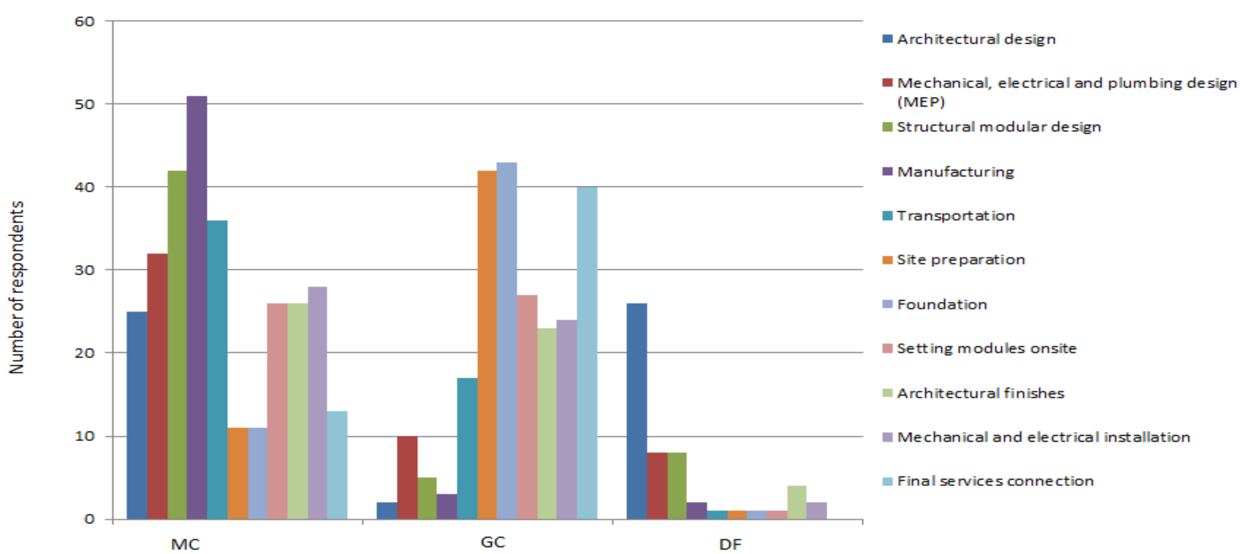
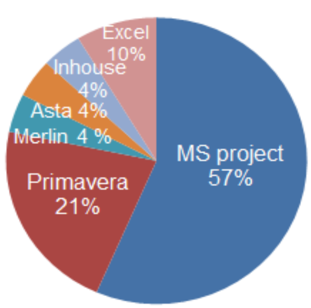
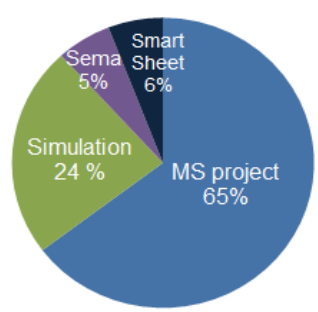


Figure I.6: Responsibility for activities in your modular projects

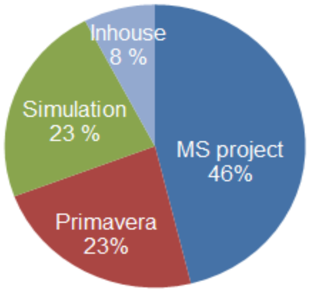
6 - What is the scheduling software/method used in your company?



DB & Scheduling software



IPD & Scheduling software

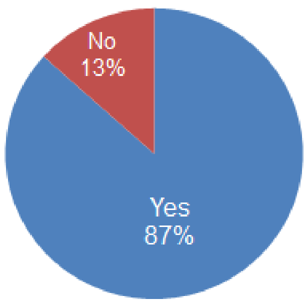


DBB & Scheduling software

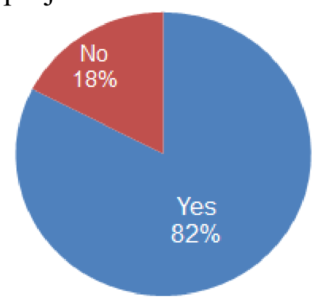
CMAR & Scheduling software

Figure I.7 : Scheduling software for modular projects

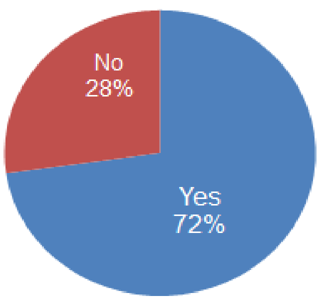
7- Are the onsite and offsite schedules synchronized in your projects?



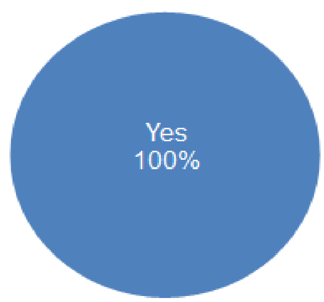
IPD & Schedules synchronization



DB & Schedules synchronization



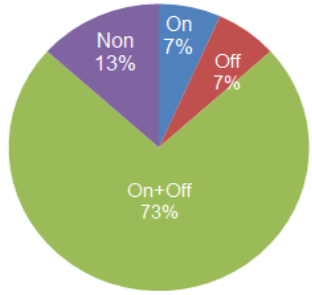
DBB & Schedules synchronization



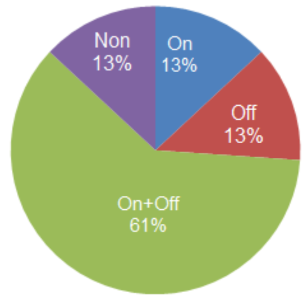
CMAR & Schedules synchronization

Figure I.8 : Synchronization of schedules in modular projects

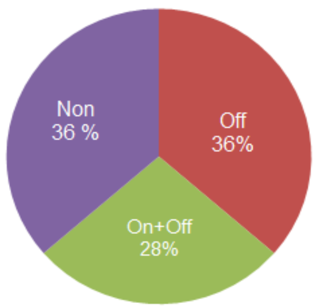
8- Is there any time study conducted to calculate productivity rates for your offsite and onsite operations?



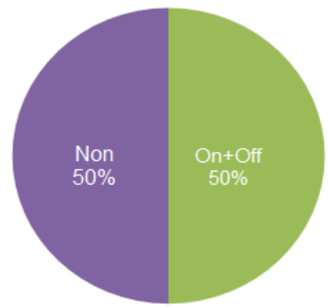
IPD & Collecting productivity rates



DB& Collecting productivity rates



DBB & Collecting productivity rates



CMAR & Collecting productivity rates

Figure I.9 : Collecting productivity rates for modular projects

9- Which Project Delivery System is commonly used?

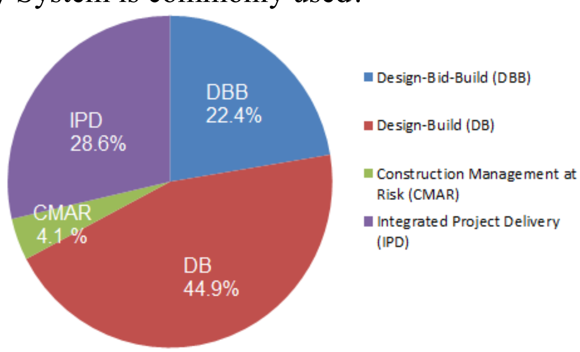
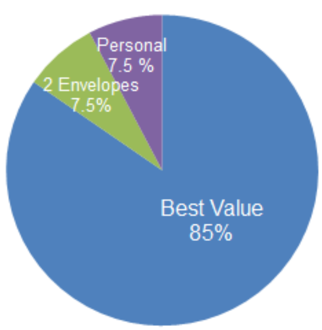
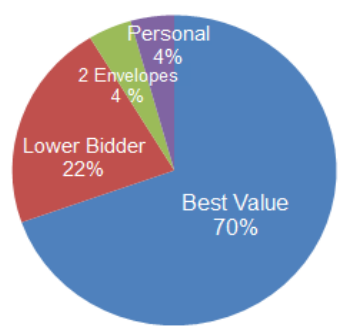


Figure I.10 : Project delivery systems for modular projects

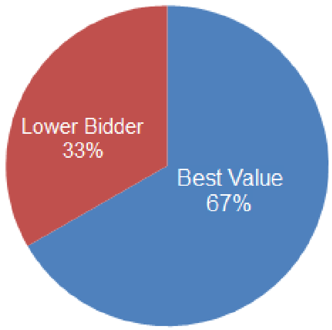
10- What is the commonly used procurement method?



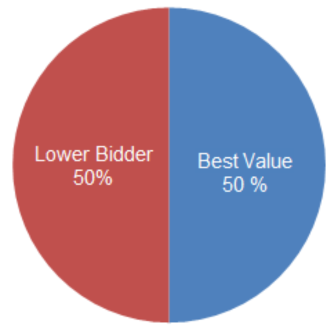
IPD & Bidding strategy



DB & Bidding strategy



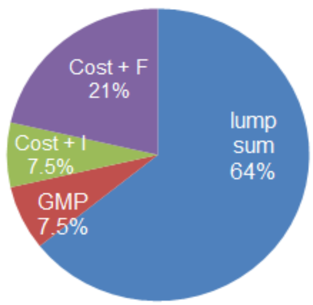
DBB & Bidding strategy



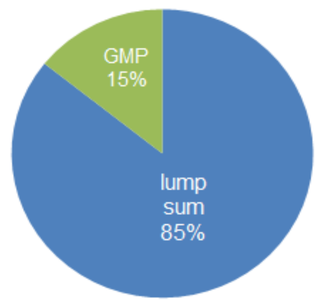
CMAR & Bidding strategy

Figure I.11 : Bidding strategies for modular projects

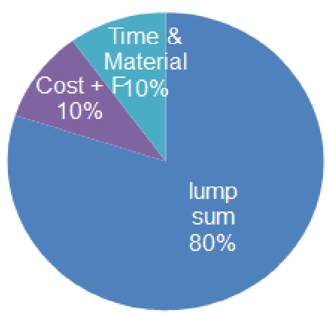
11- Which type of contracts is commonly used?



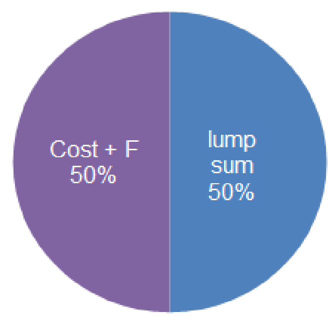
IPD & Contract type



DB & Contract type



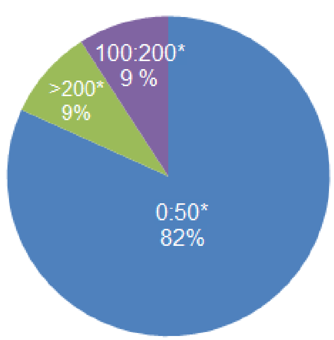
DBB & Contract type



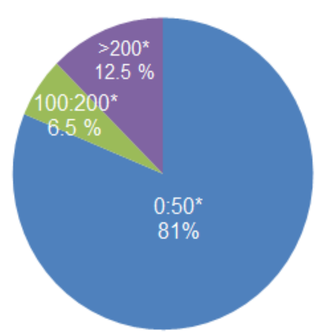
CMAR & Contract type

Figure I.12 : Contract types for modular projects

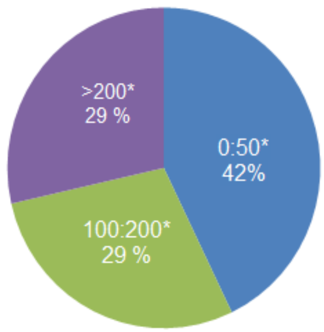
12- What is the total square footage of your project?



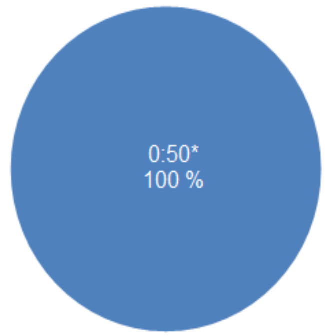
IPD & Project Size



DB & Project Size



DBB & Project Size



CMAR & Project Size

Figure I.13 : Total square footage for modular projects (* Project Size in 1000 Square feet)

13- What are the obstacles and difficulties that you faced on your project?

The obstacles and difficulties are ranked depending on the percentage of respondents as follows: 1) Contractors experience is not enough in applying modularization concepts (61.5%) , 2) Design scope was not be frozen early in project schedule (50%) , 3) Onsite and offsite schedules were not synchronized (34.6%) , 4) Module envelope limitation (dimensions limitation) restricted architectural design (32.7%), 5) Scheduling method utilized was not suitable for the project (7.7%), 6) Selected project delivery system was not suitable for the project (5.8%), 7) Attitudes of public inspectors (1.9%).

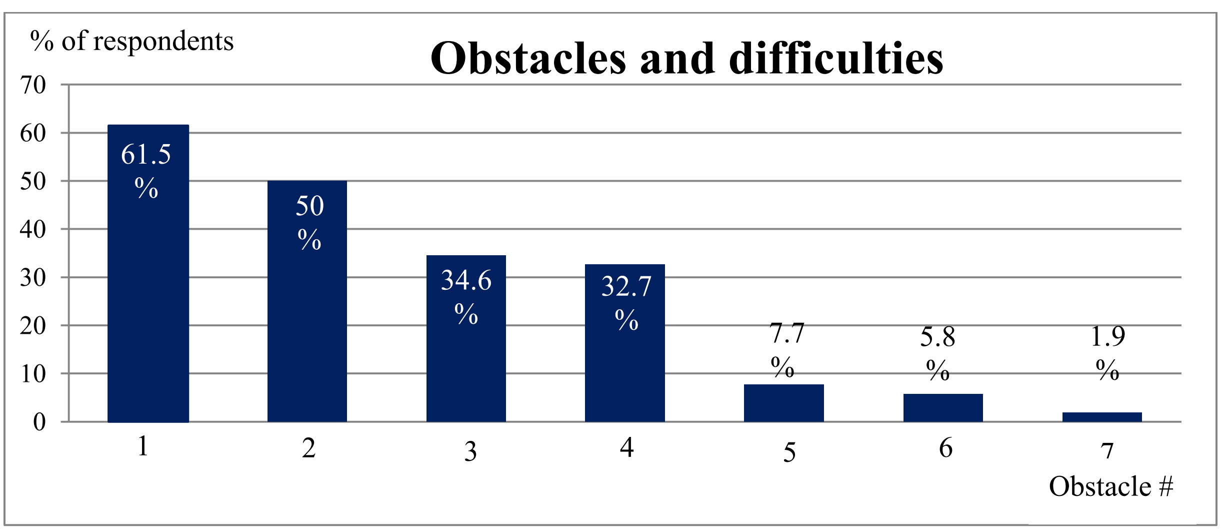
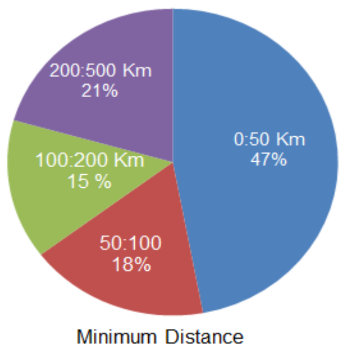


Figure I.14 : Obstacles and difficulties of modular projects

14- What is the commonly experienced distance between manufacturing facility and project construction site? Please specify: from ….. km to …. km



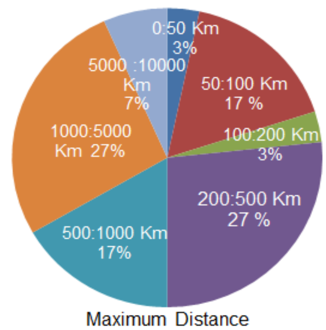
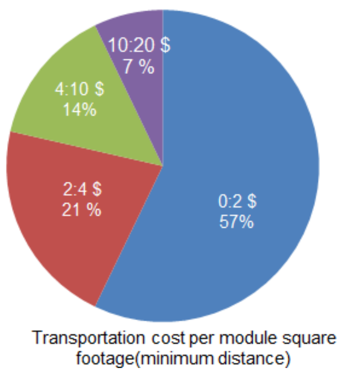


Figure I.15 : Common distance between manufacturing facility and project construction site for modular projects

15- What is the average transportation cost per module square footage?



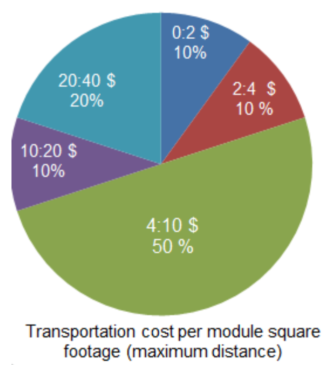


Figure I.16 : Average transportation cost per module square footage

16- How many modules the cranes lift per day onsite (daily placing rate)?

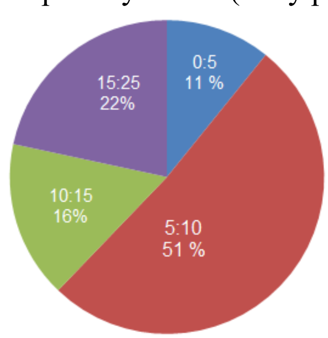


Figure I.17 : Daily placing rate of modules

17- What is commonly used crane type in lifting modules on your projects?

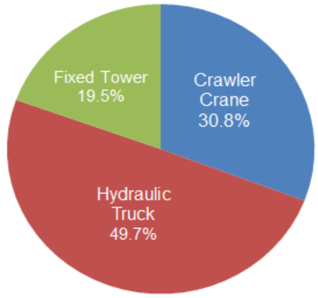


Figure I.18 : Common crane type for modular projects

18- What is the average lifting capacity of the used crane?

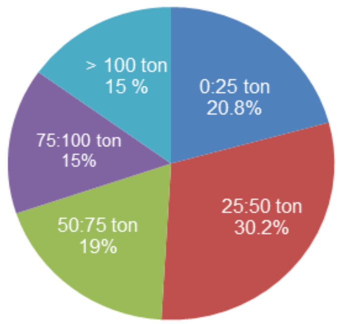
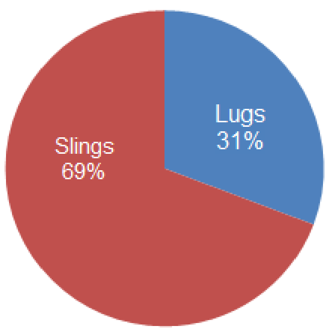
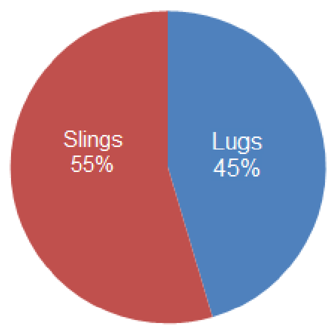


Figure I.19 : Average lifting capacity of cranes for modular projects

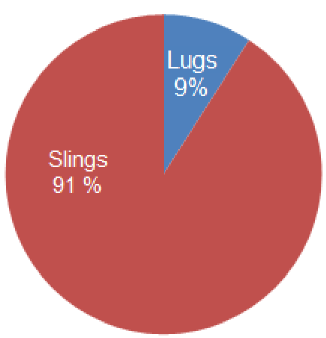
19- How is the module hoisted?



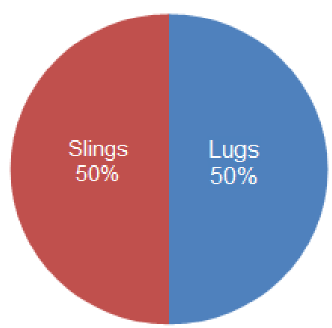
IPD & Module hoisting



DB & Module hoisting



DBB & Module hoisting



CMAR & Module hoisting

Figure I.20 : Methods of module hoisting

20- Is BIM used in your company?

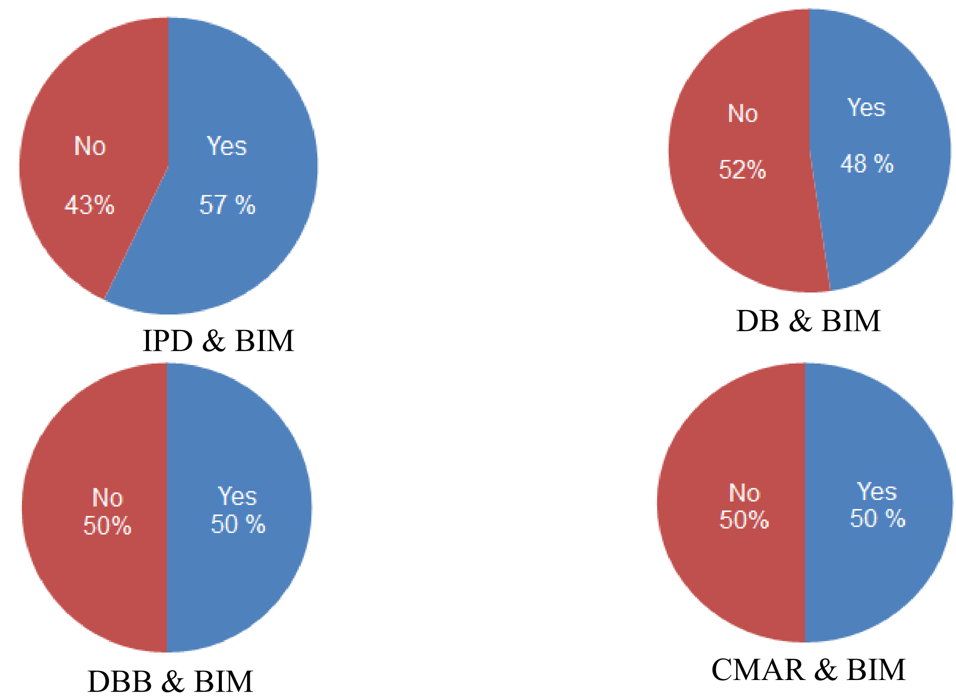


Figure I.21 : Utilization of BIM for modular projects

21- Which BIM software system is used in your company?

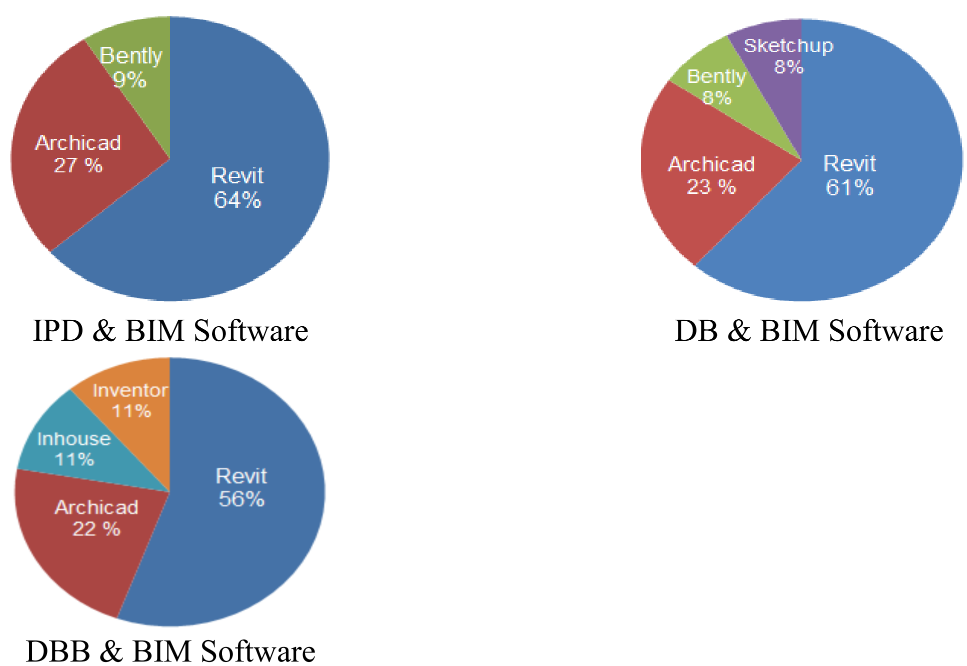


Figure I.22 : BIM software systems for modular projects

22- What BIM based applications are used in your company?

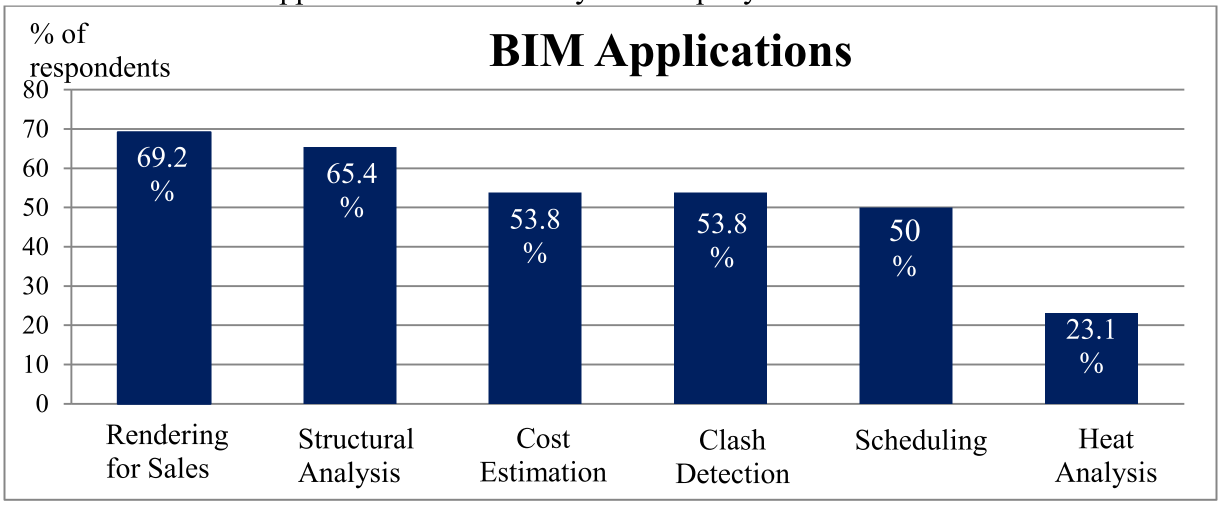


Figure I.23 : BIM applications for modular projects

23- In which project phase BIM is used your company?

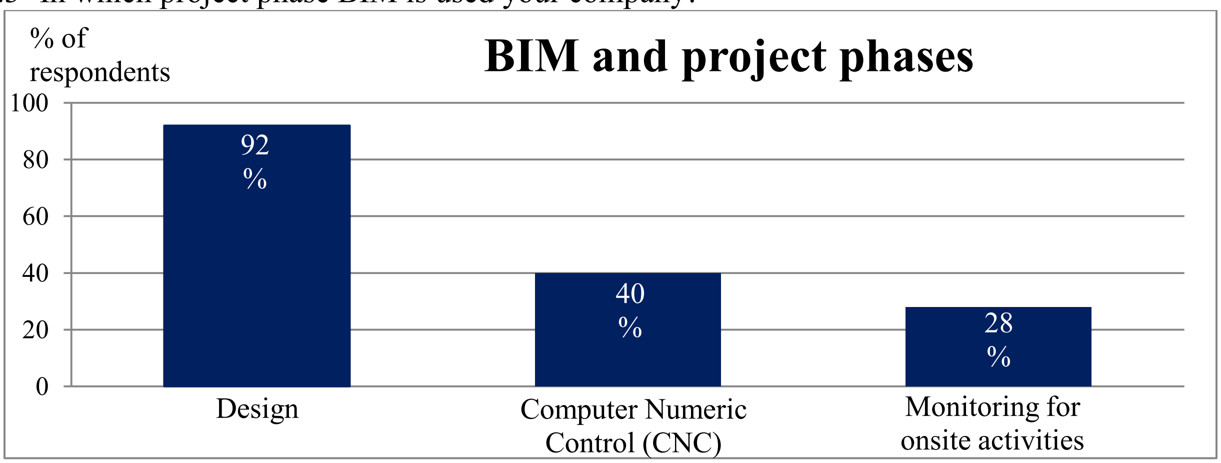


Figure I.24 : Project phase for utilizing BIM in modular projects

24- What future applications of BIM you are considering in your company?

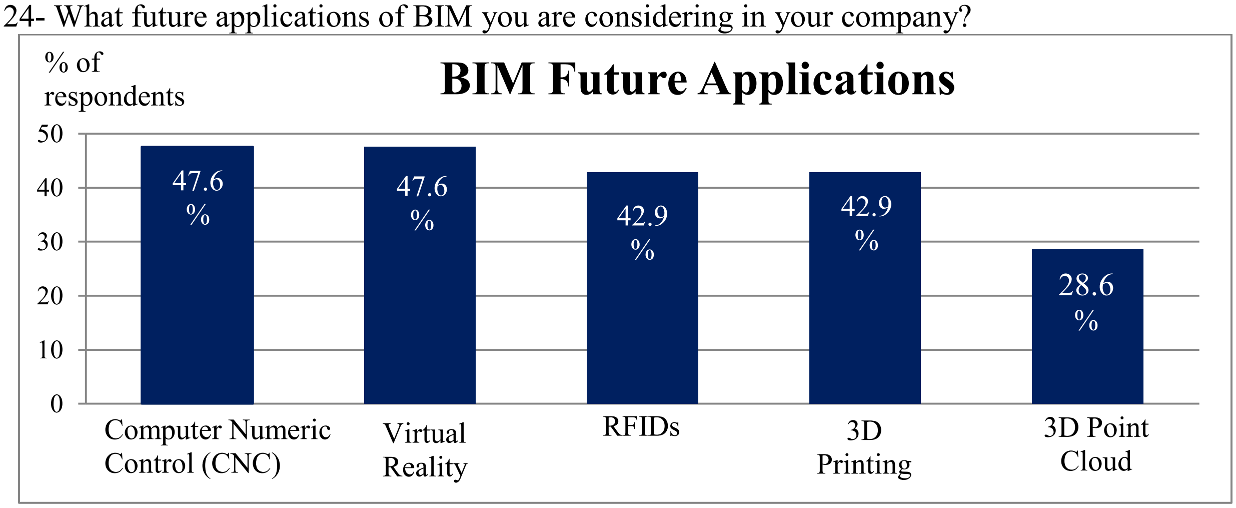


Figure I.25 : BIM future applications in modular projects

Second part (Barriers to increased market share)
The questions and responses of the questionnaire for this part are as follows:

1. Do you agree with the following statement: “There is a negative stigma associated with modular and offsite construction”?

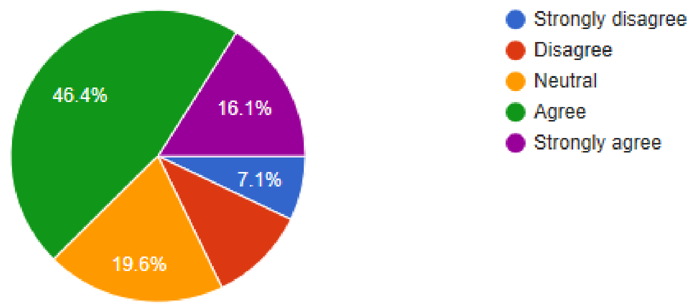


Figure I.26 : Negative stigma associated with modular and offsite construction

2. Do you agree with the following statement: “There is a misconception that modular is intended primarily for temporary, single-storey applications”?

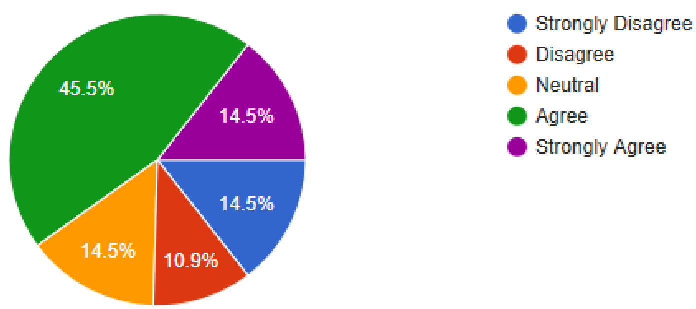


Figure I.27 : Misconception that modular is for temporary applications

3. The significant advantages modular construction offers are not communicated properly with owners.

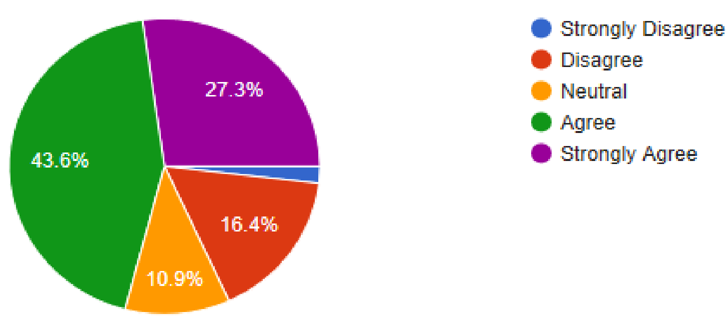


Figure I.28 : Advantages of modular construction are not communicated properly with owners

4. There is a shortage of well-designed marketing campaigns conducted by modular institutions and manufactures.

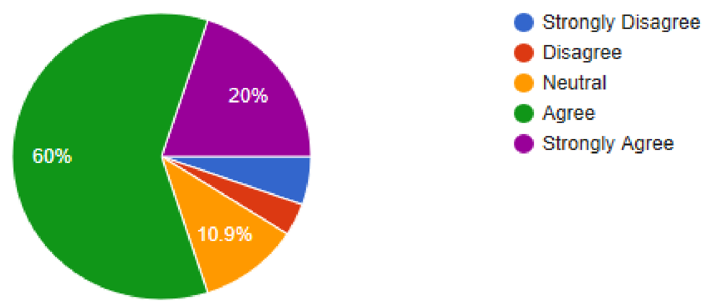


Figure I.29 : Shortage of marketing campaigns for modular construction

5. Owners are not familiar with the different products offered by the modular industry.

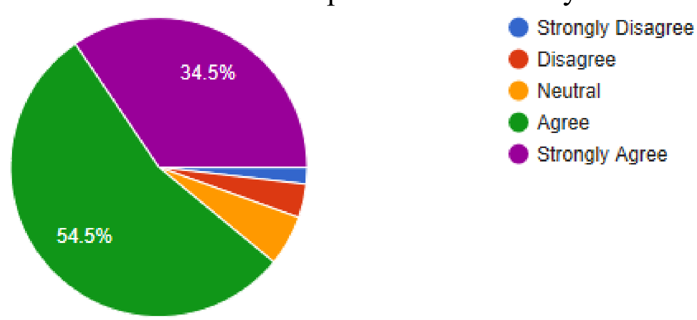


Figure I.30 : Owners familiarity with different products offered by the modular ind

6. Due to the focus of modular manufacturers on local markets, the modular industry lacks large scale partnerships and related market share.

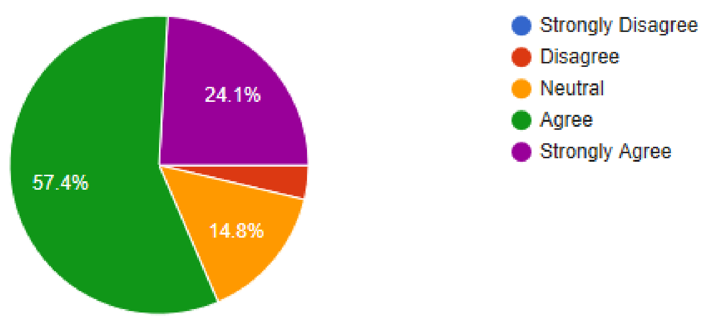


Figure I.31 : Large scale partnership in modular construction

7. There is a lack of academic research that highlights the advantages of modular construction in comparison with the conventional construction methods.

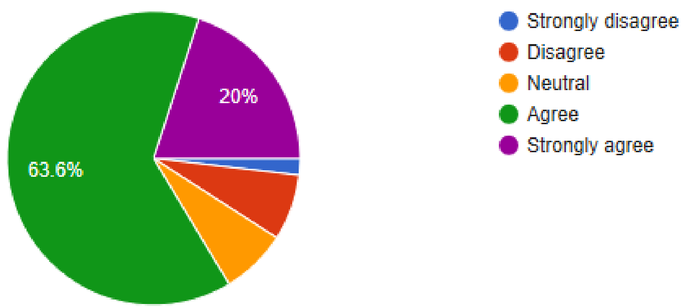


Figure I.32 : Lack of academic research that highlights advantages of modular construction

8. Modular manufacturers and institutions should organize regular facility visits open to the public to increase awareness.

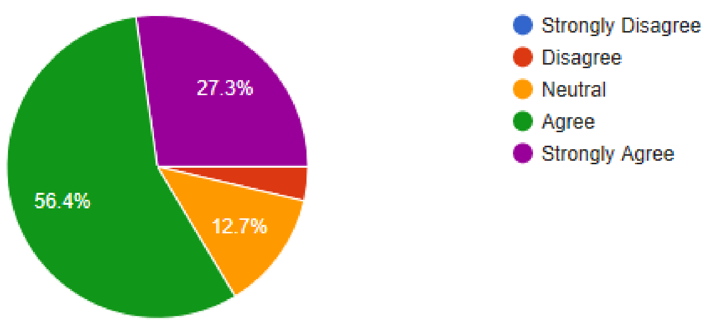


Figure I.33 : Organizing facility visits for the public to increase awareness of modular construction

9. What do you recommend MBI, PreFab Australia, PreFab NewZealand and other modular-focused organizations do to remove the stigma of modular construction?

The recommendations are as follows: 1) Promotional activities such as a formal campaign as Go RVing (66%) , 2) Establishing partnerships among manufacturers (62.3%) , 3) Organizing special workshops (52.8%) , 4) Communicating with authorities to have the building codes changed to improve industry standards between manufacturers (5.7%), 5)

Establishing specialized courses for architects and students (3.8%), 6) Disclosing cost and schedule savings studies and optimization due to utilizing modular construction (3.8%), 7) Utilizing automated systems more (1.9%).

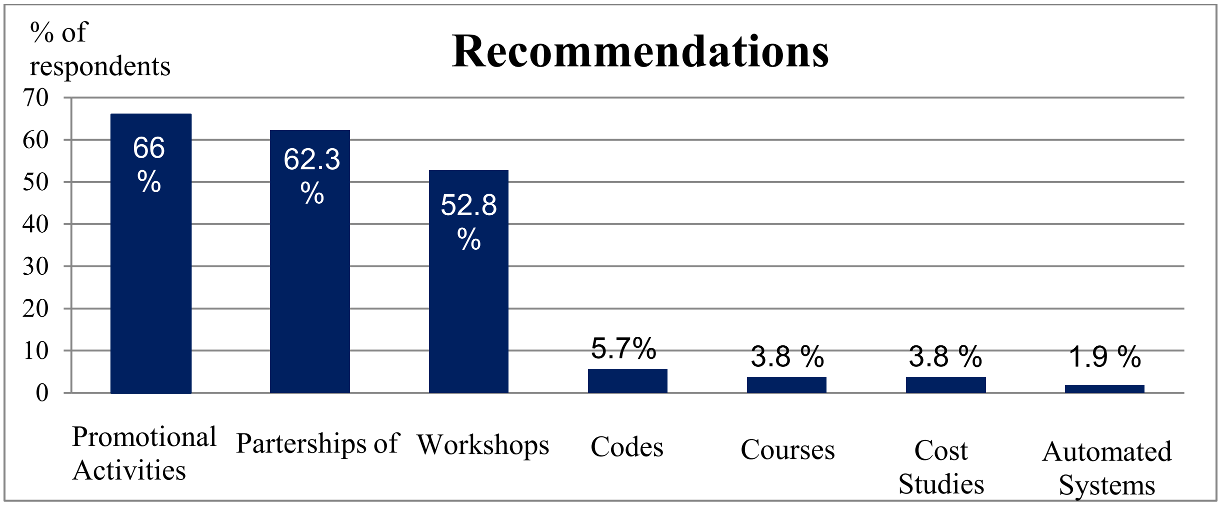


Figure I.34: Recommendations to remove the stigma of modular construction

10. What do you recommend research institutes and universities do to remove the stigma of modular construction?

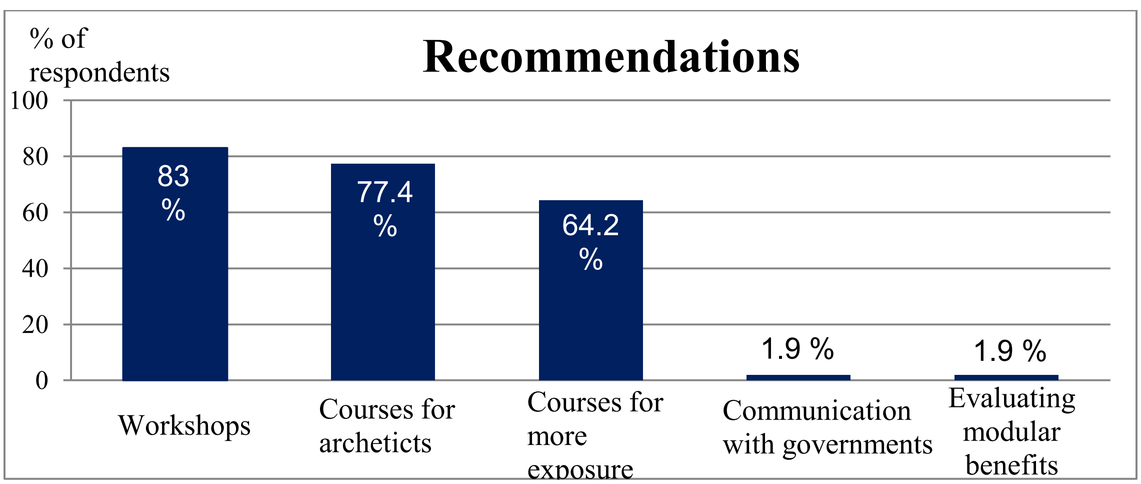


Figure I.35 : Recommendations for universities to remove the stigma of modular construction

11. What activities, events, or specialized conferences, such as the Modular and Off-site Construction (MOC) Summit and World of Modular, must be organized, other than what exists, to remove the stigma?

    a- Conducting international cooperation for all parties in the modular construction industry to show the American and Canadian ideas to the European industry and vice versa, and documenting the outcome as an open source format for everyone to share.
    b- Conducting seminars and workshops through NGOs and governmental bodies.
    c- Offering university training courses for modular construction.
    d- More collaboration between modular participants and outside organizations.
    e- Engaging industry and academic partners in a strategic planning for research and development of modular construction to promote the implementation of research outcomes in the industry.
    f- Organizing factory visits for clients.
    g- Establishing a North American advertisement campaign for the modular construction supported by an explanatory website.
    h- Conducting local events for modular construction for the community.

12. Would publicized success stories of modular be helpful in addressing the issue raised in 11 above?

    Most of responses agreed that the publicity for modular is helpful and the following comments were added:

    a- Focusing on marketing by properly communicating the pros and cons of modular construction in terms of quality, environment, flexibility in design, and return of investment (ROI).

b- Increasing the accessibility of information and training for the public regarding modular construction.

c- Focusing on the idea that modular construction reduces the risk for clients and contractors instead on showing how the modular design is innovative.

d- Improving academic-industrial communications and visits.

13. Modular construction lacks promotional materials that depict the successes and advantages.

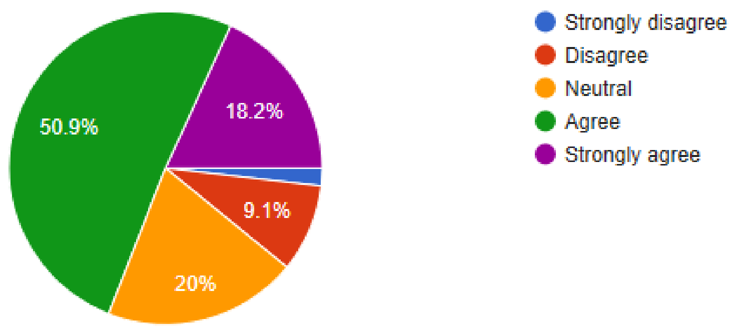


Figure I.36: Lack of promotional materials that depict the successes and advantages of modular projects

14. Owners lack knowledge about the compatibility of modular construction with different structure types and materials.

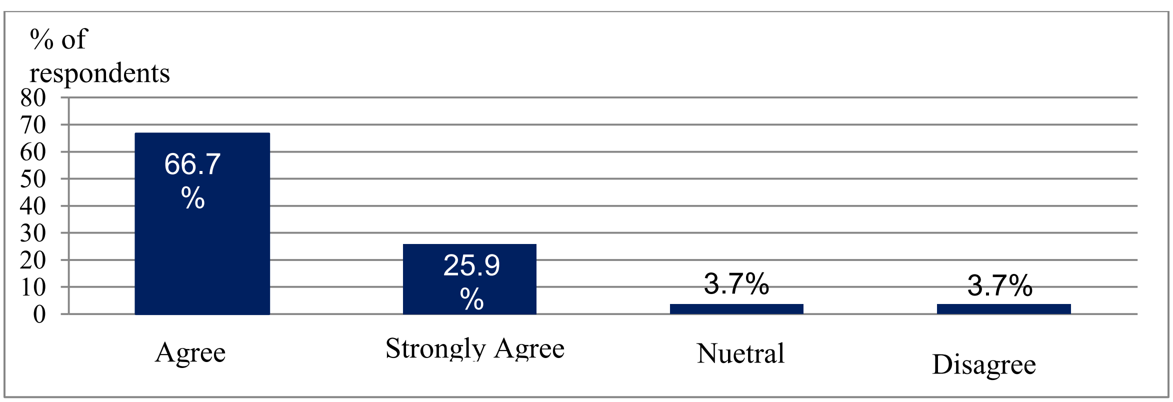


Figure I.37 : Lack of knowledge about compatibility of modular construction with structure types

15. There is a lack of worldwide documentation for lessons learned in modular construction.

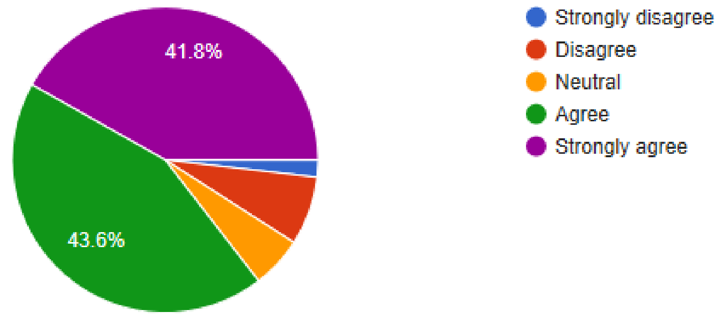


Figure I.38 : Lack of worldwide documentation for lessons learned in modular construction

16. There is a lack of nationwide documentation for lessons learned in modular construction.

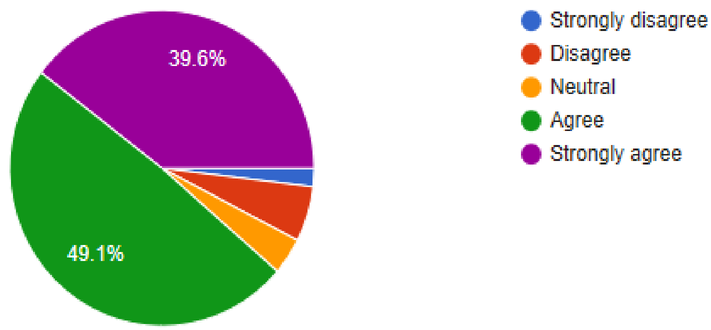


Figure I.39 : Lack of nationwide documentation for lessons learned in modular construction

17. There is a lack of government-sponsored case studies to highlight obstacles and opportunities for modular construction.

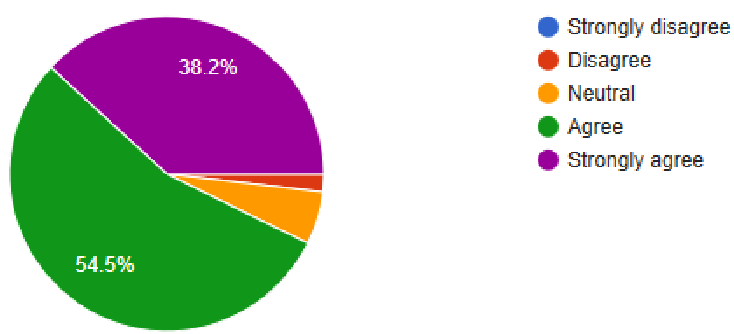


Figure I.40: Lack of government case studies to highlight obstacles and opportunities

18. There is a lack of academic research that leads modular construction by identifying potential obstacles and opportunities.

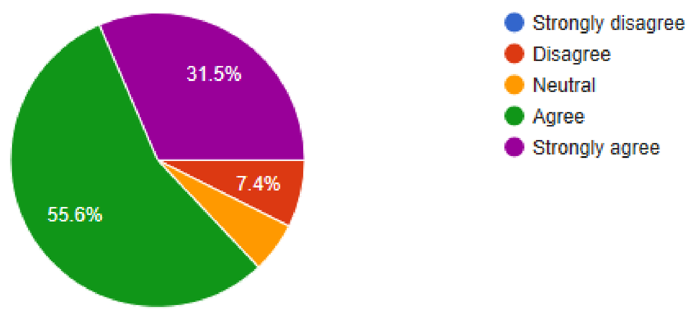


Figure I.41 : Lack of academic research for identifying potential obstacles and opportunities

19. Data available for manufacturers and owners does not support decision making with a high level of confidence.

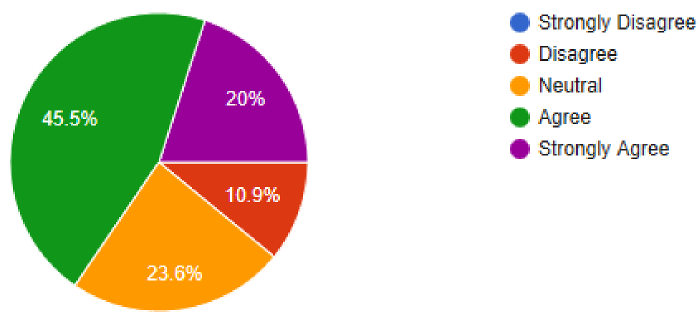


Figure I.42 : Lack of available data for manufacturers and owners to support decision making

20. What do you recommend MBI, PreFab Australia, PreFab NewZealand, and other modular-focused organizations do to publicize the success stories of modular?

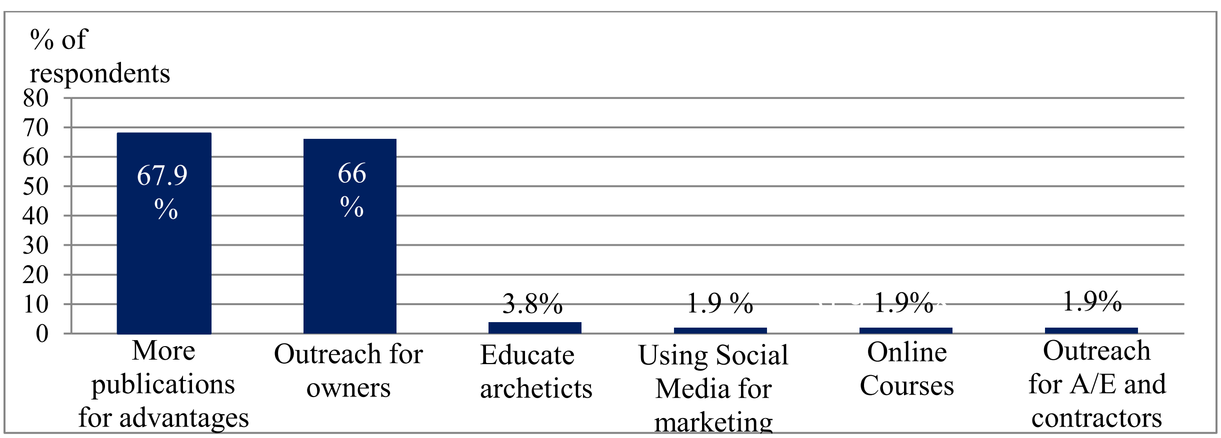


Figure I.43: Recommendations to publicize the success stories of modular projects

21. What do you recommend research institutes and universities do to publicize the success stories of modular?

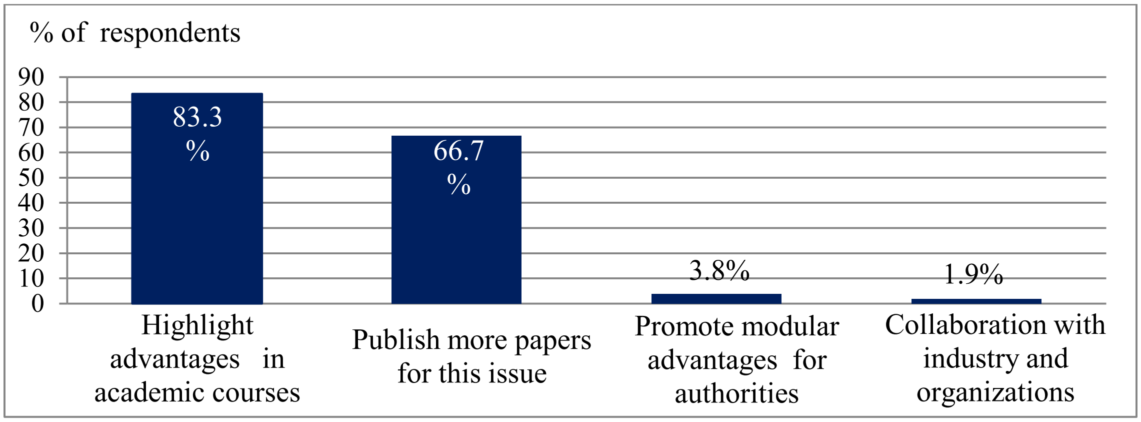


Figure I.44 : Recommendations for universities to publicize success stories of modular projects

22. Existing regulations and by-laws are not obstacles for the modular industry.

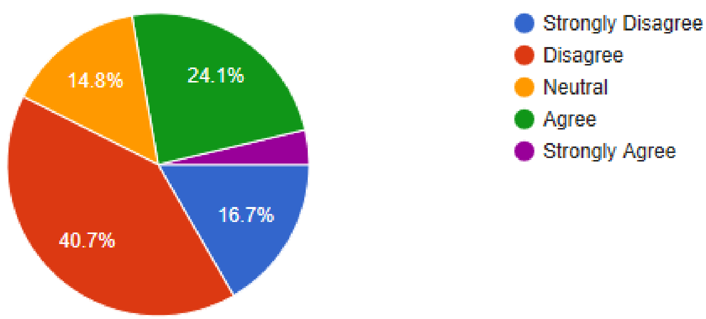


Figure I.45 : Effect of existing regulations and by-laws on modular projects

23. Although the existing regulations do not affect modular construction, the culture of inspectors, regulators, operators, etc. may place an extra burden on manufacturers.

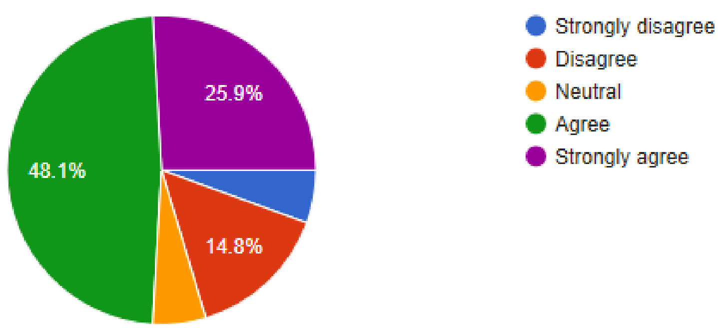


Figure I.46 : Effect of culture of inspectors, regulators, and operators on modular projects

24. Transportation regulations significantly affect the cost, time, design, etc. of the modules, and therefore burden the modular industry.

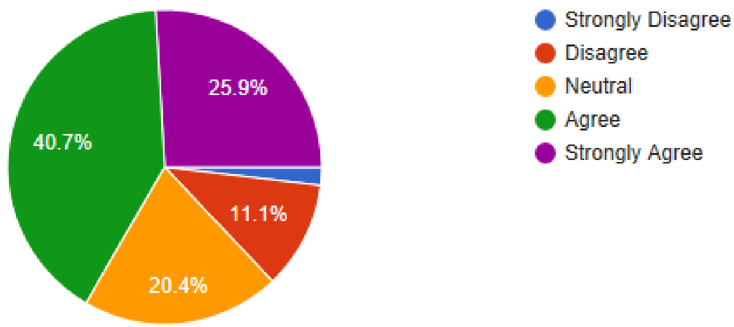


Figure I.47 : Effect of transportation regulations on modular projects

25. The changes of regulations among the different jurisdictions complicate the delivery of modules.

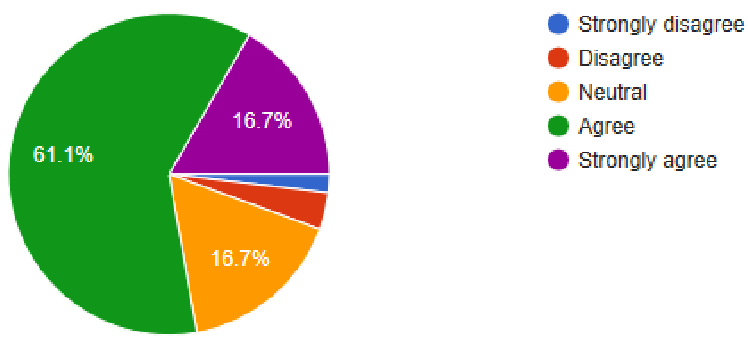


Figure I.48 : Effect of different regulations among different jurisdictions on modular projects

26. Regulations and by-laws should account for the different nature of the modular industry compared to conventional construction.

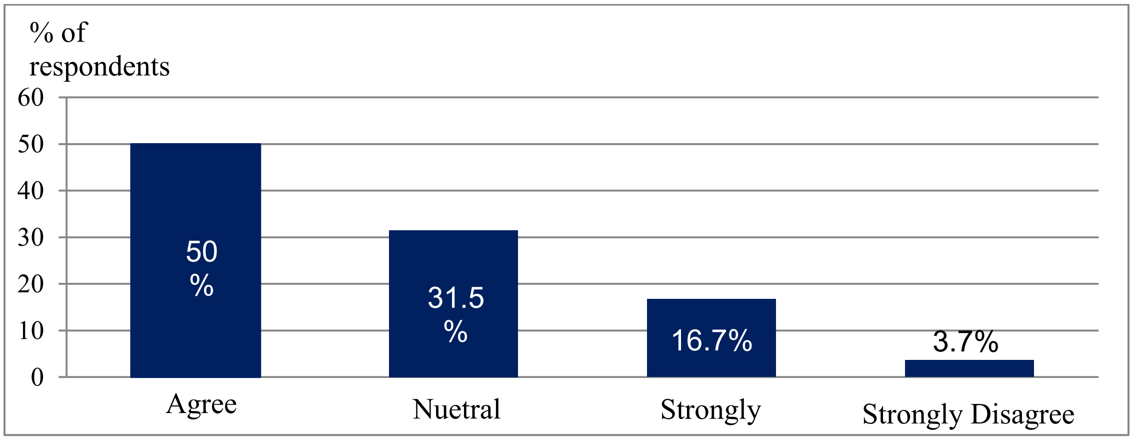


Figure I.49 : Different regulations and by-laws for modular projects

27. What do you recommend MBI, PreFab Australia, PreFab NewZealand, and other modular-focused organizations do to incorporate modular construction within the current standards and regulation?

a- Modular construction needs its own code.

b- Coordinate with code agencies to release uniform codes which are applicable across multiple jurisdictions that adopt modular and non-modular updates.

c- Adapting to current codes is better than having separate code standards which adds to the excuses contractors use against modular.

d- Lobbying for modular friendly regulations.

e- Contacting governments at all levels to promote/demonstrate through documented research the benefits of modular construction.

f- Work with (not against) existing advocacy groups for construction (i.e. NAHB).

g- Reaching the right people to make the needed changes.

h- Educating inspection community of modular construction.

i- More research and developments for modular construction.

28. What do you recommend research institutes and universities do to incorporate modular construction within the current standards and regulation?

a- Engineering departments should incorporate modular in their standard courses.

b- Finding the gaps between modular construction and current standards.

c- Develop research that ties the codes and standards with theoretical background of modular construction.

d- Introduce modular concepts to architectural departments.

e- Support lobbying for modular with case studies and data.

f- More research and developments and local outreach.

29. What activities, events, or specialized conferences, such as the Modular and Off-site Construction (MOC) Summit and World of Modular, must be organized, other than what exists, to incorporate modular construction within the current standards and regulation?

a- Review the UK growth in modular construction and adopt policies of marketing there.

b- Create events for owners, designers, contractors, and code inspectors.

c- Creating facility tours and project reviews like the UK www.buildoffsite.com.

d- Creating conferences in manufacturing facilities to show the full steps of modular construction.

e- Technical workshops to develop standards that are locally relevant and can be trusted by all stakeholders.

f- Developing standards are more important than promotional events.

g- Reach out to make presentations in other trade and professional associations.

30. Modular construction imposes changes in the perception of ownership. For instance, the purchaser holds the full ownership of the module.

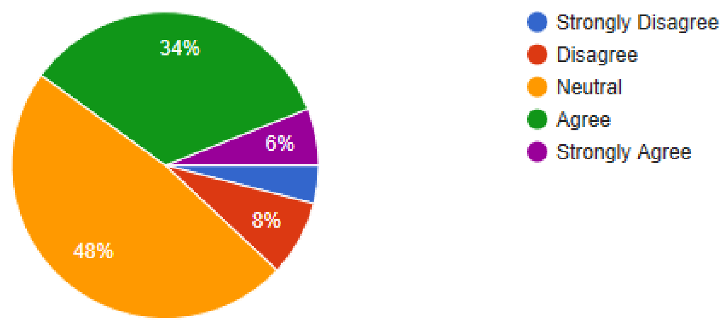


Figure I.50 : Changes in perception of ownership for modular projects

31. Due to the nature of the modular industry, the project execution plan has to be communicated up front and incorporated in the bidding process.

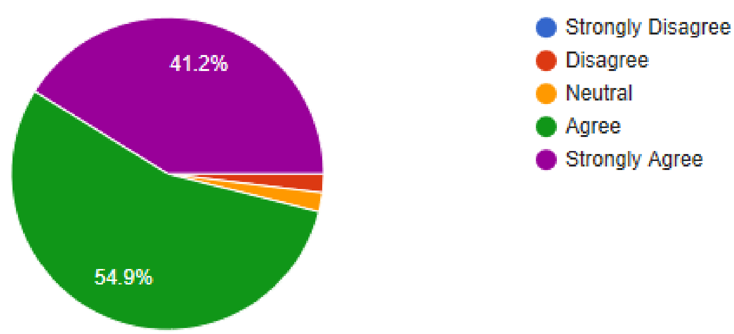


Figure I.51 : Project execution plan for modular projects

32. How can MBI, PreFab Australia, PreFab NewZealand, and other modular-focused organizations help to overcome the issues associated with procurement for modular construction?

a- Focusing on financing and insurance by studying the solar/renewable energy industries for examples of innovative financing and insurance solutions.

b- Increasing the credibility of suppliers. The problem in Australia that there are no suppliers left! Clients want to utilize modular but they can't find a credible supplier.

c- Developing codes and standards that consider procurement regulations for modular construction.

d- Implementing proper supply chain strategy.

e- By working on the biggest two issues on this regard, first is financing because lenders are afraid of losing value, the second is explaining the added value of modular manufacturing to the retail consumers.

f- Working with the industry and train companies to develop appropriate plans and approaches.

33. How can research institutes and universities help to overcome the issues associated with procurement for modular construction?

a- Analyze/measure/test/confirm the responses to this survey and distribute the results to stakeholders including debt lenders, equity/preferred equity/mezzanine equity providers, real estate investors/equity partners, real estate developers/builders/general contractors/sub-contractors/materials men-suppliers/design consultants e.g. architects, structural engineers, LEED/equivalent raters, ADA/Fair Housing reviewers, water intrusion consultants, civil engineers, traffic engineers, geotechnical engineers, environmental engineers, fire-safety engineers, sustainability/IT professionals, MPE engineers, Healthy-building/Well-building professionals, sub-metering systems providers, building code/compliance professionals, all manner of governmental subdivisions including their planners, plans reviewers, building inspectors, on/off-site improvements professional, transportation systems professionals, all utility companies/service providers, property/asset management professionals. Any/all of those have a stake in the product/end product.

b- Contractor's perception about 'buying' research need to be enhanced.

c- Develop new modular construction procurement methods that account for characteristics of modular construction.

d- Value engineering with modular construction should be a course.

e- More research and publications which can be used to demonstrate the value of automated production, quality control, strength versus stick built.

f- By conducting economic research and analysis for modular construction.

34. What activities, events, or specialized conferences, such as the modular and off-site construction (MOC) summit and world of modular, must be organized, other than what exists, to help overcome the issues associated with procurement for modular construction?

a- One big event rather than smaller less focused shows. The PreFab Australia annual conference has become a farce and is now devaluing modular in Australia and New Zealand . PreFab NZ conferences are really good but suffer from a lack of independent case studies of any scale. PreFab Australia annual conference is particularly self-interested and as such we do not attend. World of Modular is much better. Do one in Hawaii and we'll meet half way!

b- Utilizing social media promotion and long term commitment for promotion similar to the "Go RVing" campaign.

35. The predictability of cost and schedule gives the modular industry an advantage over the conventional construction.

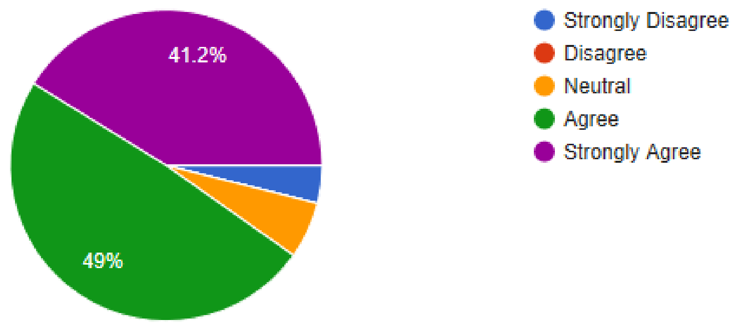


Figure I.52 : Predictability of cost and schedule for modular projects

36. The lower level of risk associated with modular construction has to encourage stakeholders to adopt new payment methods that are different from conventional construction.

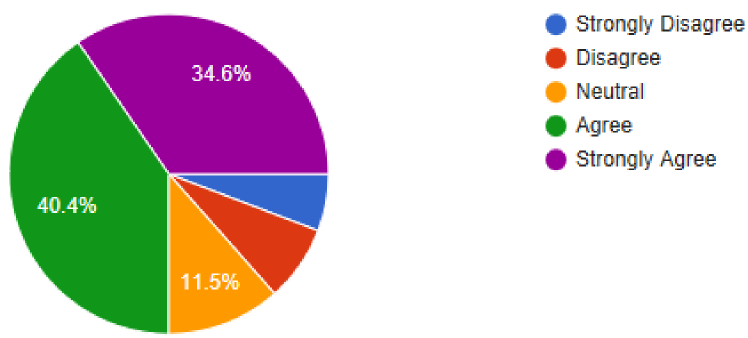


Figure I.53 : New payment methods for modular projects

37. The module belongs to the owner the moment it is fabricated, and therefore the owner should be responsible for the cost associated with storage.

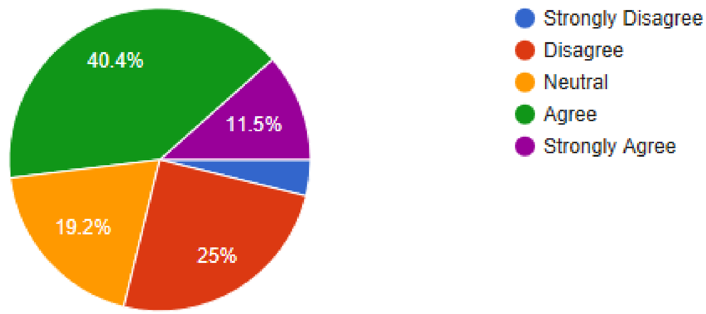


Figure I.54 : Owner responsibility for storage cost of modules the moment it is fabricated

38. If the module is fabricated on time and ready to be delivered to the owner, and for any reason it cannot be delivered to the site upon owner's request, the owner should be responsible for the cost associated with storage.

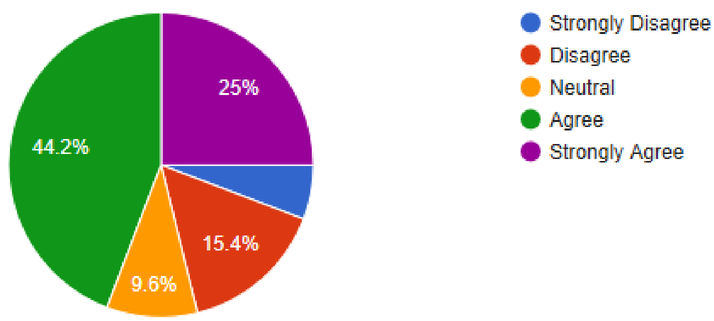


Figure I.55 : Owner responsibility for storage cost of modules if modules are not delivered onsite

39. If the module is not assembled, it is the manufacturer's responsibility to pay for any cost associated with storage.

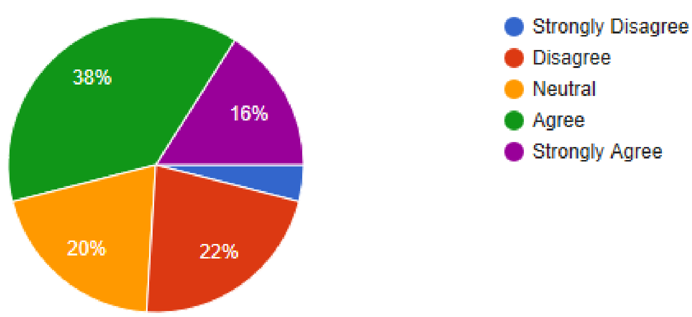


Figure I.56 : Manufacturer's responsibility for storage cost of modules if modules are not assembled

40. How often in your past projects did you have a problem with the delivered modules because they were different from the design specifications leading to difficulties in the installation process?

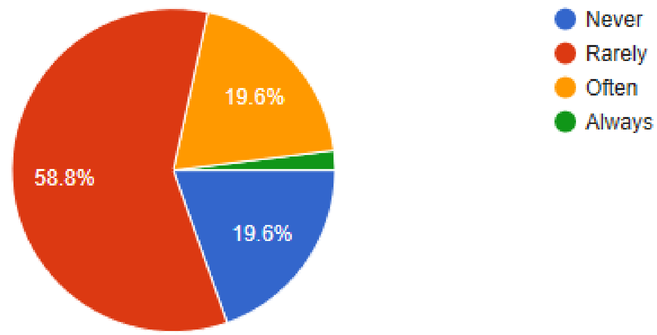


Figure I.57 : Problems if modules were different from design specifications

41. If a delivered module is not in full compliance with its design specifications and it does not fit at its final location onsite, who do you think should be held responsible for associated extra costs, e.g., storage, extra measures to fix the problem.

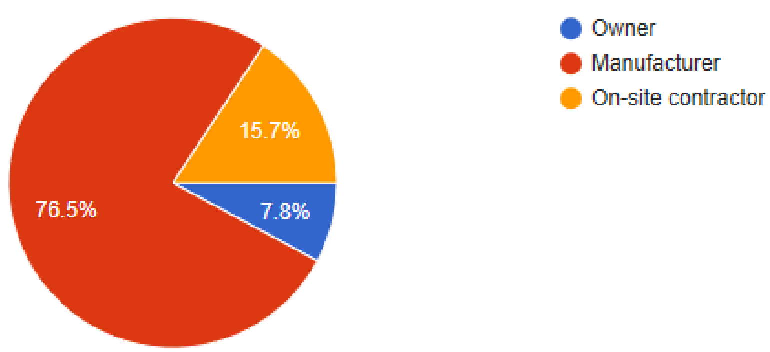


Figure I.58 : Responsible parties if problems occurred because modules are different from design specifications

42. Please indicate a percentage of the full contract price for each of the following progress levels that you think would be a fair guide for determining the progress payments to the manufacturer?

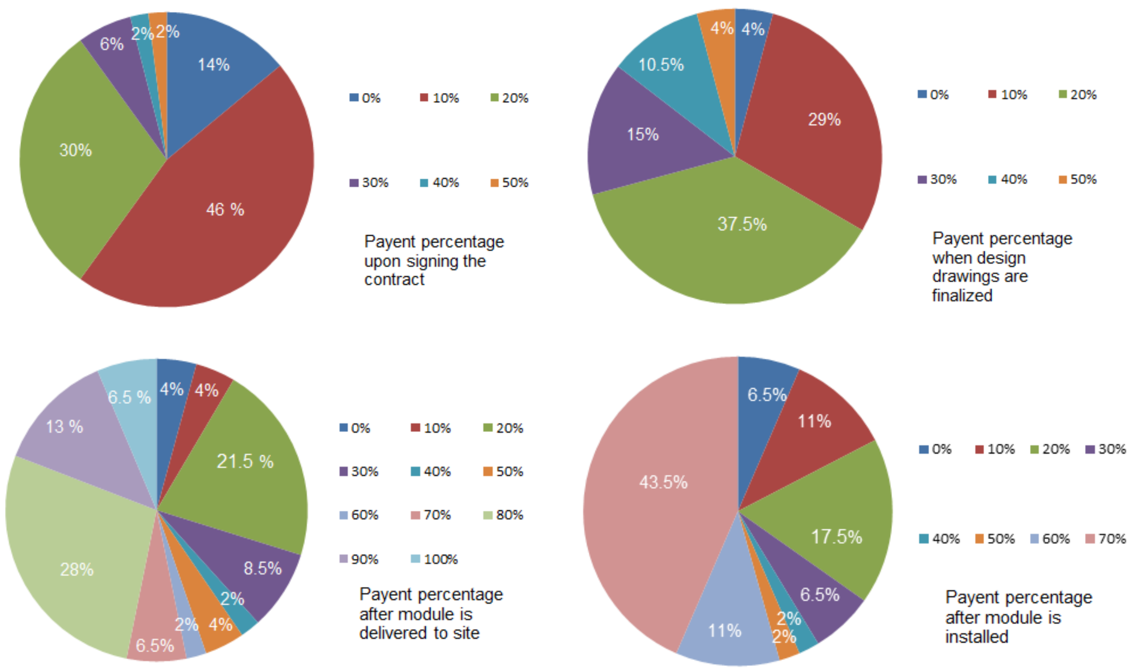


Figure I.59 : Percentage of full contract price for different progress levels

43. How can MBI, PreFab Australia, PreFab NewZealand, and other modular-focused organizations help to overcome the issues associated with project financing for modular construction?

a- Forcing finance markets to create models that consider modular construction characteristics.

b- Explaining for lenders why the manufacturing site is same as construction site for stored materials. It is the lending institutions that cause issues for the owner since many lenders do not understand modular industry.

c- Partnerships with financing houses.

d- Creating lending institutions for modular construction.

e- In the case of modular housing association prairie provinces (MHAPP) members, retail sales centres pay the manufacturer the full wholesale price for production of module at the time sales centre picks up module from manufacturer. Unless special financing is arranged between manufacturer and sales centre. The sales centre then sells the module to the end consumer. It is this part that requires a change at the lending institutions, where upon once the home is delivered, 85% of retail price is remitted to sales centres with the 15% hold back released upon connection of utilities. If sale centres do more extensive site work, an advance payment should be provided prior to delivery of the modules.

f- Educate financial institutions as to the risk reduction inherent in modular construction vis a vis stick built construction.

g- Getting banks to change lending policies.

h- Major insurance companies should insure modular buildings at a lower rate, if we can prove to them they are better built. I believe Loyd of London does this in UK. Why we cannot implement this in the USA and Canada!

44. How can research institutes and universities help to overcome the issues associated with project financing for modular construction?

a- Help customize the standard construction contract to the MOC System.

b- Educating upcoming potential construction leaders and having them understand the concept of modular and the great control of costs and tighter fixed costs.

c- Design a lending loan program for modular construction.

d- Develop cost management method that account for modular construction characteristics.

e- Education and quality acceptance is key for all parties associated with project development from governments to architects, planners, lenders, insurance companies, lawyers and real estate agents.

f- Provide studies that document risk mitigation with modular.

g- Create awareness of quality of automated production lines of housing and commercial structures and the benefits which are many. Conduct research about how they withstand hurricane force winds better than site built construction. There are so many attributes that public, contractors, builders, and developers don't understand about modular construction such as less acumulated interest due to shorter construction periods.

45. What activities, events, or specialized conferences, such as the Modular and Off-site Construction (MOC) Summit and World of Modular, must be organized, other than what exists, to help to overcome the issues associated with project financing for modular construction?

    a- Special summits to lenders.

    b- Train modular industry professionals to understand and incorporate provisions in their proposals/agreements that are standard/legally required for borrowers / developers / general contractors. Stop wasting time with agreements that won’t possibly be approved by project capital providers.

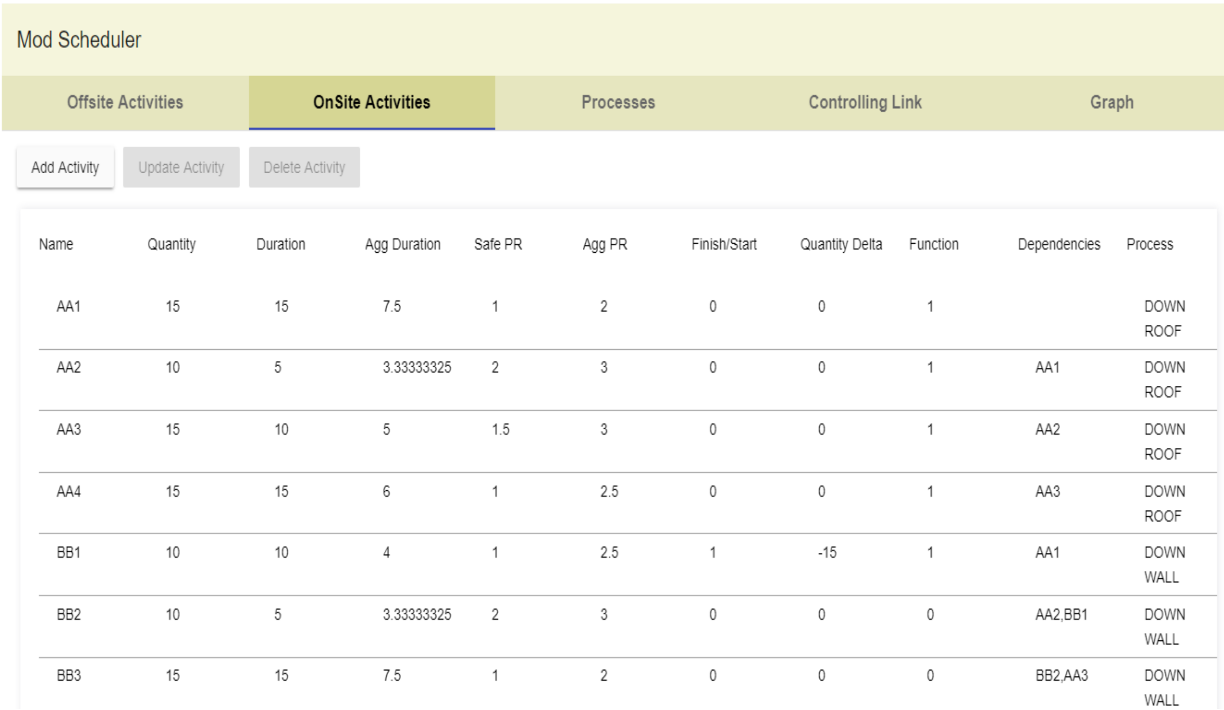
    c- Inviting government officials, architects planners lenders, insurance companies, lawyers and real estate agents to attend such events.

    d- Train and setup banks to finance modular products, because lenders are afraid that the product value isn't retained.

APPENDIX II

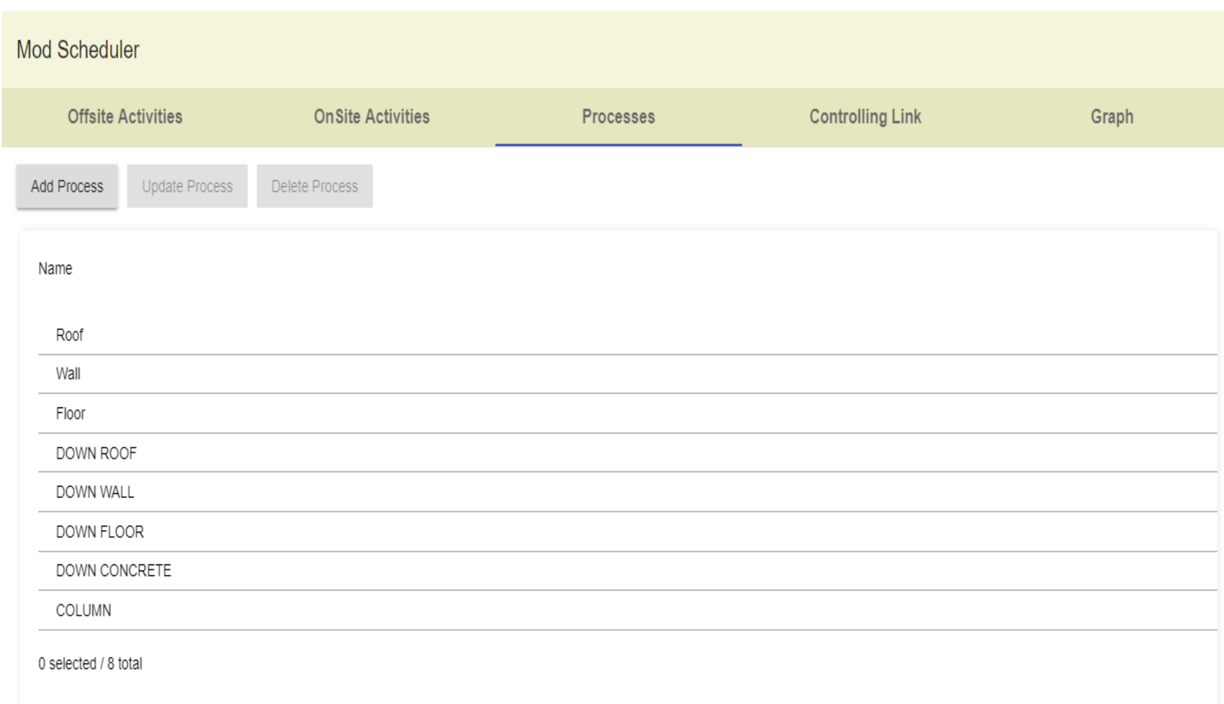
Input screens for

Mod- Scheduler



Name	Quantity	Duration	Agg Duration	Safe PR	Agg PR	Finish/Start	Quantity Delta	Function	Dependencies	Process
AA1	15	15	7.5	1	2	0	0	1		DOWN ROOF
AA2	10	5	3.33333325	2	3	0	0	1	AA1	DOWN ROOF
AA3	15	10	5	1.5	3	0	0	1	AA2	DOWN ROOF
AA4	15	15	6	1	2.5	0	0	1	AA3	DOWN ROOF
BB1	10	10	4	1	2.5	1	-15	1	AA1	DOWN WALL
BB2	10	5	3.33333325	2	3	0	0	0	AA2,BB1	DOWN WALL
BB3	15	15	7.5	1	2	0	0	0	BB2,AA3	DOWN WALL

Figure II.1: Inputs for onsite activities



Name
Roof
Wall
Floor
DOWN ROOF
DOWN WALL
DOWN FLOOR
DOWN CONCRETE
COLUMN

0 selected / 8 total

Figure II.2: Input of names for offsite and onsite processes

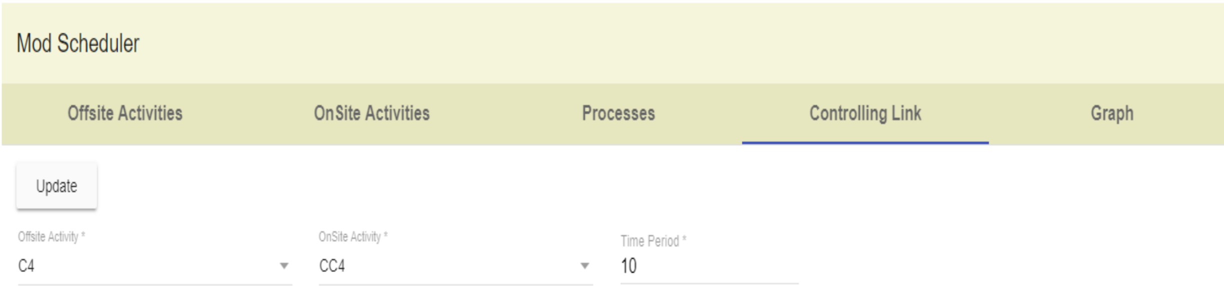


Figure II.3: Inputs of controlling link between offsite and onsite schedules

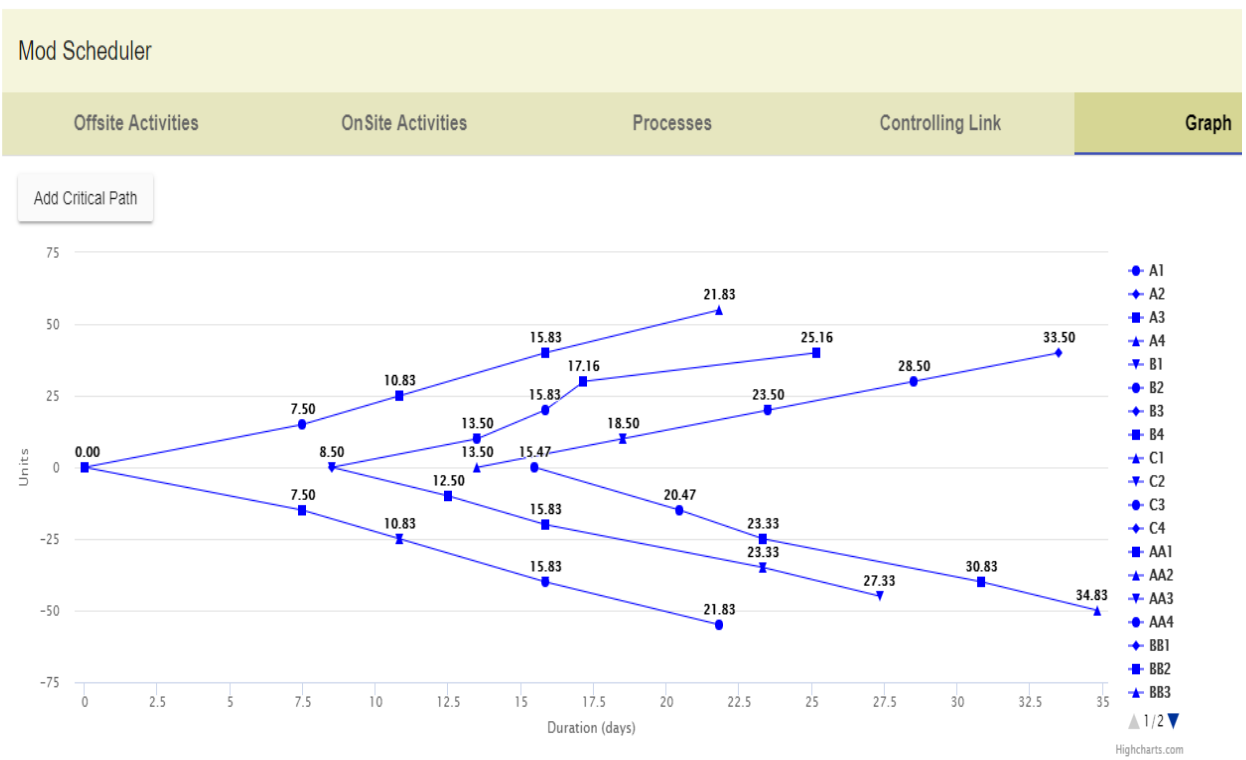


Figure II.4: Integrated schedule before adding buffers

APPENDIX III

Program Coding for

Mod- Scheduler

File: ModSchedulerCode/api/Services/ActivityProcessor.cs/(latest changes)

```
using System;
using System.Collections.Generic;
using System.Linq;
using SchedulePath.Models;
using SchedulePath.Helper;
namespace SchedulePath.Services
{
public class ActivityProcessor : IActivityProcessor
{
public Schedule Calculate(IEnumerable<Activity> activities)
{
if (!activities.Any()) return null;
CalculateActivities(activities);
return BuildProcessorResult()
.AddActivities(activities);
}
public Schedule Process(IEnumerable<Activity> activities,
Activity startingPoint, Activity endingActivity)
{
if (!activities.Any()) return null;
var criticalPaths = CalculateCriticalPath(activities, startingPoint, endingActivity, ActivityDirection.Normal);
if(!criticalPaths.Any())
criticalPaths.AddRange(CalculateCriticalPath(activities, startingPoint, endingActivity, ActivityDirection.Reverse));
var maxCriticalPath = GetMaxProjectBuffer(criticalPaths);
var feedingBuffers = CalculateFeedingBuffers(activities, maxCriticalPath, startingPoint, endingActivity);
return BuildProcessorResult()
.AddActivities(activities)
.AddCriticalPath(maxCriticalPath)
.AddFeedingBuffers(feedingBuffers);
}
private List<FeedingBuffer> CalculateFeedingBuffers(IEnumerable<Activity> activities, CriticalPath maxCriticalPath,
Activity startingActivity, Activity endingActivity)
{
var feedingBuffers = new List<FeedingBuffer>();
if (maxCriticalPath == null) return feedingBuffers;
var processFeedingBuffer = new List<KeyValuePair<int, float>>();
var orderedProcesses = new List<OrderedProcess>();
var orderedIndex = 0;
var startDurProcWithStartAct = activities.Where(a => a.ProcessId == startingActivity.ProcessId).Select(x =>
x.FromDuration).Min();
var startDurProcWithEndAct = activities.Where(a => a.ProcessId == endingActivity.ProcessId).Select(x =>
x.FromDuration).Min();
activities.GroupBy(a => a.ProcessId)
.Where(g => g.Select(x => x.FromDuration).Min() >= startDurProcWithStartAct &&
g.Select(x => x.FromDuration).Min() <= startDurProcWithEndAct)
.OrderBy(g => g.Min(a => a.FromDuration)).ToList()
.ForEach(g => orderedProcesses.Add(new OrderedProcess
{
order = orderedIndex++,
elements = g
}));
foreach (var proc in orderedProcesses)
{
float sumPreviousFbs = 0;
var criticalActivitiesInProc = proc.elements.Intersect(maxCriticalPath.ActivityDirections.Select(ad => ad.Activity));
var nonCriticalActivities = criticalActivitiesInProc.Any() ? proc.elements
.Where(act => act.FromDuration < criticalActivitiesInProc.Select(c => c.FromDuration).Min())
: proc.elements;
if (!criticalActivitiesInProc.Any()) continue;
var feedingBuffer = (float)Math.Sqrt(nonCriticalActivities
```

```
.Sum(a => Math.Pow(a.Duration - a.AggressiveDuration, 2)));
processFeedingBuffer.Add(new KeyValuePair<int, float>(proc.order, feedingBuffer));
if (processFeedingBuffer.Any(pfb => pfb.Key == proc.order - 1))
{
sumPreviousFbs = processFeedingBuffer.Where(pfb => pfb.Key < proc.order).Sum(r => r.Value);
SetPreviousFeedingBufferShiftingToElements(proc.elements.ToList(), sumPreviousFbs);
SetPreviousFeedingBufferShiftingToElements(maxCriticalPath.ActivityDirections.Select(ad => ad.Activity)
.Intersect(proc.elements).ToList(), sumPreviousFbs);
}
var link = GetLinkInCriticalPathForCurrentProcess(maxCriticalPath, proc);
if (link != null)
{
link.FeedingBuffer = new FeedingBuffer
{
StartingDuration = link.LinkDistance.StartingDuration,
PreviousFeedingBuffers = sumPreviousFbs,
Buffer = feedingBuffer,
StartingUnit = criticalActivitiesInProc.Max(a => link.Direction == ActivityDirection.Normal ?
a.StartingUnit + a.Units : a.StartingUnit)
};
link.LinkDistance.PreviousFeedingBuffers = sumPreviousFbs;
link.LinkDistance.FeedingBuffer = feedingBuffer;
}
var maxDuration = proc.elements.Max(a => a.ToDuration);
var lastProc = proc.elements.First(a => a.ToDuration == maxDuration);
feedingBuffers.Add(new FeedingBuffer
{
StartingDuration = lastProc.ToDuration,
PreviousFeedingBuffers = sumPreviousFbs,
Buffer = feedingBuffer,
StartingUnit = lastProc.ToUnit
});
}
maxCriticalPath.ProjectBuffer = new ProjectBuffer
{
StartingDuration = maxCriticalPath.ProjectBuffer.StartingDuration + processFeedingBuffer.Sum(r => r.Value),
StartingUnit = maxCriticalPath.ProjectBuffer.StartingUnit,
Buffer = maxCriticalPath.ProjectBuffer.Buffer
};
return feedingBuffers;
}
private static ActivityWithDirection GetLinkInCriticalPathForCurrentProcess(CriticalPath maxCriticalPath, OrderedProcess
proc)
{
return maxCriticalPath.ActivityDirections.Where(ad => ad.LinkDistance != null).Skip(proc.order)
.FirstOrDefault();
}
private static void SetPreviousFeedingBufferShiftingToElements(IList<Activity> elements, float sumPreviousFbs)
{
elements.ToList().ForEach(a => a.ShiftDueToPreviousFeedingBuffers = sumPreviousFbs);
}
public CriticalPath GetMaxProjectBuffer(List<List<ActivityWithDirection>> criticalPaths)
{
if (!criticalPaths.Any()) return null;
var criticalPath = new CriticalPath();
var maxProjBuf = 0.0;
criticalPaths.ForEach(cp =>
{
var projBuf = Math.Sqrt(cp.Where(a => a.LinkDistance == null)
.Sum(a => Math.Pow(a.Activity.Duration - a.Activity.AggressiveDuration, 2)));
if (projBuf > maxProjBuf)
{
```

```
maxProjBuf = projBuf;
criticalPath = new CriticalPath { ActivityDirections = cp.CloneLists() };
}
});
var maxDuration = criticalPaths.First().Where(a => a.LinkDistance == null).Max(a => a.Activity.ToDuration);
var maxUnit = criticalPaths.First().Where(a => a.LinkDistance == null && a.Activity.ToDuration ==
maxDuration).First().Activity.ToUnit;
criticalPath.ProjectBuffer = new ProjectBuffer
{
StartingDuration = maxDuration,
StartingUnit = maxUnit,
Buffer = maxProjBuf
};
return criticalPath;
}
public List<List<ActivityWithDirection>> CalculateCriticalPath(IEnumerable<Activity> activities,
Activity startingActivity, Activity endingActivity, ActivityDirection direction)
{
var results = new List<List<ActivityWithDirection>>();
var tempResults = new List<ActivityWithDirection>();
var result = "";
var visited = new Dictionary<int, bool>();
activities.ToList().ForEach(l => visited.Add(l.Id, false));
CalculateCriticalPath(activities, startingActivity, result, endingActivity, null, visited,
tempResults.CloneLists(), results, direction, ActivityDirection.Normal);
return results;
}
private void CalculateCriticalPath(IEnumerable<Activity> activities, Activity currentAct, string result,
Activity endingActivity, float?[] deltaLink, Dictionary<int, bool> visited, List<ActivityWithDirection> tempResults,
List<List<ActivityWithDirection>> results, ActivityDirection direction, ActivityDirection previousDirection)
{
if (visited[currentAct.Id]) return;
visited[currentAct.Id] = true;
if (deltaLink != null) tempResults.Add(new ActivityWithDirection
{
LinkDistance = new LinkDistance
{
StartingDuration = deltaLink[0],
StartingUnit = deltaLink[1]
},
Direction = previousDirection
});
tempResults.Add(new ActivityWithDirection { Activity = currentAct, Direction = direction });
if (currentAct.Id == endingActivity.Id)
{
results.Add(tempResults);
return;
}
if (direction == ActivityDirection.Normal)
{
foreach (var next in activities.Where(l => Math.Abs(currentAct.ToDuration - l.FromDuration) < 0.02))
{
var delta = currentAct.ToUnit - next.FromUnit;
if (delta >= 0 && !visited[next.Id])
{
float?[] dLink = null;
if (delta > 0) dLink = new float?[] { next.FromDuration, next.FromUnit };
CalculateCriticalPath(activities, next, result, endingActivity, dLink,
visited.ToDictionary(entry => entry.Key, entry => entry.Value),
tempResults.CloneLists(), results, ActivityDirection.Normal, ActivityDirection.Normal);
}
}
```

```
foreach (var next in activities.Where(l => Math.Abs(currentAct.ToDuration - l.ToDuration) < 0.02))
{
var delta = currentAct.ToUnit - next.ToUnit;
if (delta >= 0 && !visited[next.Id])
{
float?[] dLink = null;
if (delta > 0) dLink = new float?[] { next.ToDuration, next.ToUnit };
CalculateCriticalPath(activities, next, result, endingActivity, dLink,
visited.ToDictionary(entry => entry.Key, entry => entry.Value),
tempResults.CloneLists(), results, ActivityDirection.Reverse, ActivityDirection.Normal);
}
}
}
if (direction == ActivityDirection.Reverse)
{
foreach (var next in activities.Where(l => Math.Abs(currentAct.FromDuration - l.FromDuration) < 0.02))
{
var delta = currentAct.FromUnit - next.FromUnit;
if (delta >= 0 && !visited[next.Id])
{
float?[] dLink = null;
if (delta > 0) dLink = new float?[] { next.FromDuration, next.FromUnit };
CalculateCriticalPath(activities, next, result, endingActivity, dLink,
visited.ToDictionary(entry => entry.Key, entry => entry.Value),
tempResults.CloneLists(), results, ActivityDirection.Normal, ActivityDirection.Reverse);
}
}
foreach (var next in activities.Where(l => Math.Abs(currentAct.FromDuration - l.ToDuration) < 0.02))
{
var delta = currentAct.FromUnit - next.ToUnit;
if (delta >= 0 && !visited[next.Id])
{
float?[] dLink = null;
if (delta > 0) dLink = new float?[] { next.FromDuration, next.FromUnit };
CalculateCriticalPath(activities, next, result, endingActivity, dLink,
visited.ToDictionary(entry => entry.Key, entry => entry.Value),
tempResults.CloneLists(), results, ActivityDirection.Reverse, ActivityDirection.Reverse);
}
}
}
}
private void CalculateActivities(IEnumerable<Activity> activities)
{
var queue = new Queue<Activity>();
var visited = new Dictionary<int, bool>();
activities.ToList().ForEach(a =>
{
queue.Enqueue(a);
visited.Add(a.Id, false);
});
while (queue.Count != 0)
{
var item = queue.Dequeue();
if (item.ActivityDependencies.Any(d => !visited[d.Id]))
{
queue.Enqueue(item);
continue;
}
if (item.inputProdRate)
{
item.Duration = item.Units / item.SafeProductivityRate;
item.AggressiveDuration = item.Units / item.AggressiveProductivityRate;
```

```
}
else
{
item.SafeProductivityRate = item.Units / item.Duration;
item.AggressiveProductivityRate = item.Units / item.AggressiveDuration;
}
item.StartingDuration = 0;
item.StartingUnit = 0;
var itemWithMax = item.ActivityDependencies.Any() ? item.ActivityDependencies
.OrderByDescending(d => d.StartingDuration + d.DurationDefault).ToList()
: new List<Activity>();
if (itemWithMax.Any())
{
item.StartingDuration = itemWithMax.First().StartingDuration + itemWithMax.First().DurationDefault;
item.StartingUnit = itemWithMax.First().StartingUnit + itemWithMax.First().Units;
}
item.StartingDuration += item.StartToFinish;
item.StartingUnit += item.UnitDelta;
visited[item.Id] = true;
}
}
private Schedule BuildProcessorResult()
{
return new Schedule();
}
}
}
```

File: ModSchedulerCode/api/Services/ActivityService.cs/(Optimzations)

```
using SchedulePath.Models;
using SchedulePath.Repository;
using System.Collections.Generic;
using System.Linq;
using System;
namespace SchedulePath.Services
{
public class ActivityService : IActivityService
{
private ICepRepository _repository;
private IActivityProcessor _activityProcessor;
private ILinkProcessor _linkProcessor;
private IGraphProcessor _graphProcessor;
public ActivityService(ICepRepository repository,
IActivityProcessor processor,
ILinkProcessor linkProcessor,
IGraphProcessor graphProcessor)
{
_repository = repository;
_activityProcessor = processor;
_linkProcessor = linkProcessor;
_graphProcessor = graphProcessor;
}
public GraphConfig Process(bool withCriticalPath)
{
Schedule upperSchedule;
Schedule lowerSchedule;
var activities = _repository.GetActivities();
var link = _repository.GetLink();
var upwardActivities = activities.Where(a => a.Section == ActivitySection.UPWARD);
var downwardActivities = activities.Where(a => a.Section == ActivitySection.DOWNWARD);
```

```
upperSchedule = _activityProcessor.Calculate(upwardActivities);
lowerSchedule = _activityProcessor.Calculate(downwardActivities);
if (withCriticalPath)
{
var startingUpwardActivity = GetStartingActivity(upwardActivities);
var endingUpwardActivity = GetEndingActivity(upwardActivities);
var downwardStartingActivity = GetStartingActivity(downwardActivities);
var endingDownwardActivity = GetEndingActivity(downwardActivities);
if (link != null && link.DownwardAct != null && link.UpwardAct != null)
{
endingUpwardActivity = link.UpwardAct;
downwardStartingActivity = link.DownwardAct;
}
upperSchedule = _activityProcessor.Process(upwardActivities, startingUpwardActivity,
endingUpwardActivity);
lowerSchedule = _activityProcessor.Process(downwardActivities, downwardStartingActivity,
endingDownwardActivity);
if (link != null) _linkProcessor.Process(activities, link, ref upperSchedule, ref lowerSchedule);
}
return _graphProcessor.ProcessGraph(withCriticalPath, upperSchedule, lowerSchedule);
}
private static Activity GetEndingActivity(IEnumerable<Activity> upwardActivities)
{
return upwardActivities.First(a => a.ToDuration == upwardActivities.Max(x => x.ToDuration));
}
private static Activity GetStartingActivity(IEnumerable<Activity> upwardActivities)
{
return upwardActivities.FirstOrDefault(a => string.IsNullOrEmpty(a.Dependencies));
}
public IEnumerable<Activity> GetActivities()
{
var activities = _repository.GetActivities();
activities.ToList().ForEach(item =>
{
if (item.inputProdRate)
{
item.Duration = item.Units / item.SafeProductivityRate;
item.AggressiveDuration = item.Units / item.AggressiveProductivityRate;
}
else
{
item.SafeProductivityRate = item.Units / item.Duration;
item.AggressiveProductivityRate = item.Units / item.AggressiveDuration;
}
});
return activities;
}
public IEnumerable<Process> GetProcesses()
{
return _repository.GetProcesses();
}
public void AddActivity(ActivityRequest request)
{
_repository.AddActivity(new Activity
{
Name = request.Name,
ProcessId = request.ProcessId,
Units = request.Units,
SafeProductivityRate = request.SafeProductivityRate,
AggressiveProductivityRate = request.AggressiveProductivityRate,
DurationFunction = request.DurationFunction,
UnitDelta = request.UnitDelta,
```

```
StartToFinish = request.StartToFinish,
Dependencies = request.Dependencies,
Duration = request.Duration,
AggressiveDuration = request.AggressiveDuration,
inputProdRate = request.InputProdRate,
Section = request.Section
});
}
public void UpdateActivity(ActivityRequest request)
{
var activity = GetActivities().First(a => a.Id == request.Id);
activity.Name = request.Name;
activity.ProcessId = request.ProcessId;
activity.Units = request.Units;
activity.SafeProductivityRate = request.SafeProductivityRate;
activity.AggressiveProductivityRate = request.AggressiveProductivityRate;
activity.DurationFunction = request.DurationFunction;
activity.UnitDelta = request.UnitDelta;
activity.StartToFinish = request.StartToFinish;
activity.Dependencies = request.Dependencies;
activity.Duration = request.Duration;
activity.AggressiveDuration = request.AggressiveDuration;
activity.inputProdRate = request.InputProdRate;
activity.Section = request.Section;
_repository.UpdateActivity(activity);
}
public void DeleteActivity(int id)
{
if(_repository.GetActivities().Any(a => a.ActivityDependencies.Any(d => d.Id == id)))
{
throw new Exception("Cannot delete activity. It is a dependency for another.");
}
_repository.DeleteActivity(id);
}
}
}
```

File: ModSchedulerCode/api/Services/GraphProcessor.cs/(Feedback)

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Threading.Tasks;
using SchedulePath.Models;
namespace SchedulePath.Services
{
public class GraphProcessor : IGraphProcessor
{
public GraphConfig ProcessGraph(bool withCriticalPath, Schedule upperResult, Schedule lowerResult)
{
GraphConfig upwardGraph = null;
GraphConfig downwardGraph = null;
List<Series> allSeries = new List<Series>();
if (upperResult != null)
{
upwardGraph = BuildConfig().AddActivities(upperResult.Activities);
if (withCriticalPath)
{
upwardGraph.AddCriticalPath(upperResult.CriticalPath.ActivityDirections)
.AddProjectBuff(upperResult.CriticalPath.ProjectBuffer)
.AddFeedingBuffers(upperResult.FeedingBuffers);
```

```
}
allSeries = upwardGraph.series.ToList();
}
if (lowerResult != null)
{
downwardGraph = BuildConfig().AddActivities(lowerResult.Activities);
if (withCriticalPath)
{
downwardGraph.AddCriticalPath(lowerResult.CriticalPath.ActivityDirections)
.AddProjectBuff(lowerResult.CriticalPath.ProjectBuffer)
.AddFeedingBuffers(lowerResult.FeedingBuffers);
}
foreach (var serie in downwardGraph.series)
{
serie.data.ToList().ForEach(d => d[1] = d[1] * -1);
allSeries.Add(serie);
}
}
if(upwardGraph != null) upwardGraph.series = allSeries.ToArray();
return upwardGraph;
}
private GraphConfig BuildConfig()
{
return new GraphConfig
{
chart = new Chart
{
type = "line"
},
title = new Title
{
text = ""
},
xAxis = new XAxis
{
title = new Title
{
text = "Duration (days)"
}
},
yAxis = new YAxis
{
title = new Title
{
text = "Units"
}
},
plotOptions = new PlotOptions
{
line = new Line
{
dataLabels = new DataLabels
{
enabled = true
}
}
},
legend = new Legend
{
layout = "vertical",
align = "right",
verticalAlign = "middle",
```

```
borderWidth = 0
},
series = new List<Series>().ToArray()
};
}
}
}
```

File: ModSchedulerCode/api/Services/IActivitiyProcessor.cs/(latest changes)

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Threading.Tasks;
using SchedulePath.Models;
namespace SchedulePath.Services
{
    public interface IActivityProcessor
    {
        Schedule Calculate(IEnumerable<Activity> activities);
        Schedule Process(IEnumerable<Activity> activities,
            Activity startingPoint, Activity endingActivity);
        List<List<ActivityWithDirection>> CalculateCriticalPath(IEnumerable<Activity> activities,
            Activity startingPoint, Activity endingActivity, ActivityDirection direction);
        CriticalPath GetMaxProjectBuffer(List<List<ActivityWithDirection>> criticalPaths);
    }
}
```

File: ModSchedulerCode/api/Services/IActivityService.cs/(Project Setup)

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Threading.Tasks;
using SchedulePath.Models;
namespace SchedulePath.Services
{
    public interface IActivityService
    {
        IEnumerable<Activity> GetActivities();
        IEnumerable<Process> GetProcesses();
        GraphConfig Process(bool withCriticalPath);
        void AddActivity(ActivityRequest activity);
        void UpdateActivity(ActivityRequest request);
        void DeleteActivity(int id);
    }
}
```

File: ModSchedulerCode/api/Services/IGraphProcessor.cs/(Schedule Refactor)

```
using SchedulePath.Models;
namespace SchedulePath.Services
{
    public interface IGraphProcessor
```

```
    {
        GraphConfig ProcessGraph(bool withCriticalPath, Schedule upperResult, Schedule lowerResult);
    }
}
```

File: ModSchedulerCode/api/Services/ILinkProcessor.cs/(Synchronize upward and downward schedule)

```
using SchedulePath.Models;
using System;
using System.Collections.Generic;
using System.Linq;
using System.Threading.Tasks;
namespace SchedulePath.Services
{
    public interface ILinkProcessor
    {
        void Process(IEnumerable<Activity> activities, LinkWithActivity link,
            ref Schedule upwardProcessorResult, ref Schedule downwardProcessorResult);
    }
}
```

File: ModSchedulerCode/api/Services/ILinkService.cs/(Synchronize upward and downward schedule)

```
using SchedulePath.Models;
using System;
using System.Collections.Generic;

using System.Linq;
using System.Threading.Tasks;
namespace SchedulePath.Services
{
    public interface ILinkService
    {
        LinkWithActivity GetLink();
        void AddLink(Link request);
        void UpdateLink(Link request);
        void DeleteLink(int id);
    }
}
```

File: ModSchedulerCode/api/Services/ILoggingManager.cs/(Refactoring)

```
namespace SchedulePath.Services
{
    public interface ILoggingManager
    {
        void Log(string message);
    }
}
```

File: ModSchedulerCode/api/Services/IMailManager.cs/(Sending email on error)

```
namespace SchedulePath.Services
{
  public interface IMailManager
  {
    void SendEmailAsync(string email, string subject, string message);
  }
}
```

File: ModSchedulerCode/api/Services/LinkProcessor.cs/(Optimzations)

```
using System;
using System.Collections.Generic;
using System.Linq;
using SchedulePath.Models;
namespace SchedulePath.Services
{
public class LinkProcessor : ILinkProcessor
{
public IActivityProcessor _activityProcessor;
public LinkProcessor(IActivityProcessor activityProcessor)
{
_activityProcessor = activityProcessor;
}
public void Process(IEnumerable<Activity> activities, LinkWithActivity link,
ref Schedule upwardProcessorResult, ref Schedule downwardProcessorResult)
{
if (upwardProcessorResult == null || downwardProcessorResult == null) return;
if (upwardProcessorResult.CriticalPath == null || downwardProcessorResult.CriticalPath == null)
throw new Exception("Critical Path empty.");
if (!activities.Any() || link.UpwardAct == null || link.DownwardAct == null) return;
var delta = link.UpwardAct.ToDuration + link.UpwardAct.ShiftDueToPreviousFeedingBuffers +
link.TimePeriod - link.DownwardAct.FromDuration - link.DownwardAct.ShiftDueToPreviousFeedingBuffers;
downwardProcessorResult.ShiftSchedule(delta);
//Add controlling link
var lastActivityInUpward = upwardProcessorResult.CriticalPath.ActivityDirections.Last();
upwardProcessorResult.CriticalPath.ActivityDirections.Add(new ActivityWithDirection
{
FeedingBuffer = new FeedingBuffer
{
StartingDuration = link.UpwardAct.ToDuration,
Buffer = link.UpwardAct.ShiftDueToPreviousFeedingBuffers,
TimePeriod = link.TimePeriod,
StartingUnit = link.UpwardAct.ToUnit
},
LinkDistance = new LinkDistance {
StartingDuration = link.UpwardAct.ToDuration,
TimePeriod = link.TimePeriod,
FeedingBuffer = link.UpwardAct.ShiftDueToPreviousFeedingBuffers,
StartingUnit = link.DownwardAct.FromUnit
},
Flip = -1
});
var totalProjectBuffer = Math.Sqrt(upwardProcessorResult.CriticalPath.ActivityDirections.Where(a => a.LinkDistance == null)
.Sum(a => Math.Pow(a.Activity.AggressiveDuration - a.Activity.Duration, 2)) +
downwardProcessorResult.CriticalPath.ActivityDirections.Where(a => a.LinkDistance == null)
.Sum(a => Math.Pow(a.Activity.AggressiveDuration - a.Activity.Duration, 2)));
upwardProcessorResult.CriticalPath.ProjectBuffer.Buffer = 0;
downwardProcessorResult.CriticalPath.ProjectBuffer.Buffer = totalProjectBuffer;
}
}
}
```

```
}
```

File: ModSchedulerCode/api/Services/LinkService.cs/(Synchronize upward and downward schedule)

```
using System;
using System.Collections.Generic;
using SchedulePath.Repository;
using SchedulePath.Models;
namespace SchedulePath.Services
{
  public class LinkService : ILinkService
  {
    private ICepRepository _repository;
    public LinkService(ICepRepository repository)
    {
      _repository = repository;
    }
    public void AddLink(Link request)
    {
      _repository.AddLink(request);
    }
    public void DeleteLink(int id)
    {
      _repository.DeleteLink(id);
    }
    public LinkWithActivity GetLink()
    {
      return _repository.GetLink();
    }
    public void UpdateLink(Link request)
    {
      _repository.UpdateLink(request);
    }
  }
}
```

File: ModSchedulerCode/api/Services/LoggingManager.cs/(Refactoring)

```
using Microsoft.Extensions.Logging;
namespace SchedulePath.Services
{
  public class LoggingManager : ILoggingManager
  {
    private ILogger _logger;
    public LoggingManager(ILoggerFactory loggerFactory){
      loggerFactory.AddConsole();
      _logger = loggerFactory.CreateLogger("MyLogger");
    }
    public void Log(string message)
    {
      _logger.LogInformation(message);
    }
  }
```

```
}
```

File: ModSchedulerCode/api/Services/MailManager.cs/(Sending email on error)

```
using MailKit.Net.Smtp;
using MimeKit;
using MailKit.Security;
namespace SchedulePath.Services
{
public class MailManager : IMailManager
{
public void SendEmailAsync(string email, string subject, string message)
{
var emailMessage = new MimeMessage();
emailMessage.From.Add(new MailboxAddress("Schedule Criticality", "schedule.criticality@cep.com"));
emailMessage.To.Add(new MailboxAddress("", email));
emailMessage.Subject = subject;
emailMessage.Body = new TextPart("plain") { Text = message };
using (var client = new SmtpClient())
{
var credentials = new System.Net.NetworkCredential();
credentials.UserName = "jzh.softdev@gmail.com";
credentials.Password = "jzhsoftdev";
client.Connect("smtp.gmail.com", 587, SecureSocketOptions.StartTls);
client.Authenticate(System.Text.Encoding.ASCII, credentials);
client.Send(emailMessage);
client.Disconnect(true);
}
}
}
}
```