Enhancements to Methods for Planning and Scheduling Fabrication Projects Utilizing Multiskilled Labour Resources

by

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ABSTRACT

In prefabrication and off-site construction, various multiskilled work crews need to be assembled to work on different workstations to process custom-designed work units, each having specific requirements for material handling, assembly connections, welding, etc. However, the frequent labour transfers between different workspaces and the labour waiting time for forming crews at particular workstations result in non-value-adding efforts, which can cause operation interruptions and loss of efficiency. This phenomenon of dynamic formation of crews and labour movement between different workstations cannot be adequately addressed by the current approach to planning and scheduling of prefabrication construction projects due to the inherent limitations in the established planning and scheduling methods and tools. Accordingly, the labour-cost estimate derived from mainstream project scheduling software (such as Microsoft Project and Primavera P6) has largely overlooked such inefficiency stemming from dynamic labour resource transferring and crew formation between activities in the operations of prefabrication and off-site construction. Despite numerous efforts aimed at enhancing current methods in project planning, scheduling, and budgeting, there have been limited studies attempting to model the efficiency of multiskilled labour flows between different project activities. As a result, a lack of quantitative modeling was identified to understand the efficiency of labour flow at the activity level and its impact on project outcomes, particularly on project scheduling and budgeting.

This research aims to bridge the gap in knowledge and practice in planning, scheduling, and budgeting prefabrication projects by integrating current project scheduling practices with productivity measurements. The proposed research extends the theory and application of the Critical Path Method (CPM)-based project planning and scheduling. It introduces a practical

discrete-event-simulation-based framework to model the labour utilization efficiency in connection with multiskilling and dynamic crew formations in prefabrication and off-site construction, resulting in the generation of more accurate labour cost estimate and budget (S-curve). The framework provides a basis for further analysis of labour productivity and lean construction performances, enabling potential performance improvement and labour utilization optimization in the project planning stage.

In current practice of prefabrication and off-site construction featuring frequent labour transferring between different workstations in the finite dynamic shop space, precisely measuring the efficiency of labour transferring between different workstations is prohibitively expensive and practically unacceptable due to privacy infringement and ethics challenges. Hence, collecting actual job cost data to differentiate the labour time spent in crew formations and labour movement between different workstations from the productive labour time is deemed infeasible in practice. In this study, planning steel girder fabrication projects subject to resource availability and transfer constraints are modeled by a simulation methodology in order to logically represent project execution processes in sufficient details, while enabling quantitative analysis of crew formations and labour transfer times.

A new time-dependent utilization efficiency factor, called the *inter-activity resource utilization efficiency factor*, is defined to quantify the efficiency of crew formations and labour resource transfers between different workstations at each point of time during the project time span. The derived efficiency factor is then factored into the budgeted labour-hours S-curve to generate a more accurate labour cost estimate of a construction-oriented fabrication facility. The simulation results demonstrate that by properly allocating multiskilled labour resources and fine-tuning crew size, the efficiency of labour transfers between different workstations can be significantly improved, thereby giving rise to better time and cost performance for the entire project.

Further, the analytical formulation of the optimization problem is also attempted by applying Integer Programming, aimed at minimizing the labour flow and crew formations inefficiency. As demonstrated in the research, the resulting optimized solution is expected to significantly decrease Labour Flow Waste Index by utilizing Microsoft Excel Solver on small-size demonstration cases or applying established evolutionary optimization algorithms to scheduling simulation models for large-size realistic cases. The proposed methodology is verified and validated through collaboration with a steel fabricator in Edmonton, Alberta.

PREFACE

This thesis is an original work by Leila Zahedi. This thesis is organized in a paper-based format.

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AON	Activity On Node
BCWS	Budgeted Cost for Work Scheduled
BIM	Building Information Modeling
CNC	Computerized Numerical Control
CPI	Cost Performance Index
CPM	Critical Path Method
D	Duration
DES	Discrete Event Simulation
Eq	Equation
ES	Early Start
EVM	Earned Value Management
Hr	Hour
JM	Journeyman
L	Labour
LFWI	Labour Flow Waste Index

LH	Labour Hours
OHS	Occupational Health and Safety
PSO	Particle Swarm Optimization
PERT	Program Evaluation and Review Technique
RTS	Ready to Serve Time
PV	Planned Value
RU	Resource Utilization
SDESA	Simplified Discrete-Event Simulation Approach
S3	Simplified Scheduling Simulation
SW	Specialist Welder
WBS	Work Breakdown Structure

CHAPTER 1:

Introduction

This chapter presents an introduction to the research background, problem statements, research objectives, research methods, and overall thesis organization.

1.1 Research Background

In this section, a review of related literature is presented to provide background for the thesis research, laid on three main pillars: (I) prefabrication and off-site construction projects (II) productivity and labour utilization efficiency in construction, and (III) application of simulation in planning and scheduling of construction projects.

1.1.1 Prefabrication and Off-site Construction Projects

Considering the vast variety of construction projects, construction processes can be categorized into on-site and off-site construction (McGuinness and Bennett 2006). On-site construction is the traditional method of construction in which specialized trades are temporarily hired to make or install structural components with one-of-a-kind design on the construction site. In contrast, prefabrication and off-site construction involves producing different components in factories and assembling them on the construction site (Nasirian 2019).

The traditional on-site construction encountered major problems such as insufficient productivity, quality issues, adverse weather conditions (Arashpour et al. 2016), and time overruns (Arashpour et al. 2015). Furthermore, on-site construction has long dealt with challenges regarding shortage of skilled workforces (Ho 2016) and workforce wages increasing (Leu and Hwang 2002). To tackle the mentioned project pitfalls the majority of on-site production was transferred to factories known as prefabrication and off-site construction (Leu and Hwang 2001).

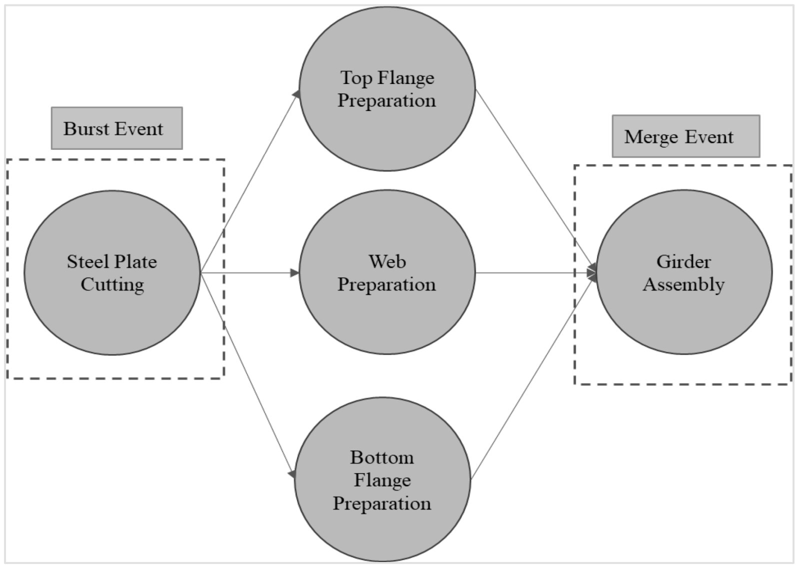
The shift from construction fields to prefabrication factories has brought many benefits including a more efficient on-site logistics (Arashpour et al. 2016), streamlined on-site operations (Alvanchi et al. 2012), improved quality (Ko and Wang 2010), and enhanced general performances of the whole project (Arashpour et al. 2018a).

Off-site construction is labour intensive due to the high quantity of handling and connection activities such as cutting, fitting, and welding. Accordingly, cost estimating of off-site construction projects entails estimating the labour-hours required to perform different activities as the main unit to measure the project direct cost. The costs of equipment, tools, and managerial staff are generally considered as indirect or overhead costs in practice, which are correlated with the direct cost in terms of labour-hours in performing cost estimate analysis. (Dozzi and AbouRizk 1993).

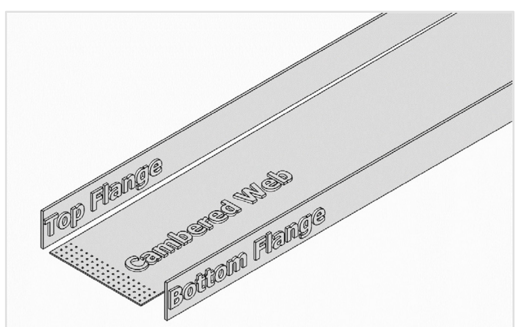
The conventional approach to labour employment and utilization in prefabrication and off-site construction management was to assign a single-skilled labour resource to a specialized task. Later, multiskilling of construction workers was introduced as one potential solution to deal with the negative effects of impaired productivity (Hopp and Oyen 2004) resulting from single-skilling. Multiskilling of a workforce is defined as training the single-skilled labour resource in one or more extra skills to improve their knowledge and competency so as to be able to work on multiple types of tasks (Nasirian et al. 2018). Multiskilling of the labour resources enables them to be allocated to different tasks during the production makespan (Nasirian et al. 2018). Moreover, multiskilling of a workforce provides advantages for the workers involved as well as the project. Multiskilling of workers enhances project productivity through improved flexibility in allocating labour resources in projects (Arashpour et al. 2015).

Off-site construction facilities bear resemblance to a typical industrial facility in manufacturing in certain aspects such as permanent employment of labour resources having a set of various skills (that is analogous to multiskilling) to operate materials handling or processing equipment, and to coordinate with robots in operating, setting up and maintaining automation systems. The production process still maintains the main characteristics of traditional construction operations such as custom-designed products, “merge and burst events” in processing logic, and being labour resource dominant. Consequently, planning and scheduling methods being utilized in traditional construction projects such as Activity-On-Node (AON) / Critical Path Method (CPM) scheduling are still widely used to plan, schedule and budget off-site construction. However, such current planning methods are criticized for their insufficient capabilities in labour utilization management which leads to impairing productivity and resource utilization efficiency and ultimately project cost and time overruns (Arashpour et al. 2018a). General features of different production environments are categorized as Table 1.1.

It is worth mentioning that *merge events* happen when two or more condition are needed to trigger the immediately preceding activity (Sharma 2006). In contrast, a *burst event* has more than one activity immediately following it (Sharma 2006). As an example, in a steel fabrication shop, the top flange, bottom flange, and the steel web should be ready to trigger the activity of girder assembly. Accordingly, the girder assembly activity would be called merge event. Moreover, the burst event of completing steel plate cutting can trigger three succeeding activities as shown in Figure 1.1.



(a)



(b)

Figure 1.1. (a) Merge and burst events in an AON example. (b) merge event example in steel fabrication in practice.

Table 1.1. General features of different production environments.

Features		Manufacturing	Traditional Construction (On Site)	Prefabrication and Off-site Construction (This Research)
Environment	Field		✓	
	Factory/Fabrication shop	✓		✓
Product Specification	Mass production	✓		
	Custom-designed production		✓	✓
Production Line Specification	Automated: utilization of automation and robots	✓		
	Semiautomated: utilization of automation and robots			✓
	Human dominant: limited utilization of automation and robots		✓	
Labour Resource Utilization	Multiskilled workers	✓		✓
	Single-skilled workers		✓	
	Labour intensive		✓	✓
	Permanent hiring	✓		✓
Planning and Scheduling Methods	Established project planning methods		✓	✓
	Production planning simulation	✓		

1.1.2 Productivity and Labour Utilization Efficiency

Productivity can be defined in various ways, depending on the measurement method and data availability used in the study. Hendrickson and Au (1989) defined productivity as "a measure of the overall effectiveness of an operating system in utilizing labour, equipment, and capital to convert labour efforts into useful output which is not a measure of the capabilities of labour alone." Economists define productivity as the ratio between total input of resources and a total output of product while project managers and construction professionals interpret productivity as a ratio between earned work hours and expended work hours to execute labour intensive projects (Hanna et al. 2005, Liu and Ballard 2008). Meanwhile, efficiency is the rate at which workers do what they are required to do at a given time and place; it is a measure of how well the labour hours are utilized (Yi et al. 2014). The terms "labour efficiency" and "labour productivity" are used interchangeably to a certain extent that labour productivity interprets the rate of physical progress where the added value has resulted from the input of human efforts only (Dozzi and Abourizk 1993); it is defined as the ratio between earned work hours and expended work hours to execute labour intensive projects (Hanna et al. 2005). Accordingly, in an attempt to evaluate the efficiency of labour intensive construction operations, this research interprets efficiency as a work time percentage by comparing labour productive work time with total expended work time.

A significant body of research has been conducted to improve labour efficiency and productivity. Thomas (2000) analyzed how labour productivity was affected by the disruption of workflow resulting from schedule acceleration and proposed matching of the labour resource to the amount of available work to perform, so as to maximize labour productivity. Gong et al. (2011) applied labour time utilization assessment methods, such as work sampling and five-minute rating. They found a statistically significant difference in crew utilization efficiency across different types of activities as well as in activities with various crew sizes (i.e., small, medium, and large). Other studies investigated the impact of change orders and reworks (Thomas and Napolitan 1995; Watkins et al. 2009; Hanna et al. 1999), workspace congestion (Thabet and Beliveau 1994) and shift work (Hanna et al. 2008) on productive labour time. Quantitative methods have been used in productivity-related research to analyze the relationships between a wide range of relevant factors and labour productivity rates. Researchers have presented various analytical models to forecast labour productivity in construction (Thomas and Sakarcan 1994; Smith 1999; Fayek and Oduba 2005; Lu et al. 2000; Nasirzadeh and Nojedehi 2013). These models took advantage of various modeling techniques, including operation simulation, artificial intelligence, expert systems, factor models, regression and artificial neural networks. Despite significant research in the literature concerning labour productivity, there have been few studies aimed at quantitatively modeling the efficiency of labour utilization with specific emphasis on dynamic crew formation and multiskilled labour movement between different workstations and labour flow efficiency at different activities.

In this research, the labour resources considered specifically refer to multiskilled workers (namely *crew members or journeymen* in a fabrication facility) who are utilized to perform various tasks from one project or from different projects. *Labour flow* refers to the workflow planning that entails the allocation of labour resources to various tasks (or work assignments) in connection with processing different jobs or activities from different projects (Thomas et al. 2002).

1.1.3 Simulation in Planning and Scheduling of Construction Projects

Simulation models have been developed in a certain resolution of details for different purposes and from different perspectives in order to facilitate making decisions by different function managers at various stages of project development. In the project management context, these models can provide valuable insights for decision-making and help project managers to identify potential bottlenecks, optimize schedule and resource allocation, and assess the impact of various scenarios on project outcomes. Additionally, simulation models can help to improve communication among project stakeholders, by providing a common platform for analyzing and visualizing project performance (Ioannou and Martinez 1996; Hajjar and AbouRizk 2002; Akhavian and Behzadan 2014). Carr (1979) developed MUD, a system for uncertainty determination that combines simulation and network scheduling to estimate activity duration, criticality index, and expected duration. Halpin and Dabbas (1982) integrated Project I, a Critical Path Method (CPM)-based software, with the simulation methodology to model repetitive activities. This hybrid approach provided improved duration estimates and was a useful planning tool for upper management. Later, Lu and AbouRizk (2000) presented a simulation model for construction project scheduling that incorporated discrete event modeling and a simplified critical activity identification method. The model showed improvement in analyzing the risk of project schedule overrun and determination of activity criticality and provided project management with a tool for alternative scenario assessment and risk analysis. The implementation of simulation platforms in construction operations had realized limited impact in terms of being adopted outside academic and research environments (AbouRizk and Hajjar 1998). The main issue with using simulation in construction is the absence of user-friendly simulation tools that are easy to use and understand while keeping modeling methods simple. Communicating the results effectively with construction practitioners and convincing them of the benefits of using simulation is essential. A flexible visual modeling environment with a high level of similarity between the model and the actual construction system is important for successful implementation in real-world scenarios. Subsequently, such an environment helps ensure that the model accurately reflects the reality of the construction process and can be easily translated into the actual system (Hajjar and AbouRizk 1999). This research is mainly concerned with effectively utilizing discrete-event simulations to extend Activity-On-Node (AON)-based Critical Path Method (CPM) scheduling from the perspective of the project planner and scheduler in efforts to produce an efficient resource job allocation plan and a realistic labour cost budget. The generated simulation model is expected to allow for visualizing and analyzing the utilization of individual resources on specific activities over a particular time period of project duration.

The present research used the *Simplified Scheduling Simulation (S3)* methodology and computer platform, which had been developed to implement Critical Path Method scheduling algorithms based on the *Simplified Discrete-Event Simulation Approach (SDESA)* (Lu et al. 2008). It serves as a resource schedule simulation platform to materialize the newly proposed project planning methodology for prefabrication and off-site construction. In addition, SDESA (S3) simulation tool offers a user-friendly and visually appealing approach to scheduling construction projects and labour allocation planning. Its reduced coding demands save time in model generation and updating. It automatically adjusts activity execution sequences so as to simultaneously accommodate both technology and resource constraints on the project (Lu et al. 2008). Leveraging Critical Path Method algorithms coupled with the visual representation of analytical results, makes it easier to communicate the project planning simulation with construction practitioners, promoting better collaboration and informed decision-making. Hence, SDESA (S3) enables the analysis of productive and semi-productive labour work hours by examining the implications of different crew sizes and labour allocation schemes subject to inter-activity technological constraints. This approach further leads to defining an optimization problem to extend the simulation analysis.

1.2 Problem Statement

The increasingly competitive construction industry has provided the impetus for businesses to specialize in certain types of construction. To meet such demands, specialized project planning and scheduling tools are desired. The Critical Path Method (CPM) is the most widely used tool, but its limitations are recognized, spawning research into improving and incorporating alternative tools such as linear scheduling, simulation techniques, and genetic algorithms for different construction activities. According to Fischer and Aalami (1996), project scheduling tools often require manual translation of design information into activities, lacking dynamic links between design information and project time and cost estimates. They presented computer-interpretable models for presenting construction methods as a solution to translate design descriptions into time and cost, enabling the automatic generation of realistic construction schedules. Furthermore, Ahuja and Thiruvengadam (2004) discussed that CPM scheduling falls short of a main limitation in providing effective resource management in scheduling and planning construction projects. It only shows technical precedence and resource availability constraints but does not consider resource allocation or utilization efficiency.

Researchers have been exploring new approaches to resource management in construction projects, with the goal of improving efficiency, minimizing disruptions, and optimizing resource utilization. Kang et al. (2001) attempted to improve the efficiency of construction resources utilization in multiple, repetitive construction processes by developing a construction scheduling model using a conceptual approach. This study proposed equations for estimating the optimal number of horizontal repetitive work areas for a crew group, to reduce the unutilized workforce. Mattila and Abraham (1998) devised an integer linear programming approach to tackle highway construction projects utilizing the resource leveling technique. This method incorporates the concepts of rate and activity float to optimize resource utilization within a specific activity. When multiple activities share common resources, the utilization of rate float can further enhance resource allocation and utilization. However, this method has a computational burden that grows with the size of the problem and takes a single objective focus on resource leveling, instead of maximizing other aspects of project performance. In order to address the limitations of traditional scheduling methods that focused on a single objective, Ipsilandis (2006) proposed a multi-objective linear programming model for scheduling linear repetitive projects. This model took into account cost elements related to project duration, resource idle time, and delivery time of project units. Alternative schedules could be generated based on the relative importance of different cost elements. However, the solutions obtained, and the method were limited to applications featuring repetitive activities, which are one-off activities requiring separate handling.

In addition, the use of stochastic S-curves (SS-curves) in project control instead of the commonly used deterministic S-curve technique in professional practice was proposed by Barraza et al. (2000) to address some of the limitations of the traditional Critical Path Method (CPM) scheduling by incorporating the variability in cost and duration of activities into the cost estimating process. SS-curves are obtained through simulation and probability distributions are provided for expected cost and duration based on the historical data of similar activities. However, the accuracy of the SS-curve method depended on the availability of sufficient historical data, making it more applicable to repetitive tasks or tasks that had been performed before.

In spite of the numerous efforts aimed at enhancing established methods in project planning, scheduling, and budgeting, little research has been conducted to model the efficiency of labour flow between different project activities and assess its impact on project time and cost performance. A lack of quantitative modeling to comprehend the efficiency of labour flow at the activity level in project scheduling and budgeting calls for further research and attention improve project planning, scheduling, and budgeting methods. In the specific context of prefabrication and off-site construction the current practice relies on transforming design specifications to associated labour-hours requirements in planning and budgeting of a certain project (Hendrickson 1989). The estimated labour-hours budget represents the cumulative work content of project activities. However, the labour-hour budget S-curve derived from commercial scheduling software, such as Microsoft Project and Primavera P6, often overlooks inefficiencies in labour utilization. To compensate for such inefficiencies in resource utilizations, seasoned schedulers often rely on a subjective "rule of thumb" approach and apply a budget scale factor based on their experience, rather than a scientifically rigorous method. This disadvantage highlights the need for a more comprehensive and systematic approach to construction scheduling and budgeting that considers the efficiency of labour resources and accommodates its impact on labour cost estimate.

More specifically, in off-site construction such as steel girder fabrication featuring labour intensive works, frequent labour transfers between different workstations in a confined shop-floor space results in inefficiency in labour utilization (defined as labour flow waste in this research). It would be prohibitively expensive and practically unacceptable to precisely measure the labour flow waste in the current practice. As such, practice resorts to the rule of thumb to estimate a working percentage against the non-working time of workers in estimating and budgeting labour costs — e.g., 45 min hour or 75%.

To summarize, a systematic and quantitative approach is necessary in order to determine the efficiency of labour utilization and support various aspects of project management such as labour cost estimating, labour job scheduling, labour utilization tracking, and labour productivity improvement in prefabrication and off-site construction. This approach should consider the detailed allocation of labour resources to various activities over time, subject to practical constraints in the real world.

1.3 Research Questions and Objectives

The primary goal of this research is to extend the theory and application of Activity-On-Node (AON)/Critical Path Method (CPM)-based project planning and scheduling by bridging the gaps in knowledge and practice with regard to planning, scheduling, and budgeting prefabrication projects. This research devises an effective yet practical project planning methodology for quantifying labour utilization efficiency as a time-dependent factor in support of generating a more reliable labour-hour cost budget on prefabrication and off-site construction projects while investigating the possible solutions to improve labour resource utilization and improve the labour productivity performance of the project with the main question being "How *to enhance the labour utilization efficiency by improving the allocation of multiskilled labour resources to various activities from multiple projects in prefabrication and off-site construction*

The above research question is divided into five different sub-questions:

1. How to accommodate the concept and application of multiskilling a crew in the context of planning and scheduling prefabrication and off-site construction projects?

2. How labour resource utilization can be enhanced in prefabricated construction by incorporating multiskilled labour resources?

3. How integration of labour productivity concepts with project scheduling and budgeting in prefabrication and off-site construction facilities can improve the accuracy of project labour-hours budgeting?

4. How to allocate a multiskilled crew to different tasks over the project time horizon in order to improve project cost and time performance?

5. How can the proposed project planning methodology integrate discrete-event simulation and optimization methodology to reduce the labour utilization inefficiency, commonly recognized as one major type of waste (motion and waiting) in the context of lean construction?

By addressing the research questions, the following objectives are expected to be achieved:

- To present a multiskilling framework which facilitates understanding of the multiskilling concept, its application in production environment with consideration of the distinct characteristics of prefabrication and off-site construction projects and quantitatively assessing the impact of multiskilling on labour utilization efficiency and labour cost budgeting.

- To propose a methodology based on discrete-event-simulation modeling for integrating the productivity concepts with project scheduling and budgeting of prefabrication project. The proposed methodology quantitatively evaluates the effect of multiskilled labour resource utilization efficiency associated with labour flow and crew formations between activities on deriving the budgeted cost for work scheduled (BCWS) S-curve in labour-hours in order to improve the accuracy of project labour-hours budget.

- To present a resource-constrained project scheduling strategy to facilitate the appropriate allocation of multiskilled labour resources over different operations so as to achieve an improved cost and time performance in planning the prefabrication and off-site projects.

- To formulate an optimization model to optimize the simulation-based allocation of labour resources and activity sequencing in an attempt to minimize the frequent labour transferring between different activities, which ultimately results in improvement to project cost and time performances.

Outcomes and findings derived from this research would potentially exert a direct influence upon current practice for estimators, schedulers and project managers to improve the accuracy of labour-hour budgeting, enhance the cost performance of the project and increase labour resource utilization.

1.4 Research Framework

1.4.1 Research Methods

In this research, simulation is used as an effective research method to analytically define the research problem and quantify the labour utilization efficiency —associated with labour transfer time between workstations— by analyzing labour resources' allocation to different activities over project time in the context of prefabrication construction. The framework is designed to simulate the scheduling of resources subject to logical constraints and resource availability, thus allowing for the observation of labour utilization throughout the project duration. Through the use of the simulation model, data on labour utilization is collected and analyzed. The research then utilizes this information to run various "what-if" scenarios, exploring the potential for labour utilization improvement. Defining and executing "what-if" scenarios through simulation not only provides insight into the problem, but also points to opportunities for further fine-tuning the simulation results. Further, optimization is built on top of the simulation model to serve as an extension to the simulation by identifying the best labour allocation and flow plan for the project.

This research is not intended to define a new optimization model from scratch, which can be over complicated, thus unacceptable to practice. Instead, the research has attempted to strike a balance between practicality and academic modeling. As a result, the developed optimization model, which is streamlined due to well-structured system definitions resulting from the simulation model, complements the analysis of the "what-if" scenarios. In other words, the optimization model provides decision support to the simulation modelers by fine-tuning the what-if scenario analysis to arrive at labour allocation and activity execution sequence plans. As such, the optimization model serves as the final step in the simulation process –namely fine-tuning the analysis of the "what-if" scenarios.

The proposed approach for enhancing project delivery performances in prefabrication construction takes a two-pronged perspective that encompasses both productivity and lean construction concepts. The methodology utilizes separate optimization formulations to examine the realization of the framework from both viewpoints, thereby providing a comprehensive solution for improving prefabrication project performances. Moreover, simulation modeling facilitates communication of optimization modeling by elaborating the optimized solution and presenting it in detailed labour allocation plans and project schedules. This would enable schedulers and planners in practice to gain insights from the optimized solution and generate more realistic cost budgets for prefabrication and off-site construction projects.

1.4.2 Verification and Validation

Verification and validation are essential steps in ensuring the reliability and accuracy of simulation models. The proposed framework emphasizes the importance of these steps as key components of the overall methodology. Verification is the process of testing the theoretical assumptions of the model and ensuring that its representation of the problem is correct for its intended use (Sargent 2009). Verifying the logic of the model involves comparing the results of the simulation model generated by the proposed framework (utilizing SDESA as a resource simulation schedule tool) with those generated by other established scheduling tools (such as Primavera P6). This step is crucial to ensure the model's underlying assumptions are reasonable and the model sufficiently reflects the problem it aims to represent and solve.

Once the model has passed the verification stage, validation is then used to ensure that the model consistently achieves a high level of accuracy in its application domain (Sargent 2009). Due to practical constraints, the framework proposed in this research along with simulation models adopts independent validation as defined by Sargent (2010). Face validation is a further step that involves presenting unseen cases to domain experts and comparing the labour cost estimates generated by the model with those generated by the experts. This step helps to determine the accuracy of the model's predictions and validate its performance in real-world scenarios. As stated by Sargent (2010), the goal of this process is to ensure the reliability and accuracy of the model's predictions and to ensure that the model fits for its intended purpose of use.

The proposed simulation-based scheduling framework to enhance the resource planning practice of multiple concurrent prefabrication projects is summarized and shown in Figure 1.2.

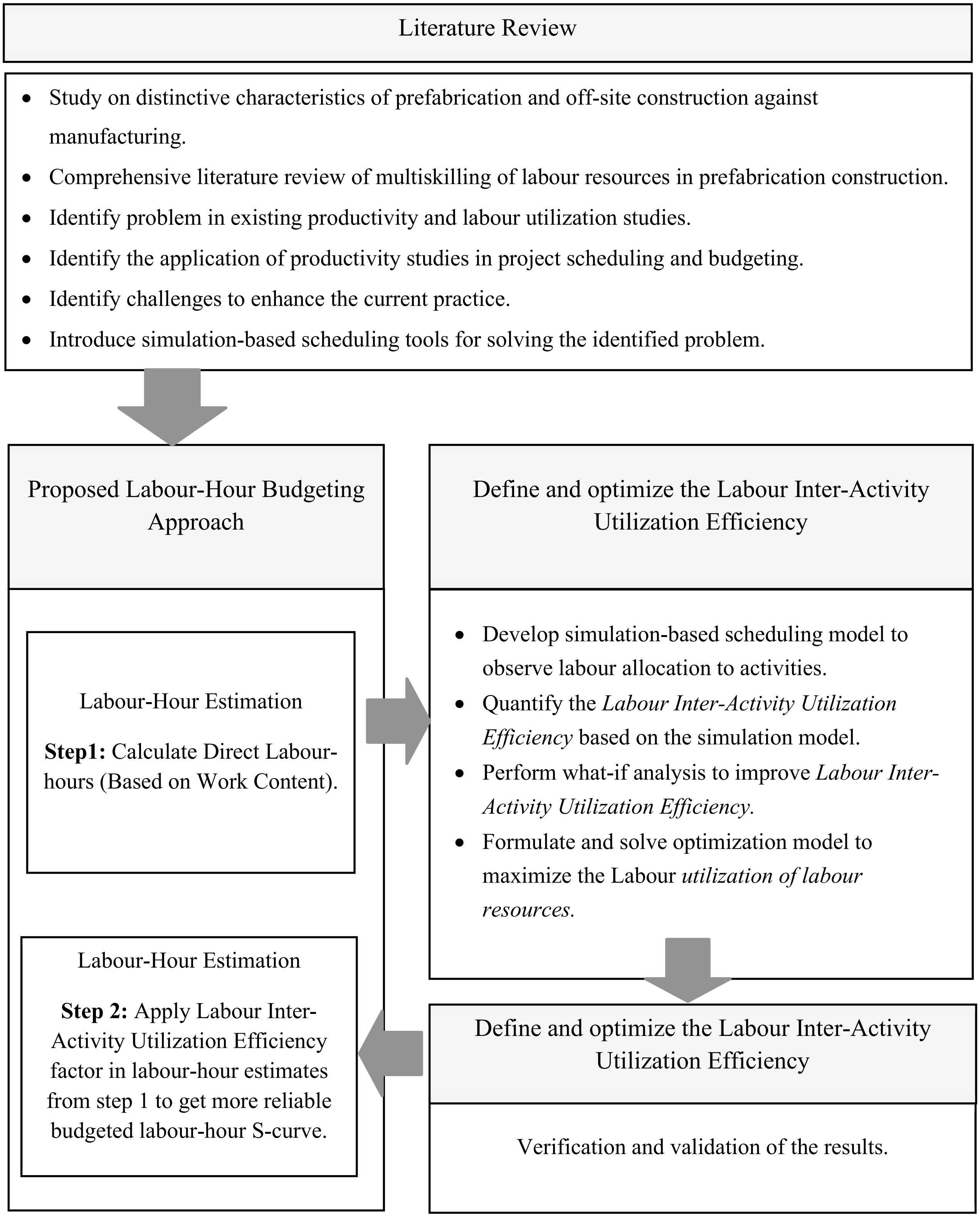


Figure 1.2. Proposed Research Framework

1.5 Thesis Organization

This thesis consists of six chapters:

Chapter 1 provides a brief overview of the research background from practical and academic perspectives. A short literature review is provided to justify the need for this research. The problem statement and research objective are later discussed in this chapter, followed by proposed methodologies and research questions to be addressed in realization of research objectives, research methods and research verification and validation.

Chapter 2 addresses research questions 1 and 2by conducting a study to generalize and contrast distinctive characteristics of prefabrication and off-site construction, traditional construction and manufacturing. Additionally, the chapter includes a comprehensive literature review on multiskilling of labour resources in production environment of prefabrication and off-site construction projects. This chapter identifies multiskilling of a workforce as a resource utilization strategy to improve resource utilization rate in prefabrication and off-site construction.

Research questions 3 and 4 are investigated in chapter 3. In this chapter a project budgeting framework is proposed by integrating productivity and project scheduling concepts. Introducing a new term on labour productivity called *resource inter-activity utilization efficiency*, these chapters try to quantitatively model efficiency of crew formations and labour transfers between different workstations by using a resource scheduling simulation subject to both technology and resource availability constraints in order to obtain a more accurate project labour-hour cost estimate. Various crew sizes and different labour allocation plans are examined through devising different what-if scenarios, aimed to enhance the time and cost performance of the whole project for a real steel fabrication case study. Chapter 3 proposes a conceptual mathematical formulation of an optimization model to minimize the unnecessary semi-productive labour-hours, leading to improved inter-activity labour utilization efficiency.

Chapter 4 describes a practical case study and presents a simulation model details and its application in scheduling and budgeting of prefabricating bridge steel girders in a real prefabrication shop in Edmonton, Canada.

Chapter 5 is a representation of research framework from the perspective of *lean construction*. This chapter is dedicated to addressing research question 5 by taking advantage of Integer Programming for optimization of the resource scheduling simulation model. In this chapter, following a lean construction approach, an optimization model for a simple demonstration case is formulated and solved by Excel Solver in order to optimize the simulation-based allocation of multiskilled labour resources and activity sequencing in an attempt to minimize the frequent unnecessary labour transferring between different activities – commonly recognized as one major type of waste (motion and waiting) by the definition of lean construction, which ultimately results in improvement to project cost and time performances.

Chapter 6 recapitulates the research, restates the academic and practical contributions, and points out the limitations of this research and the further research.

The thesis organization is shown in Fig. 1.3.

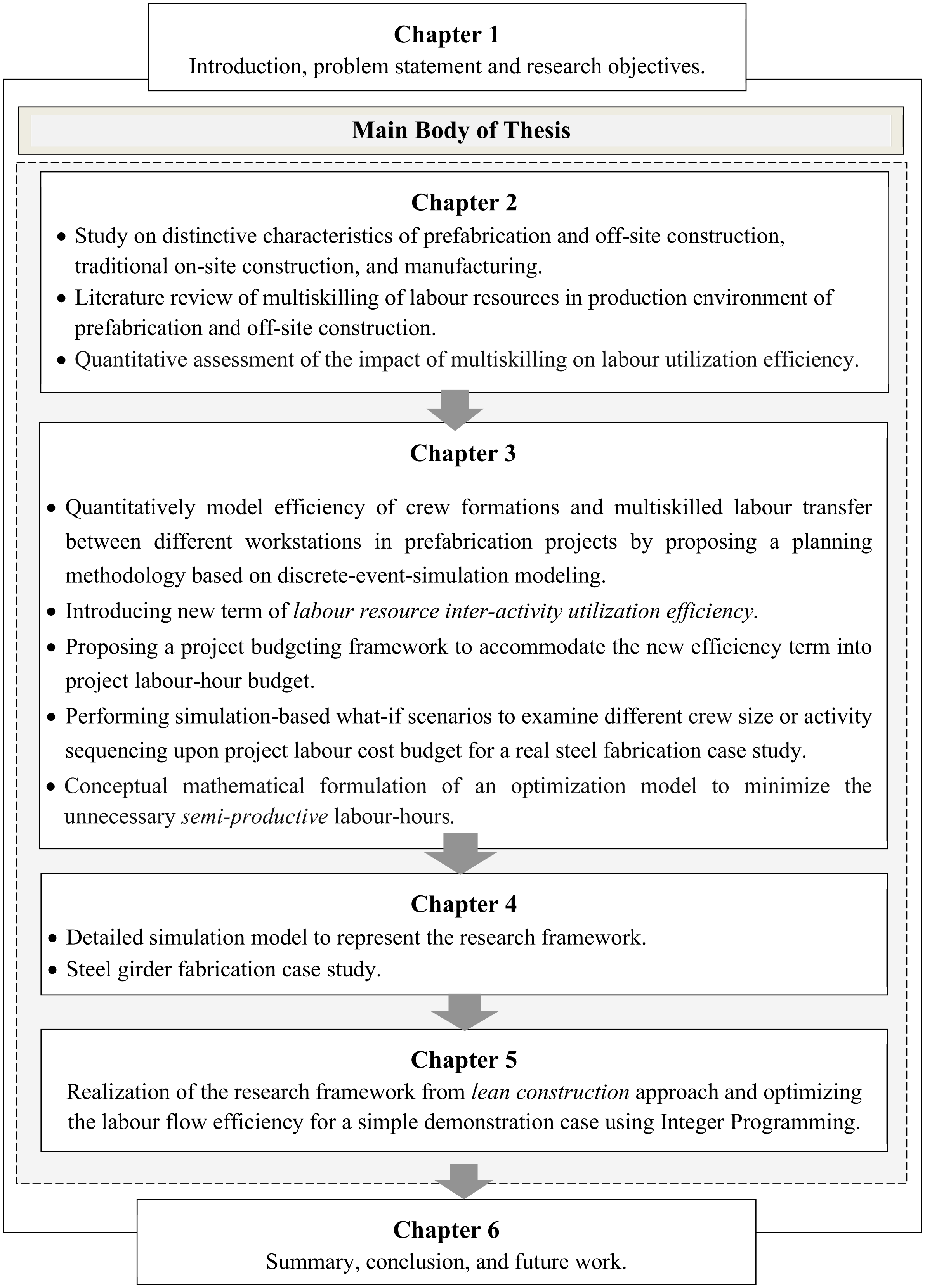


Figure 1.3. Thesis organization.

CHAPTER 2

Planning and Scheduling Fabrication Projects Utilizing Multiskilled Labour Resources

This chapter presents critical review of literature and practice, case study based on resource loaded scheduling simulation analysis, as well as general findings and insights that will advance engineering management practices in prefabrication and modular construction. The nature of the advancement lies in an improved labour resource employment strategy with demonstration of its advances for a mixed crew of multiskilled and single-skilled trades in a practical prefabrication setting. Findings and recommendations resulting from the research would be of significance to both the construction industry and the research community. In the practice of prefabrication and off-site construction, structural components are fabricated in a controlled factory setting. Common practice in construction is to use specialized single-skilled labour resources to work on specific locations on site or in a shop (e.g., workstations in fabrication). To harness the full potential of the automation technology that finds its way into the mainstream of prefabrication (such as CNC machinery linked with parametric digital design models), employment of multiskilling labour resources in an off-site fabrication facility for construction has become a widely adopted practice. The efficiency benefits from cross training of labour resources to make them able to work on different workstations potentially outweighs the associated costs. A streamlined crew of labour resources provides the set of skills required to work on different workstations. Yet, the relatively low volume of custom designed products coupled with the relatively high variability of production processes present practical challenges for labour employment planning, project scheduling and labour cost budgeting.

This research investigates the impact of multiskilled labour resources employment in prefabrication of structural components in terms of enhancing labour resource utilization rates and consequently the improved cost performance of the project. By contrasting single-skilled and multiskilled labour resource strategies based on resource scheduling simulation, a substantial improvement with the multiskilling strategy is expected to be notable. Multiskilling could also provide the potential opportunity of adjusting labour assignments and resequencing activities for labour productivity improvement, leading to optimized and lean production systems in prefabrication and off-site construction. A comparative approach is taken to contrast the two extreme ends in the labour employment spectrum at the conceptual level in an illustration case. It is noteworthy that the reality can be a middle ground between the two extremes: a mix of single-skilled and multiskilled labourers is employed, with some multiskilled labourers possessing skills to work on certain activities instead of all the activities, as demonstrated in the case study of steel girder prefabrication in Alberta, Canada.

In the case study, the multiskilled labourers are the journeymen who are capable of cutting, fitting, roll welding, and operating materials handling equipment and semi-automated workstations. In addition, single-skilled labourers such as specialist welders are also employed to conduct a particular type of work in fabrication (such as position welds). Resource loaded scheduling simulation analysis will be performed to analyze the labour utilization rate along with project time and cost performances, by varying the ratio of multiskilled vs. single-skilled labourers employed in the fabrication process.

2.1 Introduction

Prefabrication provides a solution to various uncertainties that can arise during construction, such as labour shortages. Despite the benefits of prefabrication, there are still challenges with the efficient utilization of labour resources. To address this issue, the implementation of multiskilling has been introduced to improve resource utilization. This approach involves forming a team of multiskilled workers who can be allocated to various tasks to efficiently produce custom-designed products. This chapter provides insights that can advance engineering management practices in prefabrication and off-site construction. The study highlights the practical challenges in labour employment planning, project scheduling, and labour cost budgeting. It emphasizes the need for a middle ground between single-skilled and multiskilled labour strategies. The findings and recommendations of this research are significant for both the construction industry and the research community.

2.2 Background

2.2.1 Status Quo of Prefabrication

Compared with the conventional stick-built practice, prefabrication mitigates some uncertain factors that arise from the external project environment (e.g., the influence of the weather event, the availability of proper equipment, and competent trades) (Blismas et al. 2006). In general, a crew of specialist trades performs interdependent tasks to fabricate a large number of made-to-order products based on bespoke specifications in an off-site facility. The growing implementation of prefabrication and off-site construction in practice shifts the focus of job shop scheduling in manufacturing to a construction-oriented context. In off-site construction, "made-to-order" components are produced in an industrial fabrication facility and transported to construction sites for field installation.

Over the past decades, the construction industry has evolved from utilization of simple tools to highly developed machinery and stays on the trajectory toward more AI-enabled automation features into the future (Cheav et al. 2020). Robotics and automation technology would lend numerous competitive edges in the long term with regards to improving construction productivity and efficiency and materializing cost savings (Slaughter 1999; Goodrum and Haas 2002; CII 2001; Song et al. 2008). Moreover, computer-aided automation technologies would improve accuracy and safety in construction by mitigating human factors such as absenteeism, mistakes, and injuries (Vähä et al. 2013; Cheav et al. 2020). There is a general consensus that automated construction processes would reduce the cost of construction by decreasing the number of labour-hours required to complete a task (Slaughter 1998). Accordingly, the combined application of prefabrication and automation technologies holds the potential to spur growth and technological advances in the construction industry (Barkokebas et al. 2021; Cheav et al. 2020).

Nonetheless, the relatively low volume of custom designed products coupled with the high variability of production processes still makes prefabrication facility practically infeasible to realize the full automation of fabrication processes. (Montalto et al. 2020; Goh et al. 2020). Despite advances in automation and robotics, labour resources still play a crucial role in prefabrication of construction components in the current and near future practice. In a typical fabrication shop, jobs from different clients and projects are performed simultaneously. Labour resources with specialized skills (e.g., journeymen) are employed to fabricate made-to-order products for different projects. Subject to concurrent execution of multiple projects and finite limits of labour and space available, resource interactions pose distinct challenges to the existing methods and tools for project scheduling and budgeting (Azimi et al. 2010; Liu and Lu 2018). Moreover, due to the limited availability of resources, planners often cope with the problem of scheduling a particular resource that is needed for two or more activities at the same time (Hiyassat 2001; El-Rayes 2001).

2.2.2 Labour Resource Management

Efficient management of labour resources utilization is an essential task in planning prefabrication projects (Anagnostopoulos and Koulinas 2010). In general, the planned resource requirement profile exhibits peaks and ebbs that point to unavoidable variations in project demand for particular resources (such as skilled trades) over time (Tran et al. 2016). Fluctuations in labour employment as a result of dynamic hiring and firing labour resources would cause efficiency losses and create financial difficulties on projects (Lafayette 1999; Tang et al. 2014). Moreover, any part-time or on-call employment contract could have saved labour costs for the contractor in the short run (Künn-Nelen et al. 2013); while the lack of employment stability and related work benefits would create higher social cost over the long run. For instance, flexible contracted workers had become extremely vulnerable in the event of natural disasters such as Covid-19 pandemic (Canada Labour Code Version 2020, enacted by Department of Justice Canada 1984).

While researchers propose various resource leveling techniques to reduce fluctuations in the resource requirement profile, different labour training and employment strategies have emerged for efficient utilization of existing workers. In particular, multiskilling is one of these labour utilization strategies where workers possess a range of skills and competencies allowing them to be allocated in more than one work process, where and when they are needed (Haas et al. 2001; Hopp and Oyen 2004; Burleson et al. 1998). Productivity improvement resulting from the greater flexibility in labour allocation and optimizing resource utilization has been widely recognized as the positive effect of multiskilling on construction projects (Hopp and Oyen 2004; Florez 2017; Lill 2009; McGuinness and Bennett 2006; Pollitt 2010). In particular, prefabrication in construction could significantly benefit from multiskilling in terms of improving workers' employment duration (Burleson et al. 1998), safety (Teizer et al. 2013), and job satisfaction (Carley et al. 2003).

In reality, employing multiskilled labour resources in a prefabrication facility for construction has become part of the current practice. The fabrication facility consists of various types of equipment and semi-automated machinery at workstations along with overhead gantry cranes for material handling. To keep a single-skilled labour resource utilized at a specific workstation, each workstation needs to be continuously operational, which would entail a large buffer holding incoming and outgoing in-process products (Barkokebas et al. 2020). However, due to the space constraints, it would be more practical to hire, train, and deploy a crew of multiskilled journeymen, who transfer between workstations to engage in activities at different workstations, as multiple girders are being processed in the shop. This would result in streamlined crew size, higher utilization rate and better productivity performances.

A majority of previous related undertakings concentrated on multiskilling for on-site construction (Burleson et al. 1998; Hegazy et al. 2000; Haas et al. 2001; Hopp and Oyen 2004; Gomar et al. 2002; Florez 2017; Lill 2009; Pollitt 2010; Hegazy and Kassab 2003), with little effort made to investigate the impact of multiskilling in off-site construction (Nasirian et al. 2019). This research takes the managerial perspective in planning multiskilled workforce at a prefabrication facility and applies a comparative approach to analyzing the utilization of single-skilled versus multiskilled labour resources based on computer-based simulation of resource use scheduling. In collaboration with industry partners, this research investigates the well-established practice of fabricating standardized production units (steel girders) in bridge construction. The remainder of the chapter elaborates on fabrication features in production units and finite resources available to prefabrication processes in a fabrication facility, illustrated with the critical activities of preparing the “shop splice” and the “field splice” in fabrication of bridge girders. In collaboration with the industry partner, a project case –for fabrication of twenty-one girders- is presented to demonstrate the planning of multiskilled labour resource use and identify the cost-effective crew size as well as the project duration. Conclusions are drawn at the end for the current research, and immediate future directions are addressed.

2.2.3 Labour Employment in Construction

The construction industry experienced major challenges in terms of shortage of skilled workforce (Ho 2016), increased labour wages (Leu and Hwang 2001), impaired productivity (Hopp and Oyen 2004), and inability to meet completion date demand (Hegazy et al. 2000). Prefabrication and off-site construction is championed as the potential solution to address such issues by streamlining on-site operations (Alvanchi et al. 2012), enhancing general performance of the system (Arashpour et al. 2018a) and maximizing construction crew productivity through automation (Leu and Hwang 2001).

Automation in construction generally refers to the method of performing a sequence of assigned tasks with programmable devices (Scott and Marshall 2009). In prefabrication of construction products (such as pipe spool or steel girder fabrication shop) made-to-order products from different clients are fabricated by performing a series of tasks at different workstations. To a certain degree, workstations and material handling equipment can be programmed to automatically perform laborious and tedious work, resulting in improved productivity and efficiency (Slaughter 1998;

Goodrum and Haas 2002; CII 2001). Nonetheless, the low volume of custom designed products coupled with the high variability of production processes would make the prefabrication facility practically infeasible to realize the full automation of fabrication processes (Montalto et al. 2020, Goh et al. 2020). At present, labour resources still play an indispensable role in facilitating automation technology application in prefabrication. For example, Computer Numerical Control (CNC) machines entail a human operator who is responsible for setting up the work for bespoke products and taking proper actions in case of problems (Lotti et al. 2019); a welding robot conducts the welding, but the process is still controlled and supervised by humans (Shen et al. 2020).

The conventional approach to allocate single-skilled trades to specialized tasks potentially give rise to production bottlenecks and result in productivity loss, time delays and cost overruns in prefabrication (Arashpour et al. 2018b; Barkokebas et al. 2020; Nasirian 2019). To deal with such difficulties, different operational approaches were implemented, and various labour management practices were evaluated (Iravani et al. 2007). A growing number of companies made a shift to a multiskilled workforce with the capability to perform multiple tasks (Hopp and Van Oyen 2004). Multiskilled labour resources possess multiple skill sets, and thus have the flexibility to be dynamically allocated to different workstations (Nasirian et al. 2019). Multiskilling has been reported to provide considerable benefits in terms of improving workforce employment duration (Haas et al. 2001), worker's job satisfaction (Carley et al. 2003) and productivity (Arashpour et al. 2015). It also eliminates or at least reduces the effect of absenteeism (Nasirian 2019) and alleviates skilled labour shortages (Pollitt 2010). On the other hand, the main drawbacks in connection with multiskilling from the perspectives of both employees and employers include decreased efficiency as a result of learning and forgetting effects (Wang et al. 2009; Yang 2007), licensing limitations

(Lobo and Wilkinson 2012), training cost limitations (BCA 2016; Azizi and Liang 2013), psychological effects (Campbell 2011), and restrictions in union regulations (Nasirian 2019).

The idea of construction resource planning with consideration of workforce skill sets was formally introduced in Burleson et al. (1998). Iravani et al. (2007) defined scheduling of a multiskilled workforce as "sequencing the members of the available workforce and assigning them to different tasks based on skill sets possessed by the workers in order to optimize the system performance." The managerial perspective of employing a multiskilled workforce encompasses configurations, costs, and benefits. A multiskilling configuration addresses which labour resources need to be trained in what skill sets and levels. There is a wide range of multiskilling configurations in the literature, contrasting single-skilled versus multiskilled workforce employment. Implementation of different configurations of multiskilled workforce is intended to realize specific benefits at certain costs. The complex tradeoff relationships between multiskilling benefits and related costs demanded a comprehensive analysis in order to prevent costs dominating benefits (Mi and Scacchi 1996). Such analysis is based on the proper understanding of the level of multiskilling and a sufficient modeling of resource scheduling problems (Bühner and Kleinschmidt 1988).

This research aims to justify the strategy of shifting from single-skilling to multiskilling of labour resources by analyzing the benefits of using multiskilled labour resources in a semi-automated prefabrication facility. A comparative approach is taken to contrast the two extreme ends in the labour employment spectrum at the conceptual level. In a practical application context, multiskilling is found to provide the opportunity for labour resource utilization optimization in project planning and scheduling at a bridge girder fabrication shop. In spite of the challenges in connection with multiskilling in the real world, it is maintained that construction industry would potentially benefit from multiskilling by cross training a streamlined crew of labour resources, who acquire the set of skills as required to facilitate the operation of semi-automated workstations in a fabrication shop in the real-world setting of prefabrication and off-site construction.

2.2.4 Contrasting Production Environments: Manufacturing vs. Off-site Construction

Manufacturing facilities (such as a modern automobile factory) mass-produce products that feature identical design or insignificant variations in design, which makes such facilities suitable to realize automation and utilize robots for the majority of production processes, resulting in streamlined production flows and substantial productivity improvement (Ohno 2019). Accordingly, fewer labour resources but with different skills (analogous to multiskilling) are hired on a permanent basis to collaborate with robots in setting-up, operating, and maintaining automation systems at various workstations in a manufacturing setting.

On the other hand, in the traditional construction job sites, specialized trades are temporarily hired to make or install custom-designed work units (structural components of one-of-a-kind design) in construction (Reichstein et al. 2005; Xue et al. 2017). Using automation in such a construction environment is limited to the utilization of remote-controlled demolition robots, utilization of material handling cranes, as the cluttered and congested construction sites present a challenging environment that is practically infeasible for robots to operate in (Saidi et al. 2016). Still, the majority of work units are installed by labour resources from different trades, each possessing the specialized skill to perform the work procedure and deliver the one-of-a-kind product.

In order to improve productivity, quality, safety and reliability, over the past few decades, prefabrication and off-site construction has gained momentum in practice and provide safer weather-proof work environments and more permanent employment opportunities for labour resources (Moghadam 2014; Alvanchi et al. 2012; Hegazy et al. 2000). Off-site construction facilities bear resemblance to a typical industrial facility in manufacturing in certain aspects, while still maintaining some characteristics of traditional construction operations. With the transition of the construction field to a factory, automation technologies (such as Computerized Numerical Control (CNC) machines, robotics, and semi-automated workstations) have found their way into the construction industry (Lotti et al. 2019) to prefabricate "made-to-order" components in a prefabrication facility. Nonetheless, the production processes in an off-site construction facility are characteristic of high variability and low volume in terms of custom-designed work units. This sets the construction industry apart from manufacturing and makes it practically infeasible to realize full automation (Montalto et al. 2020; Goh et al. 2020). In practice, labour resources still play the predominant role in prefabrication and off-site construction at present and in the near future. General features of different production environments are highlighted as Figure in 2.1.

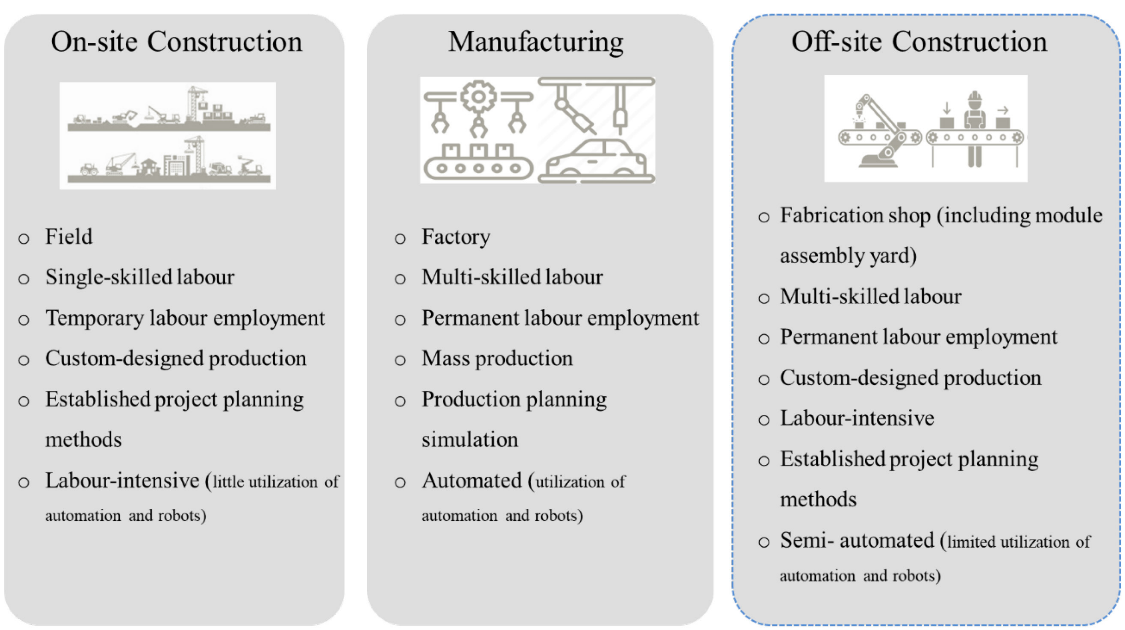


Figure 2.1. General features of different production environments.

2.3 Methodology

The objective is to enhance the planning, scheduling and budgeting of prefabrication projects using multiskilled labour resources through the application of a discrete event simulation framework. The process is as follows:

Step 1: Establish the Work Breakdown Structure (WBS), define activities to perform the project scope of work and technological relationship between activities through developing the Activity-On-Node (AON) network.

Step 2: Determine the duration of each activity (hours) required for a specified number of labourers, either by (A) employing single-skilled labourers or (B) multiskilled labourers.

It should be noted that given the same number of labourers, activities completed by single-skilled labourers will take less time than those completed by multiskilled labourers due to their higher level of skill and productivity.

Step 3: Determine the duration and number of labourers required for all other activities, using multiskilled labourers.

Step 4: Devise and run different what-if simulation scenarios on top of the simulation model for project performance improvement through adjusting crew size and the ratio of single-skilled vs. multiskilled labour resource utilization, striving for the optimal project schedule and crew makeup.

2.4 Implementation and Results

2.4.1 Contrasting Single-skilled vs. Multiskilled Labour Employment: Demonstration Case

An Activity-On-Node (AON) case is adapted from a Critical Path Method (CPM) example in Hegazy (1999) as presented in Figure 2.2, which contains burst and merge events that closely mimic the process patterns in prefabrication engineering. Activity duration and the required labour resources to perform each activity are given in Table 2.1. Using the common project planning methods such as Critical Path Method, and current computer tools such as Primavera P6, Figure 2.3 shows the duration of 32 hours with the total amount of 270 labour hours to finish the project. It is noteworthy that Primavera P6 calculates required labour hours based on the work content (labour hours) in connection with all the activities. However, labour hours due to transferring and forming crews at different activities are not accounted for but actually can be significant, as further demonstrated.

In order to evaluate the impact of single-skilling and multiskilling of resources on labour hour budgeting, the allocation of each labour resource to activities, and labour hours spending on crew forming and transferring between different activities need to be observed and analyzed. Nonetheless, in current scheduling practice of utilizing established scheduling tools such as Primavera P6, this is infeasible due to inherent limitations in the basic scheduling methods. To overcome such limitations, a resource schedule simulation approach is developed, which would make it possible to observe and analyze labour resources utilization in a more sophisticated fashion. Given thirteen labourers available, Figure 2.4 shows how to elaborate labour-resource allocation, interaction and schedule on specific activities in line with the activity bar chart schedule on a project (Table 2.1 and Figure 2.3). Moreover, it is noteworthy that given an activity bar chart schedule with specific activity sequencing as Figure 2.4(a), the allocation of specific number of resources to activities can be materialized in many different alternatives, as demonstrated in Figures 2.4(b) and 2.4(c). Note the activity bar chart given in Figure 2.4(a) is identical to the schedule generated by Primavera P6 in Figure 2.3; the detailed resource allocations to the same project schedule differ markedly in Figures 2.4(b) and 2.4(c) given the same crew size of thirteen. In the current demonstration case, this many-to-one relationship is handled by computer simulation, instead of manual processing.

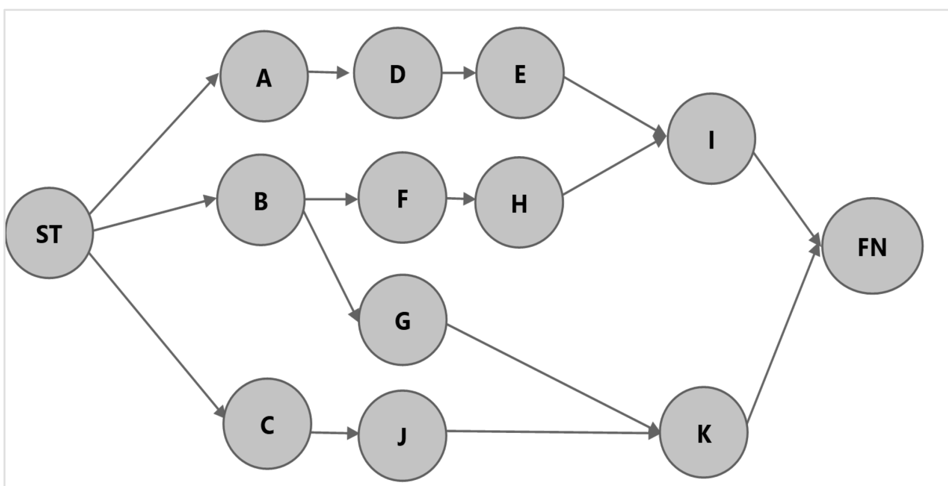


Figure 2.2. AON network of the simple demonstration case.

Table 2.1. Duration, resource requirement and predecessors of each activity.

Activity ID	Predecessors	Duration (hr.)	No of Required Resource*	Work Content	Accumulative Labour Hours
A	-	4	3	12	12
B	-	6	6	36	48
C	-	2	4	8	56
D	A	8	3	24	80
E	D	4	4	16	96
F	B	10	2	20	116
G	B	16	4	64	180
H	F	8	2	16	196
I	E, H	6	4	24	220
J	C	6	5	30	250
K	G, J	10	2	20	270

*With skill exclusive to current activity

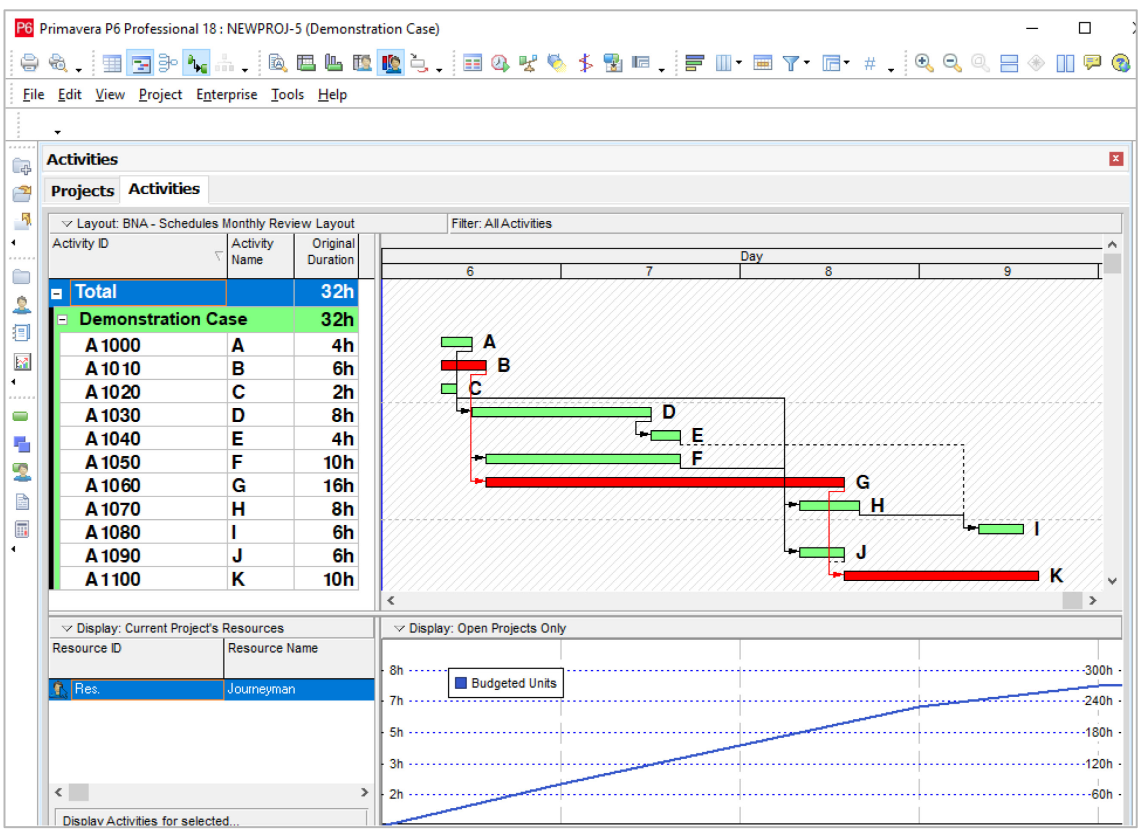
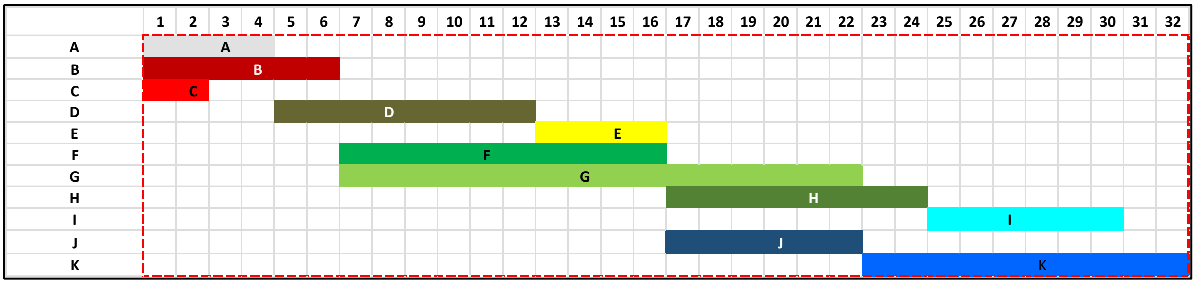
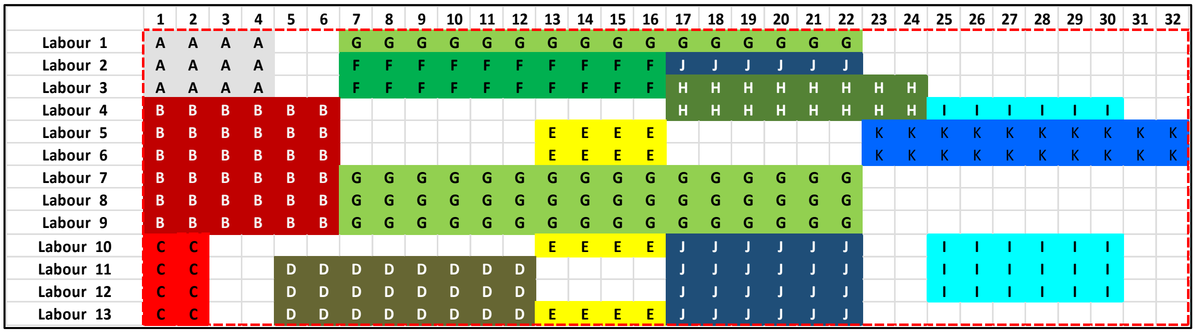


Figure 2.3. Primavera P6 solution for scheduling of the simple demonstration case.

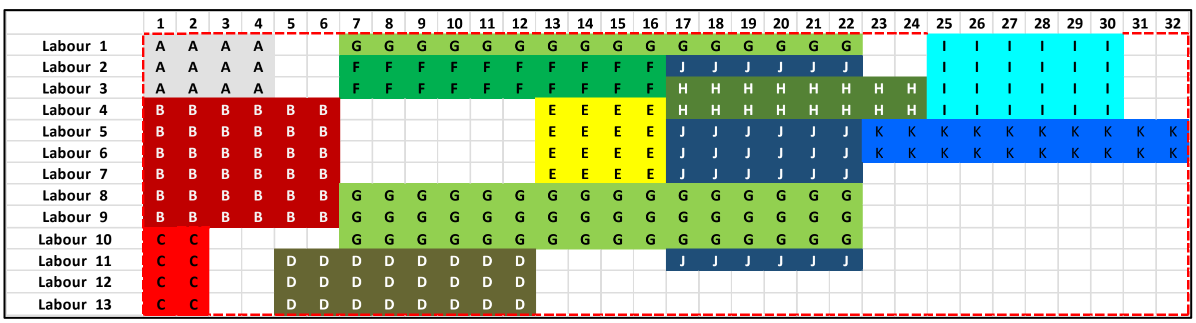
It can be further observed that, when allocating limited labour resources to activities in the same Activity-On-Node (AON) project network model, the employment of single-skilled resource or multiskilled resource exerts a significant impact on labour-activity interaction and labour allocation schedules. To elucidate on this impact, Figure 2.5 shows the two different labour allocation strategies for the same demonstration case (Table 2.1). It is worth mentioning that in the demonstration case, the two extremes on the spectrum of employment of single-skilled and multiskilled labour resources are contrasted. In single-skilling, each activity requires its specific single-skilled labour resources which cannot be utilized on other activities. It is noteworthy that the reality can be a middle ground between the two extremes: a mix of single-skilled and multiskilled labourers is employed, with some multiskilled labourers possessing skills to work on certain activities instead of all the activities.



(a)



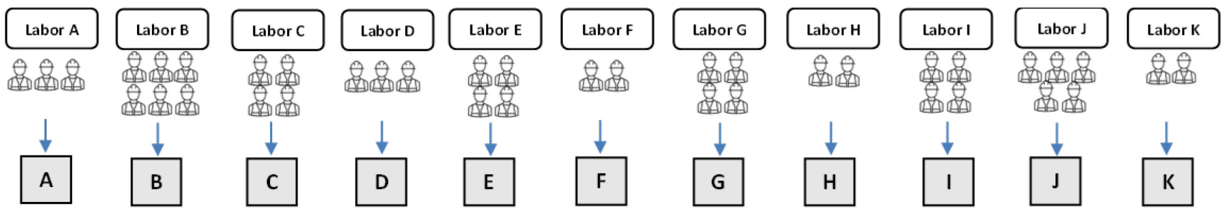
(b)



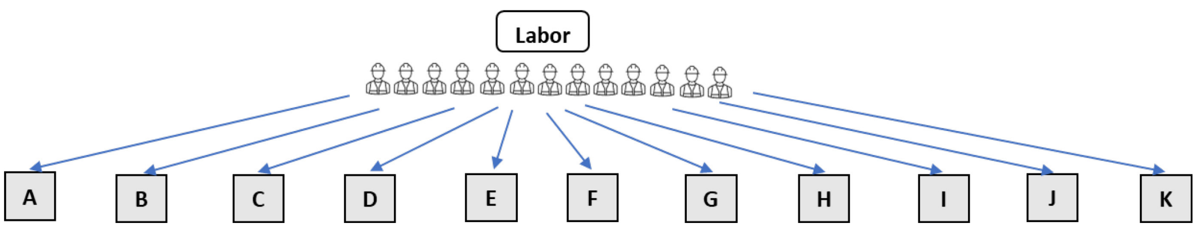
(c)

Figure 2.4. (a) Conventional bar chart (Gantt Chart) (b) expanded resource use schedule bar chart (based on resource scheduling simulation) (c) an example of alternative labour-resource allocation for the same project schedule.

As shown in Figure 2.5(a), three single-skilled labour resources with skill type A are required. Accordingly, it is assumed that each activity from B to K requires its unique skill, resulting in requirement of eleven different types of skill (A to K) to complete the whole scope of work. Note, single-skilled labour resources cannot be shared or transferred between different activities. In contrast, Figure 2.5(b) demonstrates employment of multiskilled labour resources which results in deploying a crew of labour resources each possessing all the types of skills (from A to K.) This makes each labourer qualified to be assigned to any activities as long as they are available.



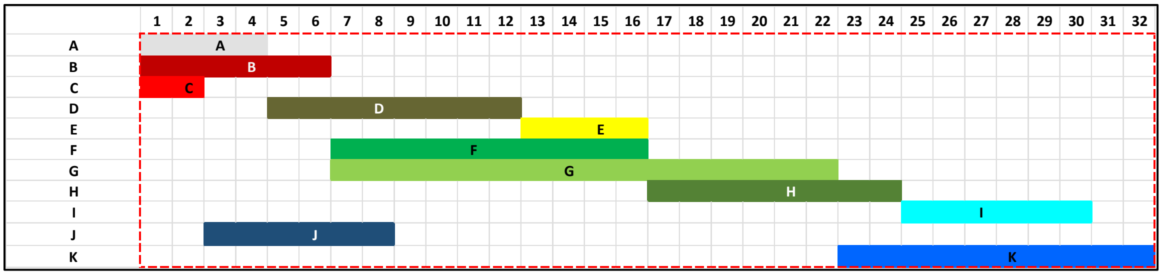
(a)



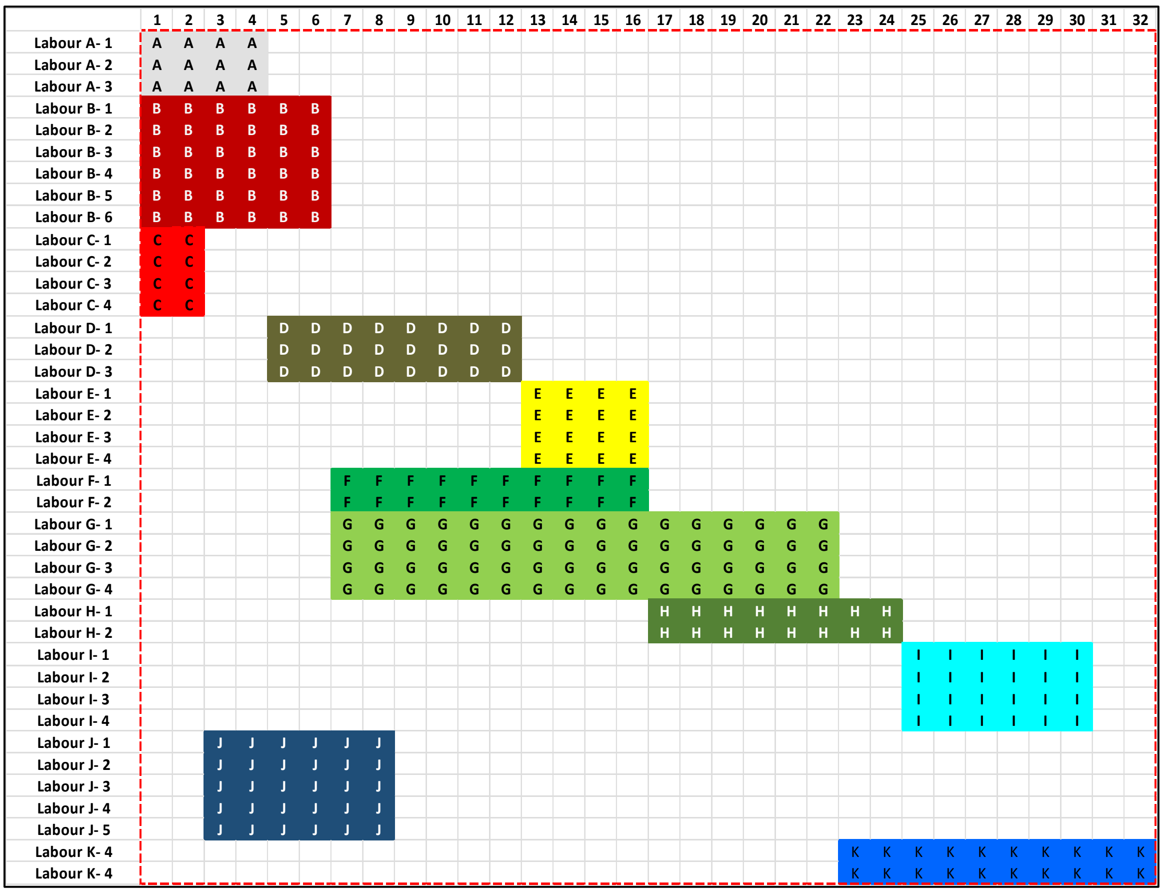
(b)

Figure 2.5. Different strategy in labour allocation: (a) single-skilled labour allocation (b) multiskilled labour allocation.

Project activities (given in Table 2.1) are scheduled based on specified labour requirements. Figure 2.6 shows single-skilled labour allocation with thirty-nine single-skilled labourers hired; in contrast, Figure 2.7 shows multiskilled labour allocation which involves the employment of thirteen multiskilled labourers.

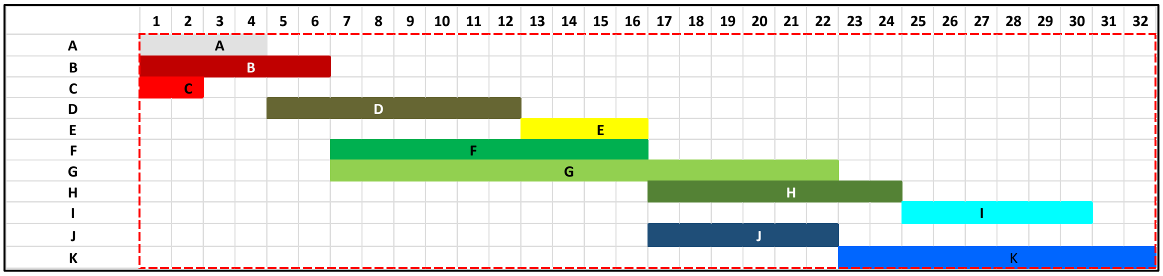


(a)

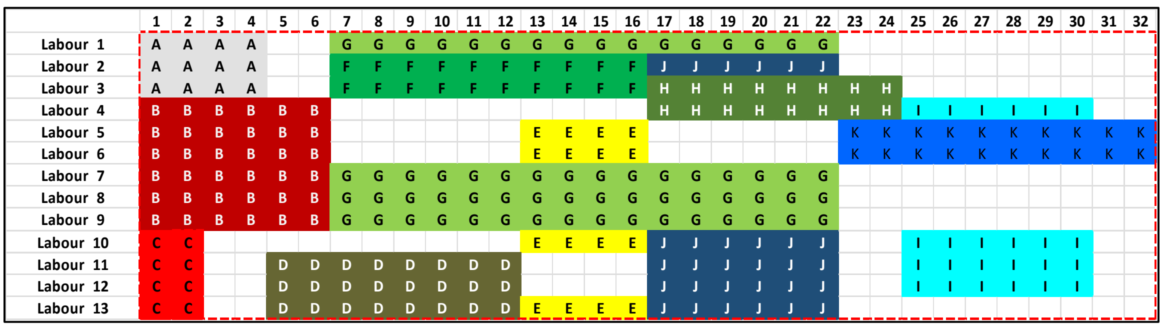


(b)

Figure 2.6. Single-skilled labour strategy: (a) project scheduling. (b) activity labour allocation.



(a)



(b)

Figure 2.7. Multiskilled labour strategy: (a) project scheduling. (b) activity labour allocation.

In Figure 2.6(b) and 2.7(b) the total allocation of labour resources in the project is denoted with the total area delimited with a slashed red line. The colored areas marked with Activity ID symbolize direct utilization of particular resources allocated to the project activities. Essentially, Figure 2.6(b) is a detailed resource work schedule subject to technological constraints and resource availability constraints with single-skilled resource availability; Figure 2.7(b) is for the case of multiskilled labour resources.

Out of the thirty-nine total labour allocation during the thirty-two hours of the project duration, 1248 labour-hours (32H×39Labourers) are incurred to complete the whole scope of work (perform activity A to K). Employing *thirteen* multiskilled labourers for the same project duration of thirty-two hours results in 416 labour-hours, or 66% decrease in labour-hour requirement.

To facilitate a quantitative analysis of resource utilization associated with different labour skill strategies, aimed at improving resource utilization, Eq. 2.1 is to formulate a general definition of resource utilization.

$$\mathrm{RU}\ \% = \frac{\left(\sum_{i=1}^{i=n} \mathrm{D}_i \times \mathrm{L}_i\right)}{\mathrm{D}_{project} \times \mathrm{L}_{availabile}} \times 100 \qquad (2.1)$$

Note, D_i is the duration of activity (i), (n) is the number of activities of the project, L_i is the required number of labour resources to perform activity (i), $\mathrm{L}_{availabile}$ is the availability of the labour resources throughout the project and $\mathrm{D}_{project}$ is the total duration of the project as the project is scheduled. Table 2.2 shows the resource utilization results of the given case study.

Table 2.2. Contrasting two different labour utilization strategies.

Strategy	No. Labour	Work Content (LH)	Total LH	RU %
All Single-Skilled Labour	39	270	1248	22 %
All Multiskilled Labour	13	270	416	64 %

Therefore, it can be deduced that the greater flexibility in allocating labour resources to different tasks results in a higher labour utilization rate. As given on Table 2.2, this improvement is from 22% labour resource utilization rate in the single-skilling case to 64% in the multiskilling case as in the given example. Hence, the extra cost resulting from multiskilling training can be potentially compensated by the direct cost saving from implementing multiskilling in practice.

It is important to note that this example represents the two opposite ends of the spectrum in terms of utilization of labour resources, either all single-skilled or all multiskilled. However, in the real work environment, organizations usually adopt a combination of both types of labour resources. Single-skilled workers are utilized for tasks that require specialist skill, while multiskilled workers are utilized for tasks that demand versatility in forming a range of skills.

Additionally, the labourer's capability of performing multiple skills could also lead to the possibility of optimizing the workforce and enhancing labour utilization by adjusting the crew size. Different scenarios under availability of different number of journeymen constraints (note journeymen are the multiskilled labour resources capable of performing all the activities on the fabrication project) were simulated for the given demonstration case (Table 2.1) and results are shown in Figure 2.8 for the five scenarios employing seven to eleven journeymen respectively.

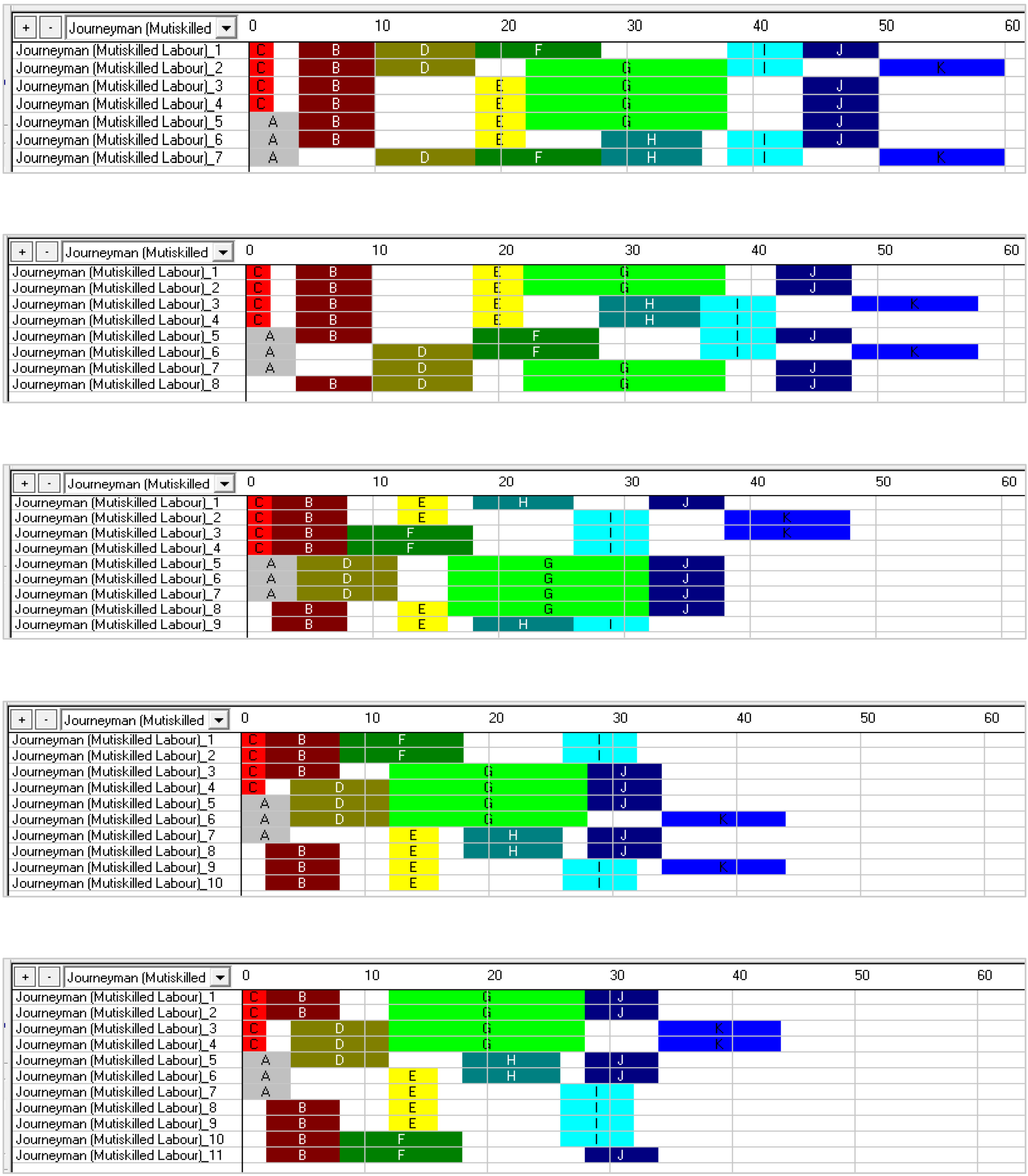


Figure 2.8. Simulated resource use schedules under different crew sizes.

The results from the five crew size scenarios in terms of different project duration and resource utilization rate (RU) are summarized in table 2.3.

Table 2.3. Results from simulated resource use schedule under different crew size.

Scenario	No. Multiskilled Labour	Duration (Hr)	Total LH	RU %
1	7	60	370	73 %
2	8	58	398	68 %
3	9	48	350	77 %
4	10	44	354	76 %
5	11	44	386	70 %

It is apparent that there is an opportunity to optimize the crew size so as to maximize the resource utilization rate. In the current case, the maximum RU is 77% obtainable in Scenario 3 where *nine* labourers are employed for executing the project in forty-eight hours. However, it is notable that adding one labourer (i.e., hiring ten multiskilled crew in Scenario 4) would result in shortening the duration by four hours at the slight trade-off of lowering RU from 77% to 76%. Therefore, Scenario No. 4 is recommended as the solution in this case.

Next, a practical application of the abovementioned multiskilling in a semi-automated fabrication facility is presented in the setting of multiskilling labour resources in fabrication of steel girder.

2.4.2 Practical Case: Bridge Girder Fabrication Shop

2.4.2.1 Bridge Girder

Girders are the structural members of a bridge that spans a physical barrier such as a body of water, a valley, or a road. Steel plate girders are prefabricated I-beams that are stacked in parallel girder lines to provide longitudinal support for the bridge deck above. Figure 2.9 shows photos of typical steel girder bridges and bridge girders. A typical steel girder's length varies approximately from

10 to 48 meters, and its weight ranges from 10 to 40 tons. The dimensions of the girder are confined by (1) the shop's physical constraints (space available to maneuver the girders, overhead crane load carrying capacity), (2) local government rules (highway limit regulation; hauler's load capacity) for carrying the oversize load, and (3) site installation constraints (site space limits and erection crane load capacity limits). For example, the government of Alberta maintains a published guidebook to assist commercial truck and bus businesses in operating safely and complying with transportation safety laws, in which the type of load and maximum limit that can be safely transported on Alberta highways are regulated (Alberta Transportation 2016). Long-span girders are often divided into segments for fabrication and shipment to the construction site, which are spliced up during the erection process to form the whole span of the bridge.

(a) (b)

Figure 2.9. Photos of a typical (a) steel girder bridge, and (b) bridge girder ready to ship off to the field from the fabrication shop.

The number of girder lines is mainly determined by the width of the bridge deck. Along each girder line, multiple girders are spliced up in the field. As shown in Figure 2.10, each segment that is delimited by "Field Splice" along a girder line is identified as a girder – which is the production unit fabricated in a fabrication shop and transported to the bridge construction site. Herein, "Field Splice" is the bolt-up connection between girders. Figure 2.10(a) and Figure 2.10(b) are schematic representation of the girder lines and girders with splice joints, respectively.

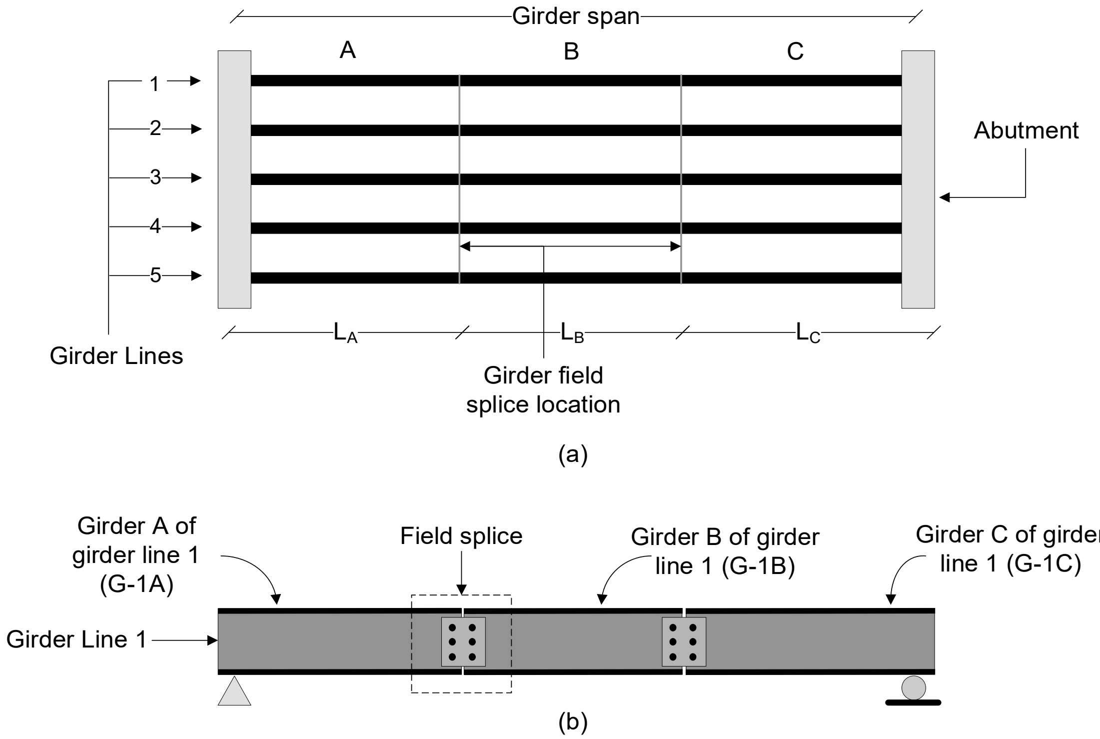


Figure 2.10. Schematic diagram of (a) typical girder line and (b) individual girder separated by the splice joint of steel girder bridges.

2.4.2.2 Girder Fabrication

In a bridge fabrication shop, the production unit is a girder which consists mainly of a middle plate (the web) welded permanently to two other plates (flanges) at the top and the bottom (Figure 2.11). Hence, the raw materials for girder fabrication consist of steel plates of different dimensions. Note rectangular plates (stiffeners) are fitted and welded perpendicularly into the web and the flanges; as stiffeners are out of the scope of the case study, they are not shown in Fig. 2.11.

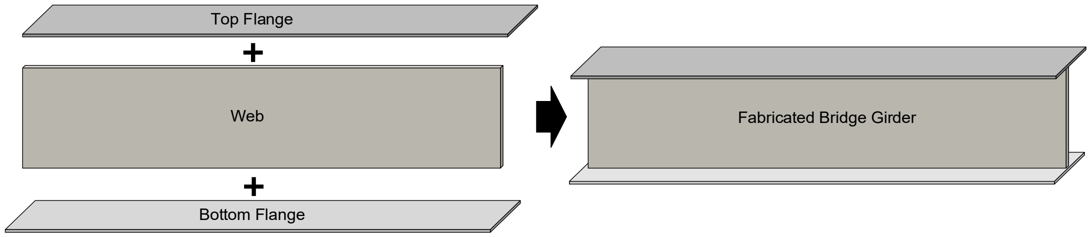


Figure 2.11. Components of a typical bridge girder.

The size and weight of a girder are mainly dependent on the workspace and crane load capacity in the fabrication shop, which is also related with allowable size limits and load capacities of the highway for transporting girders, and load capacities of the cranes for erecting girders on site. In the current case, all the girders range from 20-32 m in length (17-26 ton in weight); the width (flange width) and height (web height) of the girder are 0.6 m and 2.7 m, respectively; the thickness of the steel plates used in the web and flange fabrication is 2 cm and 6 cm, respectively. It is noteworthy the variations lie mainly in the girder length with the remainder of dimensions being identical across the board. Irrespective of the girder length, the handling and processing in fabrication relies on the use of overhead gantry cranes.

2.4.2.3 Shop Splice vs. Field Splice

In the production stage, the production manager occasionally needs to splice two steel plates in preparing the web and flanges for fabricating a girder –which is called "shop splice" in practice and dictated by the available dimensions of raw plates and the girder length. Note, the process is analogous to a tailor's cutting and seaming pieces of cloth in making clothes; however, girder fabrication substantially scales up the size and weight of the tailor's cloth. The fabricator deals with steel plates. Each piece weighs in tons and takes significant time and labour in handling, cutting and splicing with special equipment and tools. Figure 2.12 shows (a) a journeyman operating a gas torch burner at the web cutting workstation; and (b) a web plate prepared with shop slicing.

(a) (b)

Figure 2.12. (a) Journeyman operating at web cutting workstation; (b) two web plates tacked together ready for shop splicing.

In order to connect two adjacent girders in field erection, an array of holes need to be drilled at each end of the girder including both web and the two flanges along with preparing the connection plates, as shown in Figure 2.13. The process is referred to as field splicing preparation in girder fabrication. The position and alignment of holes in the two girder ends must be precisely matched to bolt up the two girders in the field. Note, for a middle girder in a girder line of the bridge (girder G1B in Figure 2.10(b), both ends need to be spliced. In contrast, an end girder requires only field splicing on one end (the other end of the span connecting to the support of the pier or abutment). In preparing the field splicing in the fabrication shop, the two girders to be spliced up in the field must be processed side by side at the same time for the crew to prepare the field splicing connection; at the end, a trial assembly process is performed in the shop for quality assurance. The end of a girder with field splicing finished is shown in Figure 2.14.

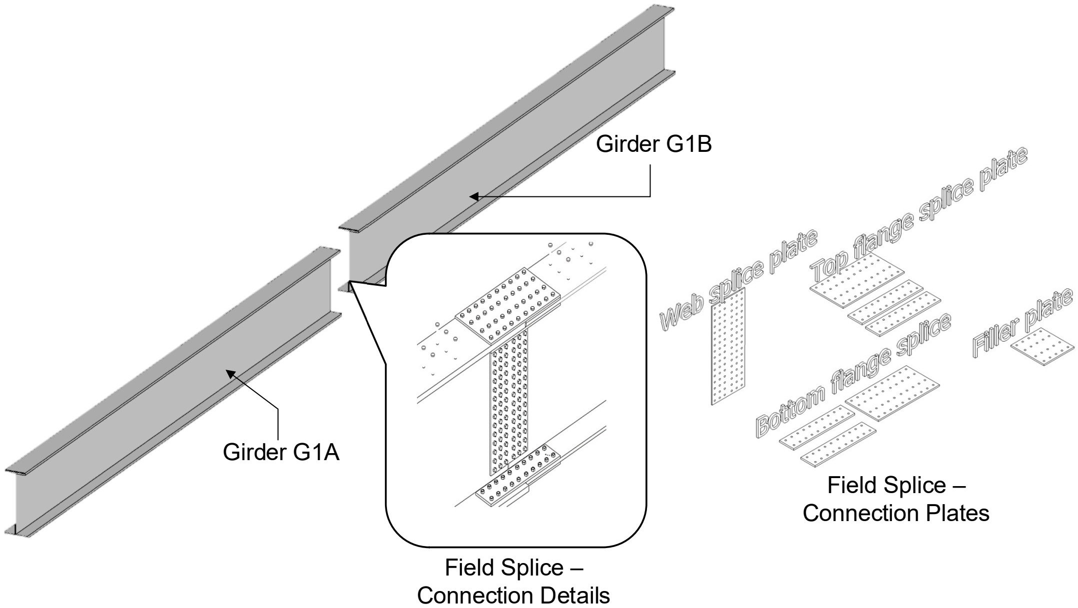


Figure 2.13. Schematic for field splice connection details between two girders.

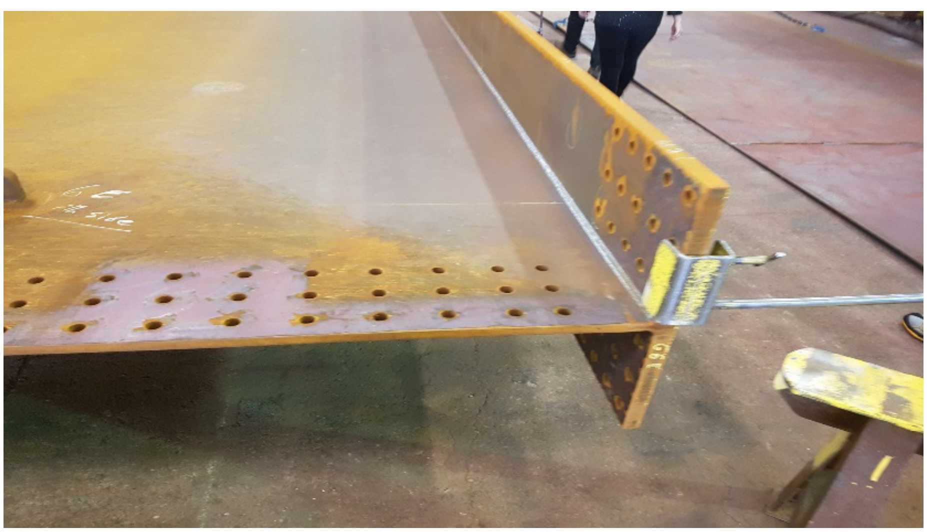


Figure 2.14. A girder with finished field spice drilling.

2.4.2.4 Discussion

A detailed fabrication activity list, labour resource requirements, activity duration, and precedence relationships for fabricating one girder (G1A) of a bridge consisting of twenty-one girders is tabulated in Table 2.4. In total, the twenty-one girders' fabrication activities resulting in the definition of two hundred forty-six fabrication activities with over one hundred technology constrained precedence relationships plus over one hundred implicit resource-constrained precedence relationships. In practice, performing a manual resource schedule simulation of real projects, in the same way as what has been done for the demonstration case earlier in section 2.4, is cumbersome and complicated. To facilitate this, S3/SDESA resource scheduling simulation tool (as given in Appendix I) is selected as a computer simulation tool to facilitate resource schedule simulation.

Two types of labour resources are employed at the fabrication shop, namely *N*m (the number of multiskilled labourers), and *N*s (the number of single-skilled specialist labourers). For the current case, the critical resources in the bridge fabrication shop are different crews of multiskilled journeymen (JM) employed in the fabrication shop. They are capable of executing work assignments at different workstations and locations such as cutting, fitting, roll welding, and operating materials handling equipment and semi-automated workstations. In addition, single-skilled labourers such as specialist welders (SW) are also employed to conduct welding stiffener (activity ID#12) in the "mix of single-skilled and multiskilled" scenario labour utilization.

In the current case study, in the "mix of single-skilled and multiskilled" labour utilization scenario, *N*s is set as 2; while, the likely values for the *N*m variable can be 3, 4, 5, 6, 7, or 8. Taking advantage of the discrete event simulation-based scheduling tool, SDESA, the objective is to identify the proper number of multiskilled labour resource (*N*m) against the number of single-skilled labour resources (*N*s) in order to balance resource utilization, total labour cost and total fabrication duration in completion of fabricating twenty-one girders of two bridges.

Table 2.4**.** Fabrication activity list for girderline G1 girder type A.

Task ID	Task Name	Duration	Predecessor Task ID	Resources Required
	G1A Fabrication			
3	Cutting Top Flanges	8 hrs		2 JM
4	Cutting Bottom Flanges	8 hrs	3	2 JM
5	Straightening Top Flanges	8 hrs	4	2 JM
6	Straightening Bottom Flanges	8 hrs	4,5	2 JM
7	Splicing Top Flange	18 hrs	5	1 JM
8	Splicing Bottom Flange	18 hrs	6,7	1 JM
9	Splicing Web	15.25 hrs		2 JM
10	Assemble Girder	20.25 hrs	8,9	3 JM
11	Welding Girder	11 hrs	10	2 JM
12	Welding Stiffener	54.1 hrs	11	2 SW
13	Splicing Girder G1A & the next girder of the girderline	13.75 hrs	12, 13	1 JM
13	Sandblast	10.5 hrs	12,25	2 JM

The case study is simulated to explore different combinations of multiskilled crew size and single-skilled labour utilization. As given in Table 2.5, resource utilization (RU%) can be improved to 54% as in Scenario 1, where five multiskilled journeymen are employed to execute the project. In addition, project time performance can be improved by fine-tuning of the utilization of different number of multiskilled labour resources vs. number of single-skilled specialist welders.

Table 2.5. Results from Summarized S3/SDESA schedule simulation model simulated project schedules under varying crew sizes for "mix of multiskilled and single-skilled" labour utilization.

Scenario	Total No. of Labourer	No. Multiskilled Labour (*N*m)	No. Single-skilled Labour (*N*s)	Duration (Hr)	Total LH	RU %
1	5	5	0	2352	11748	54%
2	6	6	0	2195	13152	49%
3	7	7	0	1923	13400	47%
4	8	8	0	1839	14585	43%
5	5	3	2	2678	13307	47%
6	6	4	2	2369	14164	45%
7	7	5	2	2036	14291	44%
8	8	6	2	1889	14985	42%
9	9	7	2	1573	13775	46%
10	10	8	2	1478	14510	44%

In arriving at the final decision, the production manager would be able to weigh all scenarios in terms of overall resource utilization rate, total labour cost, and project duration. In a practical application context, multiskilling is found to provide the opportunity for labour resource utilization optimization in project planning and scheduling at a bridge girder fabrication shop –which will be further explored in the ensuing chapter 3 and chapter 4.

The research methods were implemented, and the simulation results were verified through comparison with Primavera P6 in line with the strategy as described by Sargent (2010) in the verification by comparison to other models. The proposed framework was also verified by manually checking the detailed simulation results to ensure satisfaction of constraints, such as finite resource availability and proper sequencing of activities. The validity of the results was confirmed through an independent validation process, as described by Sargent (2009) in the face validation process. The model and labour cost estimate were evaluated by professional planning experts to determine their reasonableness and validity.

2.5 Summary

In the practice of prefabrication and off-site construction, structural components are fabricated in a controlled factory setting and then transferred to the construction site for installation. Common practice in construction is to use specialized single-skilled labour resources to work on specific locations on site or in a shop (e.g., workstations in fabrication). To complement automation technology that finds its way into the mainstream of prefabrication (such as CNC machinery linked with parametric digital design models), multiskilling labour resources employed in an off-site fabrication facility for construction has become a widely adopted practice. With technology advancing in automated materials handling systems, robots can understand exactly what to do and how to do specialized tasks. Yet, the relatively low volume of custom designed products coupled with the relatively high variability of production processes still make prefabrication facility practically infeasible to realize the full automation of fabrication processes. By having more automation and using semi-automated workstations, the benefits of cross training of labour resources to make them able to work on different workstations would outweigh associated costs. A streamlined crew of labour resources provides the set of skills required to work on different workstations, more likely to play the facilitator role to enable the application of automation and robotics on workstations (e.g., manually setting up the weld by fitting two pieces for a welding robot to make the weld).

This research has investigated the impact of multiskilled labour resources employment in prefabrication of construction products in terms of enhancing labour resource utilization rates and consequently the improved cost performance of the project. By contrasting single-skilled and multiskilled labour resource strategies based on resource scheduling simulation, a substantial improvement with the multiskilling strategy has been noteworthy. Multiskilling could also provide the potential opportunity of optimizing labour assignments and resequencing activities leading to optimized production systems in prefabrication and off-site construction. On the other hand, the downsides in connection with multiskilling should also be taken into consideration, including decreased efficiency as a result of learning and forgetting effects, licensing limitations, training cost limitations, psychological effects, and restrictions in union regulations. How to overcome those hurdles in multiskilled workforce employment point to further research problems down the path.

The status quo of modularization in the construction industry remains at a low level. Taking steel girder fabrication for example, the existing methods to cut, handle, weld steel plates lend well to girder customization to different bridge designs; nonetheless, it does not provide the basis for materializing paradigm shift in modularization (automation, robotics, 3D printing). The current standardization only provides specifications on raw materials (plates) and code for connection design (welds and bolt-ups). There is no standard module concept yet in design, fabrication and construction in steel girder fabrication. Despite advances in automation and robotics, labour resources still play an indispensable role in the practice of prefabrication of construction components. This study investigates the current practice of prefabrication in construction and shed light on its distinctive characteristics against manufacturing that could have hampered the implementation of high-level modularization.

In order to realize high level modularization in steel girder fabrication, it is envisioned that a bridge girderline is designed to standard “girder” modules (end girder, middle girder) with standard dimensions and connections; in planning for construction, contractor only orders a specific quantity of certain types of standard girders from the fabricator. The fabricator can make those standard girders of limited types –each specified by certain steel grade, length, thickness, and connection details- without specific client orders. In consequence, the fabrication process could be conducive to automation just like manufacturing. Nonetheless, this represents a paradigm shift in engineering and modularization with considerable high barriers to overcome. The process is not only confined to practices of fabrication and construction; but also involves revamping the engineering code and design procedure. Considering the efforts, the costs, the time it takes to develop the existing code, as well as the communication challenges between fragmented disciplines in engineering (structural engineering, manufacturing, and construction), realizing the proposed paradigm shift can present a daunting challenge but a great opportunity of interdisciplinary research in the near future.

CHAPTER 3

Generating Labour Cost Budget for a Construction-oriented Fabrication Facility: Simulation-based Resource Scheduling Approach

A novel labour-hour budgeting methodology is proposed by integrating productivity concepts in project scheduling and budgeting to enhance the accuracy of labour cost budgeting for planning labour intensive projects. The proposed methodology applies discrete-event simulation approach to represent crew formations, labour resource utilization and labour resource flowing between consecutive activities, which allows for quantitatively characterizing the impact of labour semi-productive time on labour cost budgeting as a time-dependent variable. Simulation-based assessment of variations in crew sizes and labour allocations is conducive to reducing semi-productive time and thus enhancing the cost performance of the whole project. The proposed methodology is then applied in a real-world case study for planning steel girder fabrication projects in construction of highway bridges. Not limited to budgeting for labour resources in construction-oriented fabrication facilities, the research contributions are also significant to other construction planning settings where Limited resources are shared and utilized among different activities.

3.1 Introduction

A significant body of labour productivity research has been conducted in the past in attempts to determine the proper proportion of productive time in connection with labour utilization efficiency (Hanna 2010; Maarof and Easeph 2017; Forbes and Ahmed 2010; Hewage and Ruwanpura 2006;

Gong et al. 2011). In general, it is claimed that about 40% to 60% of labour resource operation time is associated with productive or direct work. Related productivity studies had investigated the effect of specific factors on productive labour time. Thomas (2000) maintained labour utilization inefficiency due to workflow disruption in schedule acceleration could be minimized by matching the labour resource available to the amount of work. Gong et al. (2011) identified a statistically significant difference in crew utilization efficiency on different types of activities subject to different crew sizes (small, medium, large). Furthermore, previous studies also investigated the impact of change orders and reworks (Thomas and Napolitan 1995; Watkins et al. 2009; Hanna et al. 1999), workspace congestion (Thabet and Beliveau 1994) and shift work (Hanna et al. 2008) on labour utilization efficiency. These studies used a variety of labour time utilization assessment methods such as work sampling and five minutes rating, video-based, automated data collection (RFID, magnetic field), artificial intelligence, factor models, expert systems, operation simulation, genetic algorithm, and regression (Brisley 1952; Dozzi and Abourizk 1993; Thomas and Sakarcan. 1994; Smith 1999; Fayek and Oduba 2005; Tam et al. 2001; Lu et al. 2000; Nasirzadeh and Nojedehi 2013; Park et al. 2016; Lin et al. 2013; Zhao et al. 2019; Teizer et al. 2020; Cheng et al. 2011); all suggesting that detailed crew-level planning is crucial to enhance labour time utilization despite the fact that theories and systematic methods in construction planning have yet to advance for implementation in practice. Furthermore, labour resource planning problem for a fabrication facility in the construction industry entails concurrent execution of multiple projects with finite limits of labour resources and space available, presenting distinctive challenges for current practice based on popular project management tools (e.g., P6 or MS Project.) (Azimi et al. 2010; Liu and Lu 2018).

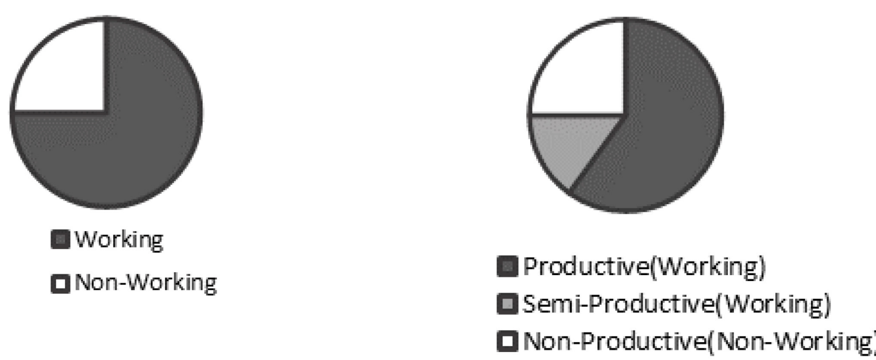
The implementation of prefabrication and off-site construction places the job shop scheduling problem in a construction-oriented perspective. An industrial fabrication shop servicing the construction industry resembles a factory in manufacturing in that jobs from different clients and projects are generally performed simultaneously. Labour resources like journeymen are employed at the fabrication shop to process made-to-order products for different projects. Each journeyman is part of teams temporarily formed in conducting a wide range of material-handling and connection activities at different workstation locations in a fabrication shop. Notably, labour cost makes up a bulk of the direct cost of a fabrication project and is conventionally determined independently of equipment use (Barrie and Paulson 1992; Jarkas 2010; Rivas et al. 2011). Labour-hour (LH) based budgeting is a common practice in making budgets for labour costs on industrial construction projects (Hu et al. 2014).

The Budgeted Cost for Work Scheduled (BCWS) – plotted as an S-curve – displays the cumulative budgeted labour cost against the project time in Earned Value Management (EVM), providing the baseline for evaluating labour cost performance in connection with project schedule control (Fleming and Koppelman 2005). For industrial projects where work progress is measured in labour-hours spent for completing various types of work, the Cost Performance Index (CPI) is generally referred to as Productivity Index (PI) in practice (Kim and Ballard 2000), which is calculated as per Eq. 3.1 at a specific data date in executing the project (Hanna et al. 2005).

$$\mathrm{PI} = \frac{\text{Earned Labour} - \text{Hours}}{\text{Actual Labour} - \text{Hours}} \tag{3.1}$$

Hence, how to generate a realistic and accurate S-curve of the budgeted labour-hours provides one main driver for defining the present research. To estimate labour-hours on a particular activity, labour productivity and labour utilization efficiency is an important consideration which could vary broadly among different projects (Barrie and Paulson 1992; Jarkas 2010; Rivas et al. 2011).

In general, labour time is categorized into working time vs non-working time. The commonly applied efficiency factor of 45-min hour (equivalent to 75%) accounts for the working time vs. non-working time of workers (Figure 3.1(a)). Note the non-working time represents regular breaks for resting and socialization during operation hours that is necessary to keep up the physical and mental states of workers in performing productive work during the working time (Folkard and Tucker 2003). Thus, the common practice in project scheduling and budgeting is to factor the non-working time in the estimated activity time (e.g., if 45-minute hour non-working time efficiency applies, the activity time is divided by 75% or multiplied by 1.33) (Gong et al. 2011). Furthermore, the labour working time consists of productive time (utilizing hands or tools to complete a specific scope of work and deliver valuable output) and semi-productive time (workers' time to get ready instructions, tools, materials, or needed support from another worker prior to starting a productive activity) (Dozzi and Abourizk 1993; Haas et al. 2017; Oglesby et al.1989) (Figure 3.1(b)).



(a) (b)

Figure 3.1. (a) Working vs. non-working; (b) productive, semi-productive, and non-productive work.

A significant body of research in construction productivity has been established with particular emphasis on productive labour time. Nonetheless, one critical question in construction planning remains yet to be addressed: how to characterize the impact of semi-productive labour time upon labour cost budgeting on labour intensive projects by considering project-specific factors such as crew size, crew formation and labour flow efficiency. Notably, traditional labour time utilization assessment methods such as work sampling and five minutes rating distinguish predefined semi-productive modes from productive and non-productive (or nonworking) modes (Dozzi and Abourizk 1993). Yet, these techniques rely on an observer's field observation and judgment and are limited in scope and expensive to scale up in practice. On the other hand, video recording or other technology-enabled direct onsite observation approaches for collecting data on semi-productive hours lend potentially cost-effective solutions. Nonetheless, technology application is not well accepted in the real world due to privacy infringement and ethics challenges; while, implementing such data collection efforts in the field could present a challenge (Hewage 2009). In the construction field, workers generally deem direct measurement of work time based on onsite observations as performance monitoring and administrative control. It is noteworthy that advanced data collection technology does not circumvent the basic psychological barrier in observing human behavior and performance: workers tend to behave differently when they know that a study is being conducted and they are being watched. In social sciences, this is referred to as the Hawthorne Syndrome (Mayo 1933).

In this research, a novel labour-hour budgeting approach is proposed by integrating productivity concepts in project scheduling and budgeting in order to enhance the accuracy of labour cost budgeting for planning labour intensive projects. The proposed methodology applies a discrete-event simulation approach to represent crew formation, labour resource utilization and labour resource flowing between consecutive activities on a project, which allows for quantitatively characterizing the impact of labour semi-productive time on labour cost budgeting as a time-dependent variable. The main research contributions are summarized as follows:

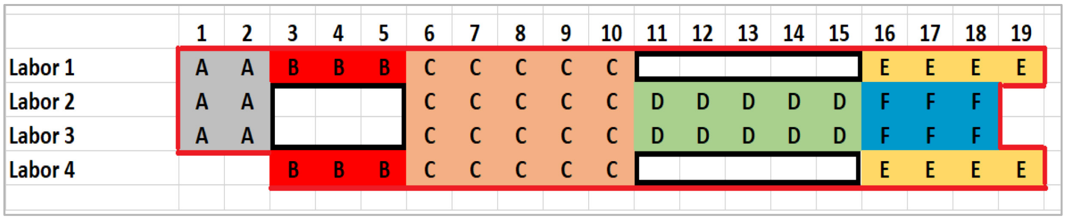
- Analytically representing semi-productive time resulting from inefficiencies in labour flow and crew formations during project duration through resource scheduling simulation modeling subject to both technology and resource availability constraints.
- Integrating productivity study concepts with project scheduling and budgeting methods to define the *resource inter-activity utilization efficiency* in deriving the S-curve for budgeted cost for work scheduled (BCWS) in order to improve the accuracy of project budget.
- Reducing semi-productive time and thus enhancing the cost performance of the whole project through simulation-based assessment of variations in crew sizes and labour allocations, resulting in the adjustment on activity sequencing and the improvement on labour flow efficiency between different activities.
- Implementing the proposed methodology in a real-world case study for planning steel girder fabrication projects in construction of highway bridges.

In this research, the Simplified Scheduling Simulation (S3) tool, which had been developed in house based on the Simplified Discrete-Event Simulation Approach (SDESA), is used to simulate Primavera P6 scheduling in terms of critical path scheduling under resource constraints (Oracle 2012). Notably, application of the discrete-event simulation methodology has resulted in analytical outputs that exceed P6's functionalities in terms of generating a resource-loaded project plan with more detailed information such as a resource allocation and activity sequencing bar chart, which allows for tracing the allocation of relevant resources to particular activities and visualizing labour flows between activities. Simulation allows schedulers and planners to analyze the semi-productive labour time and determine how the amount of semi-productive labour time varies through examining different what-if scenarios. Based on simulation results, the new efficiency factor of *Resource Inter-Activity Utilization Efficiency* is defined, whilst the effect of resource inter-activity utilization efficiency on deriving the budgeted cost for work scheduled (BCWS) S-curve is evaluated. The objective of this research is to reduce the semi-productive proportion within the total allotment of resource working time. Hence, a hypothesis is investigated through this research, namely: if the semi-productive percent is reduced, then, labour inter-activity utilization efficiency increases, leading to decreasing the total labour-hour budget. The application of the proposed analytical method is illustrated with a case study based on a real word steel fabrication project.

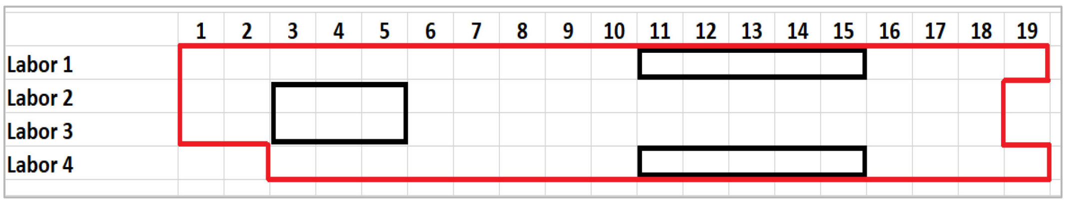
3.2 Resource Utilization Efficiency and Labour Cost Budgeting

3.2.1 Resource Inter-Activity Utilization Efficiency

The newly defined efficiency factor called *Resource Inter-Activity Utilization Efficiency* is proposed based on how efficiently a resource flows and moves between executing consecutive activities in a detailed resource schedule. In a fabrication shop, with limited number of labour resources each labour resource such as journeyman is a part of teams temporarily formed with other journeymen, conducting various material-handling and connection activities at different workstations. Accordingly, improving crew formations and resource movements between different activities is a crucial consideration in fabrication workforce planning.



(a)



(b)

Figure 3.2. (a) Detailed resource work schedule subject to technological constraints on the project; (b) semi-productive resource time (black blocks) vs. total labourers' efforts (red framework).

To analyze resource inter-activity efficiency, it is necessary to determine the semi-productive time associated with all the labourers involved. The term "semi-productive time" is originated from productivity study as a broad definition, including (1) essential labour-hours spent on activities in support of production activities in project execution, such as labour-hours spent in checking instructions, confirming specifications and drawings, reassuring safety measures, and getting ready prior to executing upcoming activities; (2) non-essential labour-hours such as workers' waiting time for matching required resources (collaborating crew members and or materials) prior to executing production activities. Subject to application need and data availability in practice, this research narrows down the *semi-productive time* as the labour-hours resulting from labour flowing between different activity locations, which consists of movement and waiting time in order to execute different activities on one or different projects.

Herein, it is important to clarify the workers' waiting time incurred in matching required resources from a practical operations perspective. During the "waiting" time, a worker can be actually involved in performing a wide range of supporting activities instead of idling; nonetheless, details on related activity breakdown, sequencing and time requirements are generally unavailable for modeling as the required data are not tracked in the real world or too expensive to collect on a practical scale. It is noteworthy that in-depth modeling of "semi-productive time" demands data more than practically available at present and hence remains an ill-structured problem that is out of the scope of the current research. Nonetheless, this barrier is considered irrelevant to the present research because this research addresses projects planning, labour resource planning and labour cost budgeting at the pre-construction bidding stage instead of operations planning and production planning and control.

In Figure 3.2, semi-productive time is visually defined with a black frame (the total sixteen units semi-productive time in this case); while its proportion to total labour efforts, which is confined in the red frame (the total efforts of seventy-two units), determines the labour inter-activity utilization efficiency. Thus, the rate of 77.8% is calculated (i.e., 56/72) as the resource inter-activity utilization efficiency factor associated with crew formation for the current crew of four labourers. In Figure 3.2, the difference between total labour efforts (confined in the red frame) and the semi-productive time (confined in the black frame) actually corresponds with the total budgeted labour efforts that are calculated by the popular P6 system for project scheduling (Oracle 2012) –which is the summation of labourer hours based on the actual duration of each activity (fifty-six units) without accounting for additional labour-hours for compensating the effects of semi-productive time.

3.2.2 Proposed Framework for Project Labour-Hour Budget

The current practice for deriving labour cost budget for project planning and control is to tally the cumulative labour-hours up to a data date in the project schedule. The cumulative labour hours required at a particular time point (*t*) of the project is equal to the total of all activities completed or partially completed up to time (*t*) as per Eq. 3.4. Eq 3.2 calculates the direct labour-hours required for completing the activity (i), using activity duration (D_i) multiplied by the number of the required labourer (L_i) for performing activity (i). Required labour-hours for each activity (*i*) are calculated as Eq. 3.3, which results from the Eq. 3.2 factoring in the "non-working" resource utilization efficiency (Eff_{NW}).

$$\mathrm{LH}_{Direct,i} = D_i \times L_i \tag{3.2}$$

$$\mathrm{LH}_{Total,i} = \frac{\mathrm{LH}_{Direct,i}}{\mathrm{EFF}_{NW}} \tag{3.3}$$

$$\mathrm{LH}_t = \sum_{i=1}^{n} \left(\mathrm{LH}_{Total,i} \times \frac{t_i}{D_i} \right) \tag{3.4}$$

$$t_i = \begin{cases} t - t_{st,i} & t_{st,i} < t \text{ , and } t_{st,i} + D_i > t \\ D_i & t_{st,i} < t \text{ , and } t_{st,i} + D_i < t \\ 0 & t_{st,i} > t \text{ and} \end{cases}$$

Note, t_i is time elapsed for activity (*i*), (t) is time elapsed for entire project and $t_{st,i}$ is start time of activity (*i*) as per project schedule.

Eq 3.5 mathematically formulates the new term of labour inter-activity utilization efficiency. Accordingly, the S-curve for budgeted labour-hours is generated by plotting $\text{LH}_{Budgeted,t}$ values (Eq. 3.6) at different time points (*t*) along with the total project duration (T_{Total}).

$$\text{Eff}_{\text{inter}}(t) = 1 - \left(\frac{\sum_{0}^{T_{Total}} \text{SemiProductive LabourHour}_t}{\sum_{0}^{T_{Total}} \text{Total LabourHour allocation}_t} \right)$$

$$= \left(\frac{\text{LH}_t}{\sum_{0}^{T_{Total}} \text{Total LabourHour allocation}_t} \right) \tag{3.5}$$

$$\text{LH}_{Budgeted,t} = \left(\frac{\text{LH}_t}{EFF_{\text{inter}}(t)} \right) \tag{3.6}$$

Where $\text{Eff}_{inter}(t)$ is the labour inter-activity utilization efficiency factor at time (*t*); semi-productive labour hour_t is the semi-productive time due to the crew formation at a specific time (t) over the project duration; T_{Total} is the project duration; and $\text{Total LabourHour allocation}_t$ denotes total labour-hours which is shown as the red framework in Figure 3.2. Figure 3.3 presents an overview of the proposed framework for deriving the S-Curve, by factoring in the newly defined factor of labour inter-activity utilization efficiency.

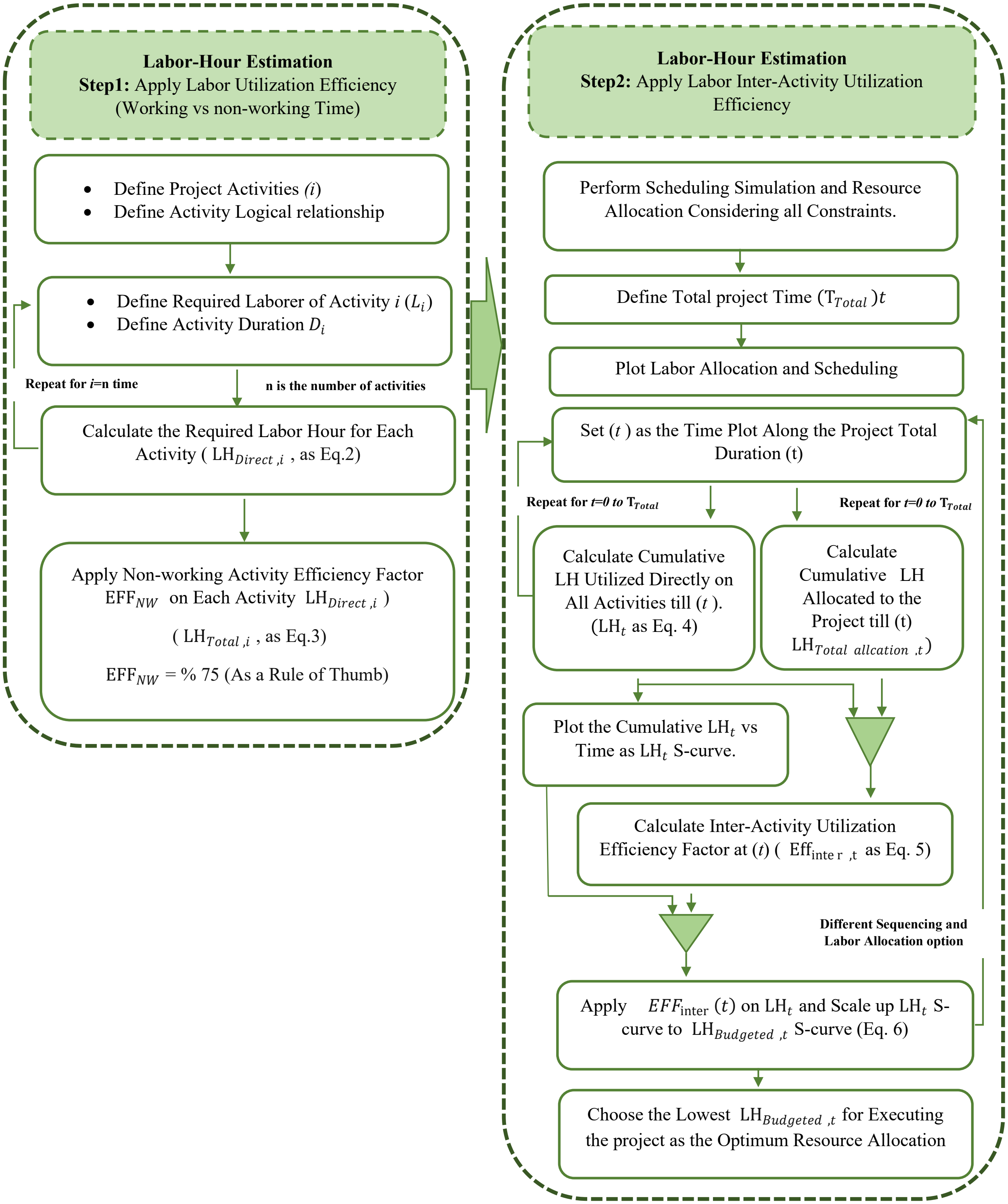


Figure 3.3. Proposed framework for project budgeting (Consideration of inter-activity utilization efficiency).

3.2.3 *Simplified Scheduling Simulation*

To overcome limitations inherent in Critical Path Method (CPM) scheduling under limited resource constraints, Lu et al. (2008) proposed a resource scheduling methodology based on the Simplified Discrete-Event Simulation Approach (SDESA), resulting in an in-house developed computer too called Simplified Scheduling Simulation (S3). S3 is capable of automatically adjusting activity execution sequences subject to simultaneously accommodating both technology and resource constraints on the project (Lu et al. 2008). In short, S3 enables the analysis of utilization of individual resources on specific activities over a particular time period of project duration. In the present research, S3 is utilized as a resource schedule simulation tool to produce a valid project schedule along with the corresponding resource allocation plan, which provides input to generating a realistic LH budget and allows the analysis of the resource inter-activity utilization efficiency as a time-dependent variable during the execution of the project. A detailed description of how the S3 scheduling model is generated is given in Appendix I.

As resource share and transfer between different activities vary along the project duration, the labour inter-activity efficiency changes at each time point (t). Note the "LH_t" is equivalent to the labour-hour S-curve derived by using the resource levelling function of P6. The S-curve is then adjusted based on labour resource inter-activity utilization efficiency at a given control time point (t) over the project duration. The semi-productive labour-hours and the total labour-hours spent up to (t) are tracked based on resource scheduling simulation, as demonstrated in Figure 3.4 Further, Figure 3.5 trends the change of resource inter-activity efficiency factor over time in one project.

Figure 3.4 shows this factor varies over time and is applied to adjust labour-hour budget (solid blue line) against the P6-produced budget (dashed blue line). The vertical blue dash line denotes a given control time point (t) in the project duration. In Figure 3.4, after the second hour, the colored area marked with activity ID represents labour utilized on Activity A, incurring zero semi-productive resource time. It means out of the total labour-hours spent (six hours marked with "A"), all six hours are actively engaged in executing "A". Thus, the rate of 100% is calculated as the resource inter-activity utilization efficiency at the end of the second hour of the project. Moving along the time, inefficiency is encountered and varies over time, which is herein denoted as semi-productive cells (white cells confined in black boxes). Figure 3.4 shows out of the total labour-hours spent at the eleventh hour of the project (forty-two hours, which is calculated from the start of Activity A), thirty-four hours are actively utilized in executing activities A, B and C and D with the remainder of eight hours identified as semi-productive hours. Thus, the rate of 81% is calculated (i.e., 34/42) as the resource inter-activity utilization efficiency at the end of the eleventh hour. At each point of time (t), the vertical dashed line denoting the LH_t is adjusted by applying the inter-activity utilization efficiency factor fixed at that particular point of time, resulting in the solid line denoting the " $\mathrm{LH}_{Budgetted,t}$".

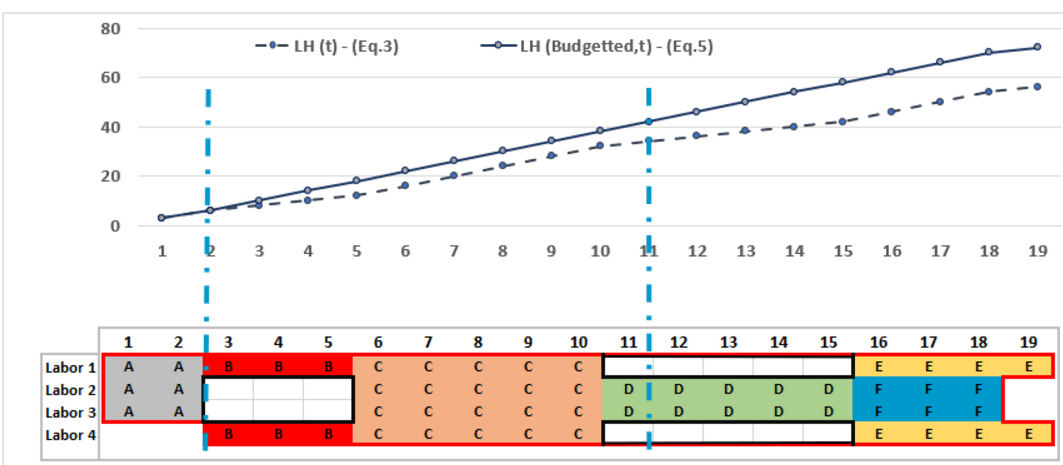


Figure 3.4. Presentation of the labour's effort in different points of time; at the end of the second and eleventh hour.

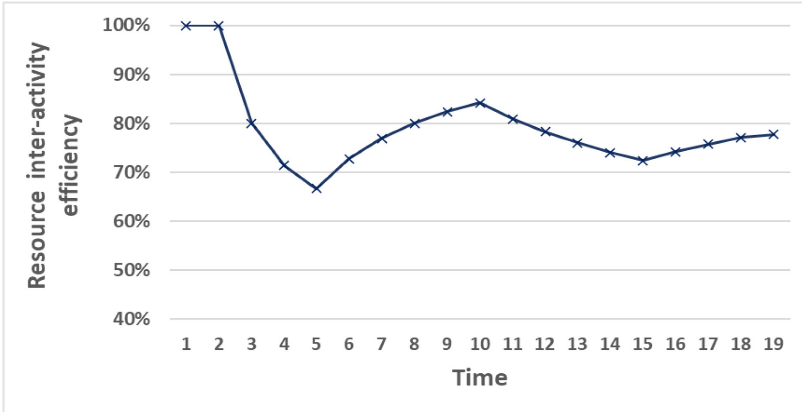


Figure 3.5. Time-dependent labour inter-activity utilization efficiency factor.

3.3 Demonstration Case

Table 3.1 shows a fictitious project with time unit in hours. The associated Activity-On-Node (AON) is presented in Figure 3.6. Note this case is adapted from a Critical Path Method (CPM) example in Hegazy (1999). The Critical Path Method (CPM) analysis under eight journeymen availability constraints is performed using S3, resulting in fifty-two hours project duration, as shown in Figure 3.7.

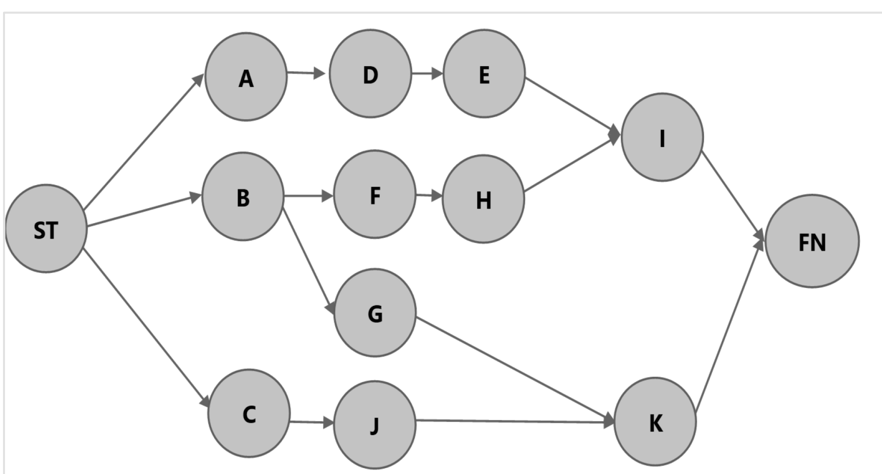


Figure 3.6. Activity-On-Node (AON) for Table 3.1.

Table 3.1. Duration, resource requirement and predecessors of each activity.

Activity	Predecessors	Duration (hr.)	Resource Requirement
A	-	4	3
B	-	6	6
C	-	2	4
D	A	8	-
E	D	4	4
F	B	10	-
G	B	16	4
H	F	8	2
I	E, H	6	4
J	C	6	5
K	G, J	10	2

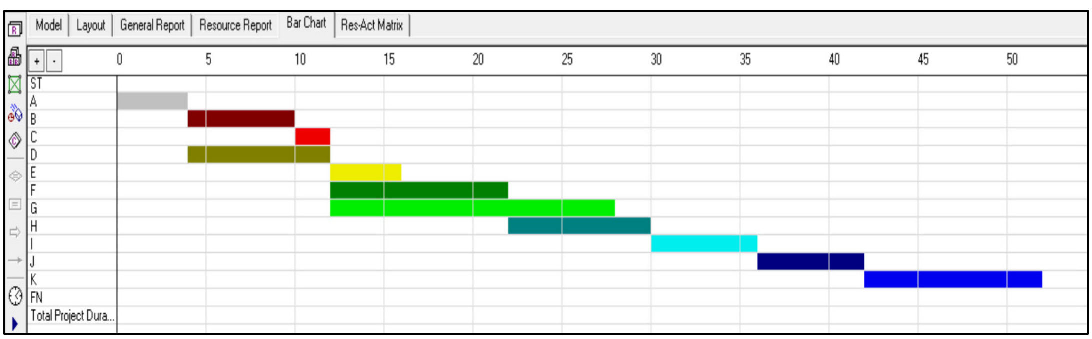
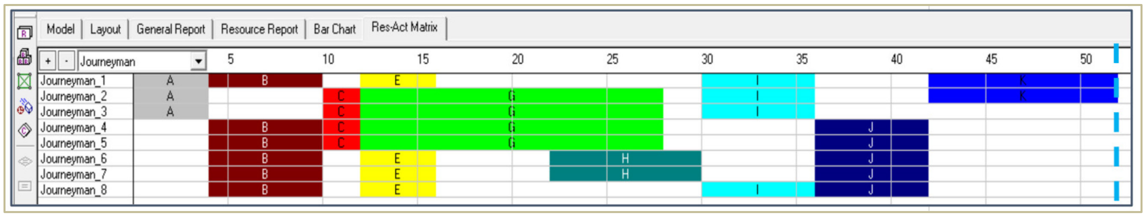
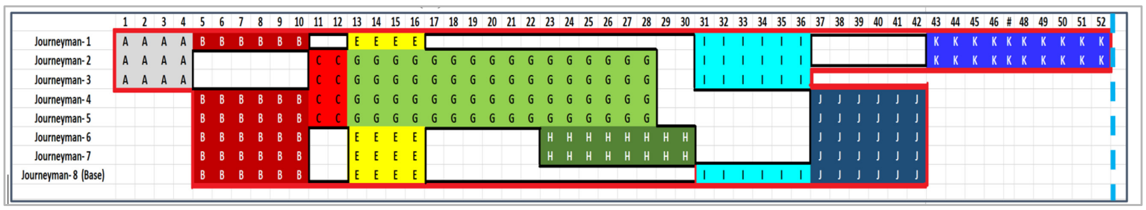


Figure 3.7. CPM activity bar-chart schedule under eight journeymen availability constraints in S3.

S3 produces a time-dependent resource utilization matrix, as shown in Figure 3.8. Setting control time at the end of the project (i.e., fifty-second hour), the inter-activity utilization efficiency is calculated as 68.5%.



(a)

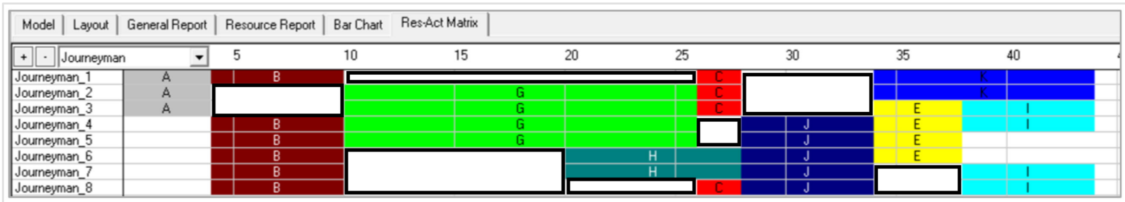


(b)

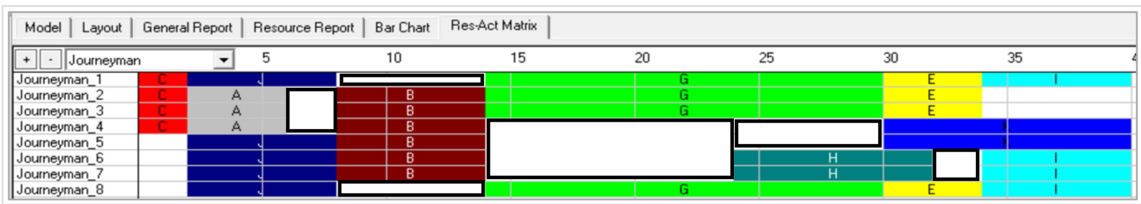
Figure 3.8. (a) S3 simulation generated solution in the form of a time-dependent resource utilization matrix. (b) semi-productive resource time (black blocks) vs. total journeymen's efforts (red framework).

3.3.1 Different Activity Sequencing Options

In allocating limited resources to activities of a project, different priorities in resource allocation can impact relative activity sequencing, subject to not violating any technology or logical constraints. Given the same Activity-On-Node (AON) network, varied activity sequencing could give rise to a different resource allocation schedule. Figure 3.9 shows two valid alternative activity sequencing options from the base case scenario (i.e., Option 1 as depicted in Figure 3.8) for the current case.



(a)



(b)

Figure 3.9. (a) Activity sequencing and journeymen allocation option 2 for Table 3.1 case study. (b) activity sequencing and journeymen allocation option 3 for Table 3.1 case study.

Changes in semi-productive labour-hours for the different options are summarized and contrasted in Table 3.2. The productive labour-hours in the three options are the same, i.e., 226 LH, which is equal to the labour budget resulting from P6. On the other hand, the semi-productive labour-hours and inter-activity efficiency factor vary considerably in various options. Note Option 3 is recognized as the best scenario, featuring the lowest Total $\mathrm{LH}_{Budgeted}$ (300 LH) at the end of the project, which corresponds with the highest labour inter-activity efficiency of 75.3%.

Table 3.2. different labour allocation (for table 3.1) makes changes in inter-activity efficiency factor and Total $\mathrm{LH}_{Budgeted}$.

Sequencing Option	Productive LH (P6 Budgeted LH)	Semi-productive LH	Inter-Activity Efficiency (%)	Budgeted LH as Per Proposed Methodology
1	226	104	68.5%	330
2	226	90	70.6%	316
3	226	74	75.3%	300

3.3.2 Crew Size

By fixing a particular activity sequencing option, changing the number of resources also results in variation in the inter-activity utilization efficiency factor. For various crew size scenarios of the particular activity sequencing Option 1 in this case, journeyman inter-activity utilization efficiency and budgeted labour-hours are summarized in Table 3.3; the labour-hour budget S-curve for different crew sizes is plotted in Figure 3.10. It is notable that as crew size increases (larger number of journeymen), the journeymen's inter-activity utilization efficiency factor decreases, while the total labour cost budget (LH) increases. The "six journeymen crew size" scenario is identified as the best in terms of the lowest total budget (272 LH) and the highest inter-activity efficiency factor (83.1%).

Table 3.3. Simulation results for different scenarios based on the case study project.

Crew Size	Semi-productive LH	Inter-Activity Efficiency (%)	Budgeted LH as Per Proposed Methodology
6	46	83.1%	272
7	86	72.4%	312
8	104	68.5%	330
9	116	66.1%	342
10	130	63.5%	356
12	154	59.5%	380

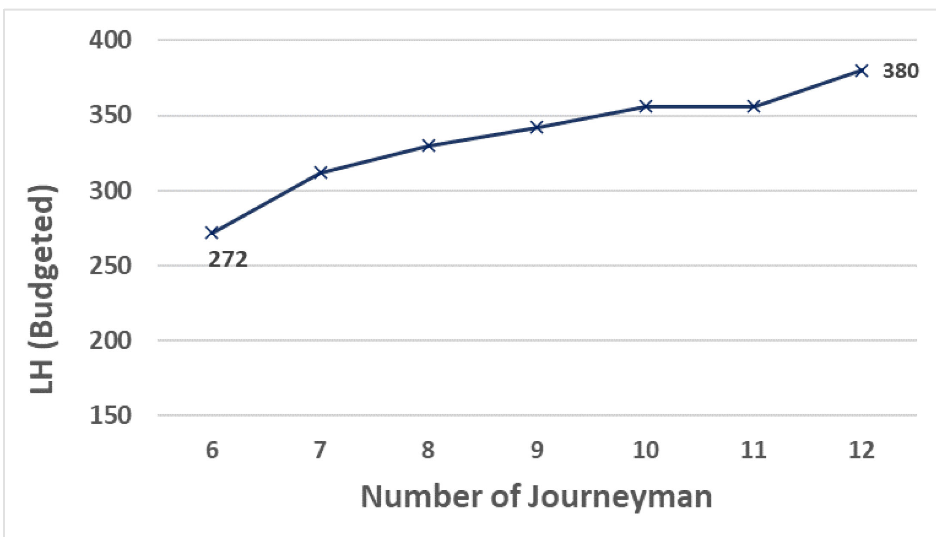


Figure 3.10. The effects of changing the number of journeymen on total labour-hour (activity sequencing option one).

In short, this small project case clearly demonstrates the effect of changing activity sequencing or crew size on the inter-activity efficiency factor and labour-hour budget. In the ensuing section, a practical case study of applying the proposed methodology for project labour cost budgeting is presented.

3.4 Practical Case of Bridge Girder Fabrication

Being the crucial structural component in a typical highway bridge, a steel plate girder consists of one web, two flanges (the top flange and the bottom flange), stiffeners, and shear studs (Krause 2015). To reach the designed bridge span, girders are spliced on-site to form a continuous girder line. In practice, one project consists of multiple girder lines; each girder line is made up of multiple girders. At the fabrication shop, raw steel plates are processed through a series of operations: (1) flange cutting, (2) flange straightening, (3) flange splicing, (4) web splicing, (5) assembling the girder by fitting flanges to web (6) welding the girder into one piece, (7) fitting and welding studs and stiffeners, (8) drilling holes for field splicing, (9) sandblasting and finishing.

The Activity-On-Node (AON) project networks for girder fabrication processes and technology-constrained precedence relationships are described in Liu and Lu (2020). Note, for simplicity of representation, only two of the three bridges found in the case study given in Liu and Lu (2020) were selected and used in the current case for analyzing the inter-activity resource utilization efficiency factor. In chapter 4, workstation-based fabrication activities, the duration of individual activities, technology-constrained precedence relationships, and the required resources are given in Table A1 and Table A2 only for the two selected girders (G1A and G1B) of Bridge 1.

In total, the project is to fabricate twenty-one girders of the two bridges, as shown in Figure 3.11. The project breakdown defines (1) two hundred forty-six fabrication activities, (2) over one hundred technology constrained precedence relationships, and (3) over one hundred implicit resource-constrained precedence relationships.

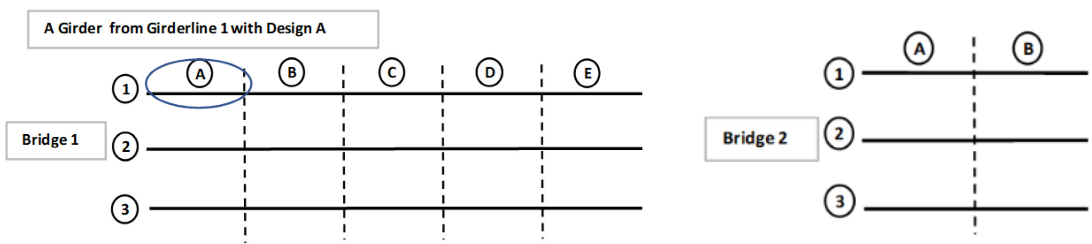


Figure 3.11. Engineering design of bridge1 and bridge 2.

The S3 model was developed to schedule two hundred forty-six fabrication activities in the project. It is notable that S3 delays activity start time until (1) the required resources are available and (2) all the specified logical constraints are satisfied. Running the S3 schedule simulation model under imposed resource constraints resulted in a total project duration of 2511 hours. Next, the time-dependent inter-activity efficiency factor is analyzed based on the proposed approach. More details about the two-bridge simulation model and its variables are given in chapter 4. Six scenarios, each denoting a specific combination of activity sequencing option and crew size, are simulated using S3; the obtained results are summarized in Table 3.4.

Scenario 6 is found to be the best solution in terms of the lowest total LH budget (10044 LH) and the highest labour inter-activity efficiency factor (63.56%). In Scenario 6, the total labour-hours budgeted for this project is 10044 hours. The productive time portion of the labour cost budget, namely: 6384 LH total productive hours, is also cross-checked against Primavera P6 for validation

(Figure 3.12). Figure 3.12 shows the BCWS for the journeymen derived by Primavera P6. It is emphasized herein P6 doesn't determine semi-productive labour-hours (i.e., 3660 LH) due to the inherent limitation of its underlying scheduling algorithms.

Table 3.4. Journeyman utilization rate in different scenarios.

ID	Crew Size	Semi-productive LH	Inter-Activity Efficiency (%)	Budgeted LH as per Proposed Methodology
1	6	6768	48.54 %	13152
2	6	5636	53.12%	12018
3	5	5365	54.34%	11748
4	5	4835	56.90%	11220
5	4	3804	62.67%	10187
6	4	3660	63.56%	10044

The labour cost budget of 6384 LH (derived by P6) thus is an underestimate against the labour-hour budget resulting from this research by factoring in resource inter-activity utilization efficiency. The inter-resource utilization efficiency at the end of the project is calculated as per Eq (5): $\mathrm{Eff_{inter}} = 1 - \left(\frac{3660}{3660+6384}\right) = \left(\frac{6384}{10044}\right) = 63.56\%$. Finally, based on Scenario 6, the S-curve budget with and without applying the resource inter-activity utilization efficiency is contrasted in Figure 3.13.

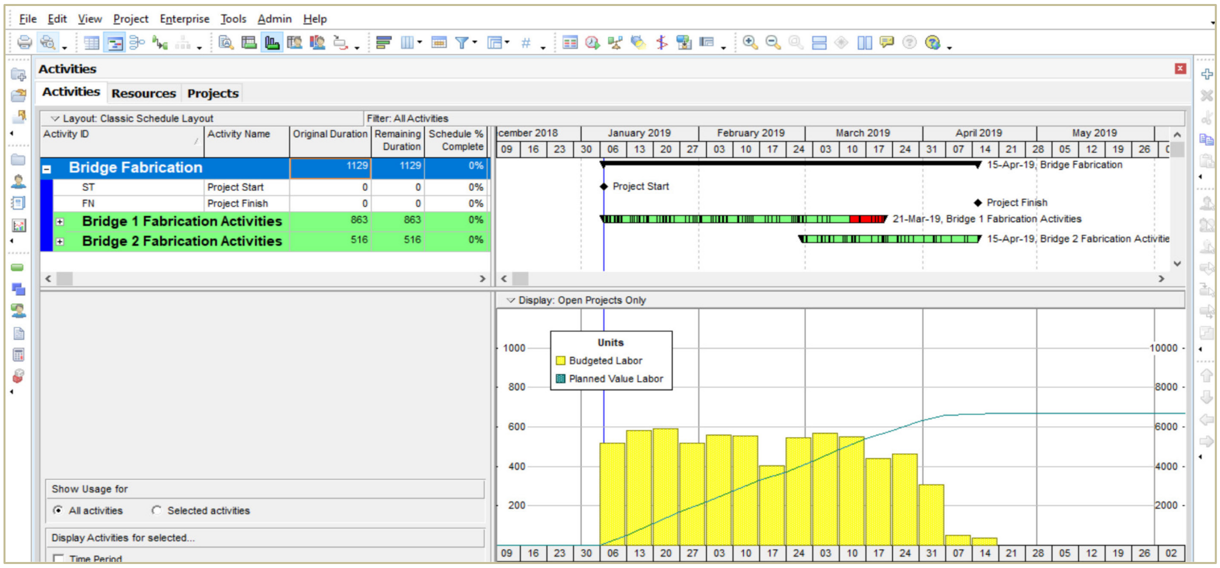


Figure 3.12. Labour-hour budgeting for the two-bridge project in P6.

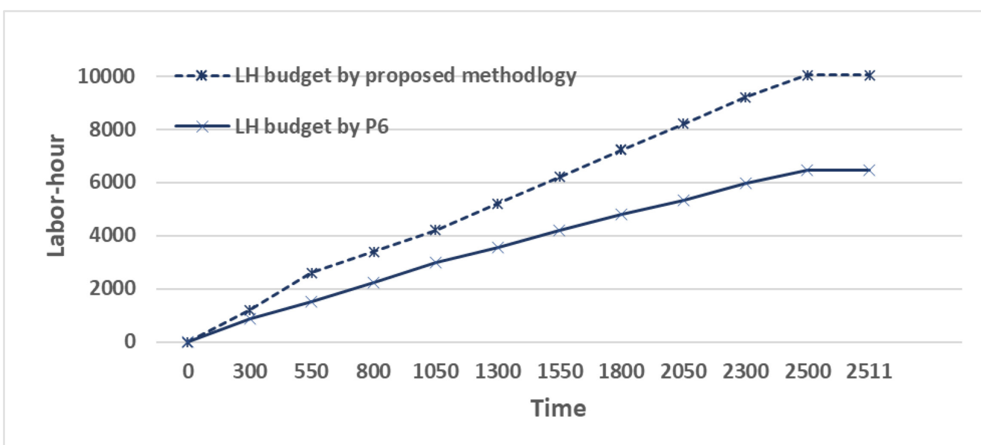


Figure 3.13. Journeyman budgeting with P6 compared with the proposed method for two-bridge project (Scenario 6).

3.5 Further Discussion

Given the same problem definition to analyze the semi-productive labour-hours, this lays the basis for further analyses in connection with labour productivity performance that enables potential performances improvement and optimization in the project planning stage. Accordingly, the journeymen's semi-productive hours can be used to further illustrate the formulation of the resource inter-activity utilization efficiency optimization problem. The earliest possible start time of an activity according to the journeyman availability is equal to the early finish time of the preceding activity, as per Eq. 3.7. (For the first scheduled activity it is zero).

$$\mathrm{S}L_i^n = Early\ Fininsh\ Time_{(i-1)}^n \tag{3.7}$$

Where: $\mathrm{S}L_i^n$ is earliest start time activity *i* with respect to journeyman availability and *n* is the number of journeymen in the shop.

The earliest possible start time according to activity availability with consideration of technology constraint is the earliest date the activity could start if there are no constraints due to the journeyman availability (Eq. 3.8)

$$\mathrm{S}A_i^n = Scheduled\ Fininsh\ Time_{(i-1)}^n \tag{3.8}$$

Where: SA_i^n is earliest start time of activity i with respect to only technology constraints.

Since activity cannot start until its predecessor has finished or until all the required journeymen working on the activity are available, the earliest start time for each activity is set as the latest of SA_i^n and SL_i^n (Eq. 3.9).

$$\text{Early Start Time}_i^n = Max\ (SL_i^n, SA_i^n) \tag{3.9}$$

For activity *i*, if the earliest start time according to technology-constrained precedence relationships, *SA*, is later or equal to the earliest start due to journeyman availability, *SL*, the activity could start immediately. If the earliest start time, *SA,* is earlier than the earliest start due to journeyman availability, *SL*, then the activity would not have proceeded until the journeyman has finished working on the previous task (Eq. 3.10). At any point of time, the number of journeymen engaged in ongoing activities deducted from the total number of journeymen results in the number of journeymen being idle according to Eq. 3.11.

$$ASD_i^n = \begin{cases} SL_i^n - SA_i^n & if\ SL_i^n > SA_i^n \\ 0 & if\ SL_i^n \leq SA_i^n \end{cases} \text{journeyman } Idle_i^n \tag{3.10}$$

$$\text{Journeyman}Idle_i^n = Total \text{ journeymen} - JRAy_i^n \tag{3.11}$$

Where: ASD_i^n is activity semi-productive duration and $JourneymenIdle_i^n$ is idle number of journeymen for activity *i* and JRA_i^n is journeyman required for activity *i*. Therefore, journeymen's semi-productive hours (JIH) under the above constraints is calculated according to Eq. 3.12, given the "*n* journeyman available" scenario.

$$JIH = \sum_{1}^{i} (\text{Journeyman } Idle_{i-1}^{n}) \times \text{ASD}_{i}^{n} \tag{3.12}$$

The quantity of journeymen which is required for performing a particular fabrication activity depends on its work content. Generally, the location of machines is fixed at particular working zones in the fabrication shop, named *workstation*. In contrast, the journeymen move between the workstations to handle different activities belonging to multiple bridge projects simultaneously.

3.6 Summary

In general, when applying Critical Path Method (CPM) scheduling under resource constraints, the derived budget does not consider the efficiency of crew formation as Critical Path Method (CPM) methodology is not able to account for resource schedule details. At best, seasoned schedulers would apply a budget scale factor based on experience in order to compensate for such impact, which is essential to follow the "rule of thumb" without applying scientific rigor. This research addresses a resource-constrained scheduling and cost budgeting problem in the practical context of planning labour intensive construction projects. The research essentially improves the baseline in Earned Value Management (EVM) by developing a more realistic S-curve for planned value calculation. In particular, productivity study is integrated with project scheduling and budgeting in evaluating the effect of semi-productive labour time on the budgeted cost for work scheduled (BCWS) S-curve curve, which is the baseline for earned value analysis in cost control. A new efficiency factor called *Resource Inter-Activity Utilization Efficiency* is defined in order to quantitatively investigate the impact of semi-productive time resulting from the crew formations and labour allocation in project planning.

In contrast with the Critical Path Method (CPM)-based solution, the scheduling simulation approach is capable of accounting for the sequence of executed activities for each individual resource. By running a simulation model and examining results for different what-if scenarios, the effect of varying crew size or activity sequencing upon project labour cost budget can be revealed in an analytical way.

It is emphasized that the applied simulation methodology is discrete-event simulation (DES) without random sampling or Monte Carlo. This research addresses project planning, labour resource planning and labour cost budgeting at the pre-construction bidding stage, with emphasis on investigating the impact of semi-productive work hours in developing labour intensive project labour cost budgets (i.e., S-curve). The randomness of the duration in simulation modeling can be an extension in the future, given sufficient input data is available. In fact, this feature can be readily implemented in the simulation tool (S3) by updating activity time input models to statistical distributions. Additionally, when the problem is scaled up in size and complexity, applying Excel would be cumbersome and practically infeasible. This is actually an advantage of discrete-event simulation: the computer automatically sorts hundreds of thousands of critical events scheduled in the timeline.

Finally, this research did not compare all the possible resource-allocation scenarios or analytically optimize the solution in the presented case studies. Instead, only limited feasible alternatives were compared to identify the best scenario among them in terms of the lowest labour-hour budget.

CHAPTER 4

Analyzing Impact of Semi-productive Work Hours in Scheduling and Budgeting Labour intensive Projects: Simulation-based Approach

This research investigates labour productivity based on resource-constrained project scheduling simulation models in order to render analytical decision support in planning crew size and worker-activity allocation for steel girder fabrication projects. In the dynamic environment of a structural steel fabrication facility, each labourer (journeyman) is part of teams temporarily formed at particular workstations to conduct various material-handling and connection activities. Discrete-event-simulation-based resource-constrained scheduling analysis is instrumental in analyzing semi-productive work hours resulting from labour transferring between activities and crew matching. In the case study, semi-productive work hours can be lowered from about one half of the total working time to a third by fine-tuning the crew size and work sequencing based on the simulation model, thereby resulting in enhancements on the time and cost performances of the entire project.

4.1 Introduction

Economists define productivity as the ratio between total input of resources and a total output of product; while project managers and construction professionals interpret productivity as a ratio between earned work hours and expended work hours (Hanna et al. 2005). For the current research, labour productivity is defined as the ratio between completed earned work hours and expended work hours to execute a labour intensive project. Measurement of labour productivity in the construction industry is a complicated undertaking. Ongoing research efforts aim to devise cost-effective data collection and analysis programs to improve such capabilities (Haas et al. 1999; Goodrum et al. 2002). Construction productivity is generally measured at different levels (e.g., company, project and activity) and for different purposes (Park et al. 2005). For detailed estimating and project scheduling, productivity is measured at an activity level. Industrial construction is labour intensive due to the substantial number of components in handling and connection activities (such as welding); measuring and analyzing productivity at the activity level generally entails the collection of work hours data (Dozzi and AbouRizk 1993).

Work hours are essentially categorized into working time versus non-working time. Labourer's working time consists of productive time and semi-productive time. It is noteworthy that semi-productive time is essentially required to support the productive labour time, such as checking the instructions and getting ready prior to the next activity. Nonetheless, semi-productive time that is irregular or excessive could also impair labourer's morale by causing work interruptions, frequent adjustments in crew makeup and "stop-and-go" operations, resulting in productivity loss (Hanna et al. 1999). In industrial construction like steel girder fabrication featuring frequent labour transferring between different workstations in the finite dynamic shop space, semi-productive times occur more irregularly during the operation, which is generally infeasible to measure precisely in the current practice. Hence differentiating the semi-productive labour time from productivity labour time based on actual job cost data is too cumbersome to be practical in labour intensive operations. In this study, steel girder fabrication projects subject to resource availability and transfer constraints are modeled by a simulation tool in order to logically undertake project execution processes in sufficient details, while enabling quantitative analysis of the semi-productive labour time. By examining different crew sizes and different plans for crew allocation to activities based on resource scheduling simulation, this research is intended to determine the semi-productive work hours in a quantitatively reliable way and increase labour productivity by minimizing the semi-productive time. Ultimately, the present research is to prove the hypothesis that a reduction on the semi-productive labour time enhances time and cost performances in delivering the whole project at the end.

4.2 Literature Review

4.2.1 Productivity in Construction

In productivity studies, the percentage of worker's productive time relative to the total time the person is involved in an operation is defined as labour efficiency (Dozzi and AbouRizk 1993). Hanna (2010) defined productive time as value-added operation time. Accordingly, the more productive the labourers are, the more value-added operation time generated out of the total time the labourers are involved in an operation, which results in higher labour productivity.

In general, workers' operation time classifies into working and non-working time (Figure 4.1(a)). As per Figure 4.1(b), working time consists of productive (direct work) and semi-productive time (support work). In labour intensive work, semi-productive time is an activity that does not directly add value to making the components but is generally required in running the operation, which is essentially associated with the time of labourers transferring between activities, setting up, mobilizing, getting ready prior to the next activity (locating materials, confirming drawings, checking safety) (Dozzi and AbouRizk 1993; Oglesby et al. 1989; Haas et al. 2017). Notably, the non-working time is generally considered non-productive operation time representing the worker's resting time, coffee breaks, and lunch breaks etc. The non-working time can be interpreted as 10 min or 15 min time in an hour (as shown in Figure. 4.1(a)) that workers take a break to adjust physical and mental states prior to resuming work, which is vital to maintain productivity and safety over working time (Folkard and Tucker 2003; Dababneh et al. 2001).

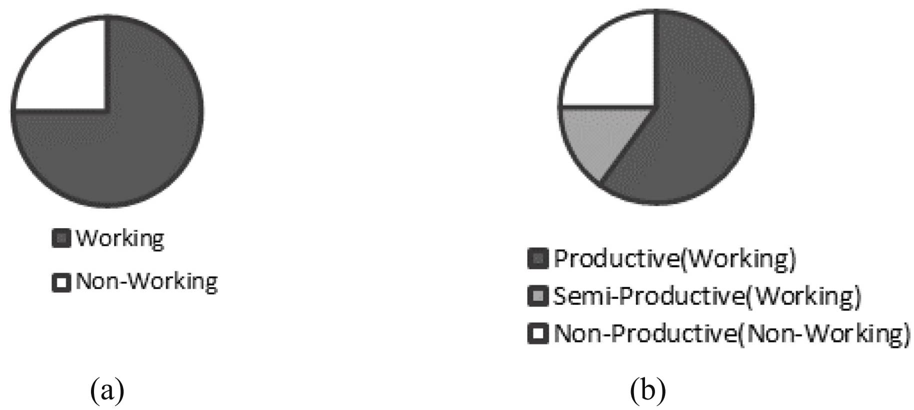


Figure 4.1. (a) Working vs. non-working; (b) productive, semi-productive and non-productive work hours.

A significant body of labour productivity research has been conducted in the past, which attempts to increase the productive labour time. Thomas (2000) analyzed how productive labour time was affected by the disruption of workflow resulting from schedule acceleration, and proposed matching of the labour resource to the amount of work available to perform, so as to maximize labour productivity. Gong et al. (2011) applied labour time utilization assessment methods, such as work sampling and five-minute rating. They found a statistically significant difference in crew utilization efficiency across different types of activities as well as in activities with various crew sizes (i.e., small, medium, and large). Other studies investigated the impact of change orders and reworks (Thomas and Napolitan 1995; Watkins et al. 2009; Hanna et al. 1999), workspace congestion (Thabet and Beliveau 1994) and shift work (Hanna et al. 2008) on productive labour time. Quantitative methods have been used in productivity-related research to analyze the relationships between a wide range of relevant factors and productivity rates. Researchers have presented various analytical models to forecast labour productivity in construction (Thomas and Sakarkan. 1994; Smith 1999; Fayek and Oduba 2005; Lu et al. 2000; Nasirzadeh and Nojedehi 2013). These models took advantage of various modeling techniques, including operation simulation, artificial intelligence, expert systems, factor models, regression and artificial neural networks. Despite significant research in the literature concerning the productive labour time, few studies have attempted to quantitatively model the impact of activity-specific factors upon semi-productive labour time, including number of crew size, crew matching and labour flow efficiency between different activities.

In this study, considering the non-productive portion (white) is fixed, the objective for productivity improvement is specifically set to increase the productive labour time percent proportion (dark grey) by reducing the semi-productive labour time percent proportion (light grey) (Figure 4.1(b)). Particularly, by examining various numbers of crew size and different labour allocation plans, which results in changes in activity sequencing, the semi-productive time will be reduced. As result, the hypothesis that time and cost performances of the whole project are enhanced by reducing the semi-productive labour time is validated in the end.

4.2.2 Operations Simulation in Construction

Due to the complexity involved in most construction projects, simulation is frequently taken as the appropriate —and sometimes the only possible— analytical tool to address issues and solve problems in construction operations (Martinez 2010; AbouRizk 2010). The functionalities of simulation tools to represent interdependencies between operations, use of resources, and routing subject to uncertainties make them suitable for modeling industrial construction processes.

Computer simulation also allows quick modification of major project parameters for the purpose of analyzing different options for optimization without the need to conduct real-life experimentation. Among different simulation-based techniques, discrete-event simulation has been used in most simulation-related research efforts to model and improve construction operations (Martinez 2010).

Simulation models have been developed in a certain resolution of details for different purposes and from different perspectives in order to serve the needs for decision support by different function managers at various stages of project development. For instance, Hasan et al. (2019) applied discrete-event simulation for simulating the steel girder fabrication shop from the perspective of the production manager on the shop floor; the simulation model accounted for sufficient details in time and logic in labourers' work steps, aimed to generate a well-structured workface plan. In contrast, this research is mainly concerned with improving the cost and time performance of project delivery. Hence, the steel girder fabrication process is simulated from the perspective of the project planner and scheduler in efforts to produce an efficient resource job allocation plan leading to higher productivity in handling multiple concurrent fabrication projects.

In previous research, a resource scheduling simulation methodology called Simplified Scheduling Simulation (S3) had been developed based on the Simplified Discrete-Event Simulation Approach (SDESA) (Lu et al. 2008). S3 is used as the simulation tool for planning project execution subject to labour availability and transfer constraints, facilitating the determination of productive and semi-productive work hours in the application context of labour intensive steel girder fabrication projects in bridge construction. S3 automatically adjusts activity execution sequences so as to simultaneously accommodate both technology and resource constraints on the project. It allows for visualizing and analyzing the utilization of individual resources on specific activities over a particular time period of project duration.

The present research used S3 as a resource schedule simulation tool to produce a valid project schedule along with the corresponding labour allocation plan, which provides input to determine the time and cost of the project and generate the associated project execution plan. It enables the analysis of productive and semi-productive labour work hours by examining the implications of different crew sizes and labour allocation schemes subject to inter-activity technological constraints.

4.2.3 Steel Girder Fabrication Shop

An industrial fabrication facility (such as a steel girder fabrication shop) resembles a factory in manufacturing in that jobs from different clients and projects are simultaneously performed subject to the space and resource constraints of the shop. labour resources such as journeymen are employed to process made-to-order products from different projects. Each journeyman is part of teams that are temporarily formed to conduct a wide range of material-handling and connection activities such as cutting, welding, and splicing at different workstation locations in a fabrication shop.

In consideration of the complicated labour interactions in concurrent execution of multiple projects— given the finite limits of labour resources and space available in a fabrication shop, as well as a multitude of complex inter-related factors affecting labour productivity—using simulation tools is justifiable for analyzing the semi-productive labour time on steel girder fabrication projects.

4.3 Overview of Case Study

As the main structural component in a typical highway bridge, a steel girder consists of (1) one web, (2) two flanges (the top flange and the bottom flange) which are connected perpendicularly to the web plate, (3) stiffeners which are fitted perpendicularly into the web and the flanges, and are used to prevent web buckling at supports or under concentrated loads, and (4) shear studs that are generally attached to the top flanges of girders to ensure shear connections between steel and concrete and prevent relative motions in both vertical and horizontal directions. In one girder, the horizontal flanges resist the bending movement, while the web resists the shear stress (Krause 2015). Figure 4.2 depicts a typical girder finished with key features annotated.

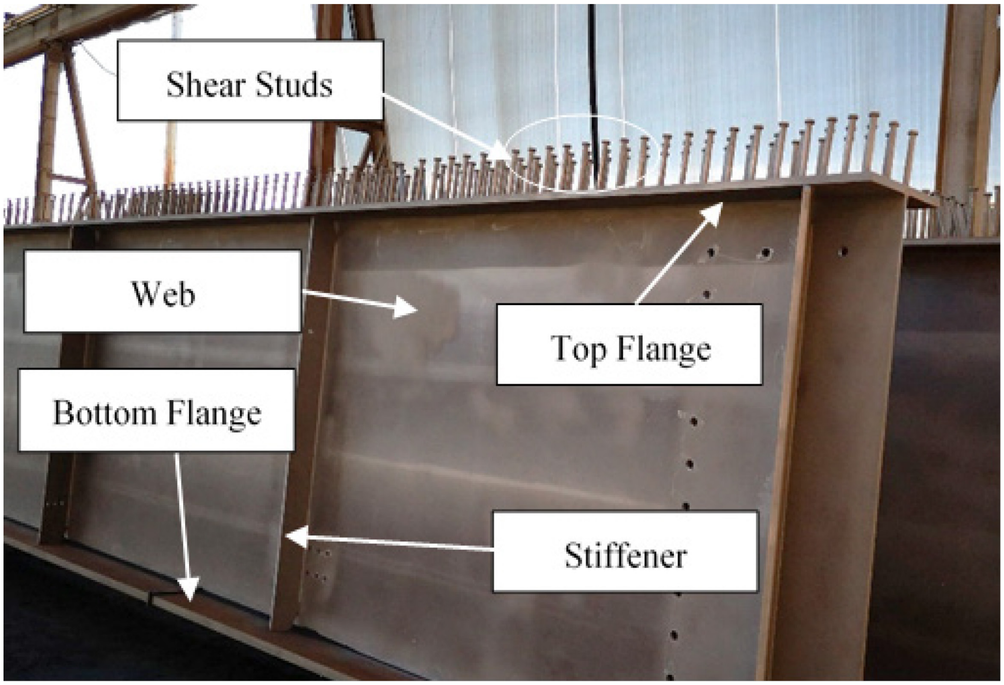


Figure 4.2. Finished girder ready for shipping.

To reach the designed bridge span, girders are spliced together on-site to form a girder line, and girder lines are arranged in parallel in a bridge engineering design. In practice, one project consists of multiple girder lines; each girder line is made up of several girders. In the fabrication shop, raw steel plates are processed through a series of operations: (1) flange cutting (flange preparation), (2) flange straightening (flange preparation), (3) flange splicing (flange preparation), (4) web splicing (web preparation), (5) assembling girder by fitting and welding flanges to the web (6) girder welding, (7) studs and stiffeners fitting and welding, (8) girder splicing, (9) sandblasting and finishing (See Figure 4.4). The work breakdown definition in terms of associated activity list for girder fabrication of two bridges is based on a real case originally developed by Liu and Lu (2020). Two of the three bridges are used in the current case study, with the configuration of girders shown in Figure 4.3. Resource limit, workstation-based fabrication activities, duration of each activity, precedence relationships, and required resources are given in Table 4.1 and Table 4.2 for two selected girders (G1A and G1B) of Bridge 1. Based on design features of a girder including the girder length, girder depth, shape, web thickness, and the number and type of stiffeners attached to the girder, the girders are classified into A, B, C, D and E design types. In total, the twenty-one girders of two bridge projects are considered, as shown in Figure 4.3, resulting in the definition of two hundred forty-six fabrication activities with over one hundred technology constrained precedence relationships. In addition, over one hundred resource-constrained precedence relationships can be further imposed due to resource flows and resource links.

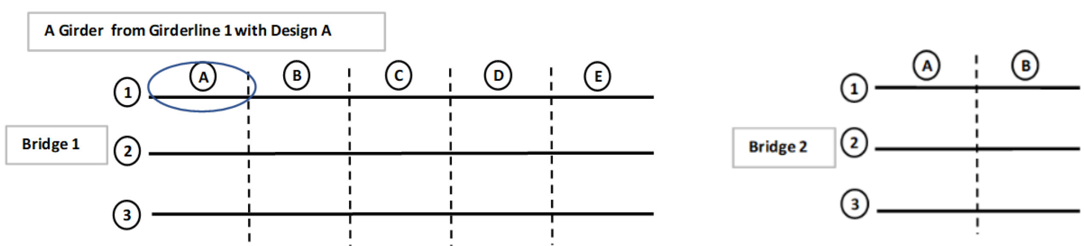


Figure 4.3. Engineering design of Bridge 1 and Bridge 2.

The Work Breakdown Structure (WBS) of Bridge 2 is designed from the perspective of a project planner in practice, given as per Figure 4.4 Note, the cutting flanges process is separated into two activities relevant to bottom and top cutting flanges for each girder. In a similar way, straightening and splicing activities are defined.

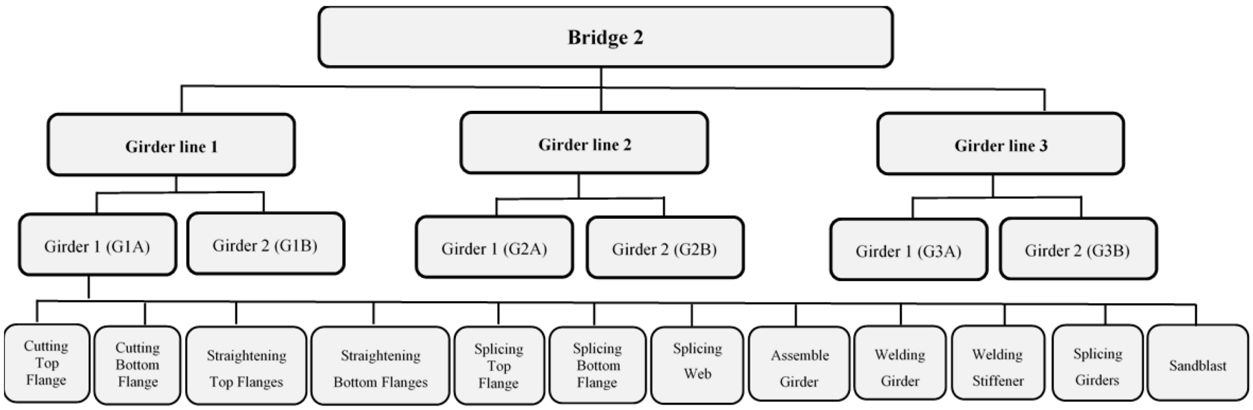


Figure 4.4. WBS of Bridge 2 project.

Table 4.1. Resource limit for steel bridge fabrication project.

Resource ID	Resource Type	Limits
1	Flange cutting station	1
2	Flange straightening station	1
3	Flange splicing station	1
4	Web splicing station	1
5	Girder assembly station	1
6	Girder welding station	2
7	Stiffener welding station	2
8	Girder splicing station	2
9	Sandblast station	3
10	Journeyman	6

It is important to note that the number of required journeymen varies over time when processing a particular girder at specific workstations. On the one hand, journeymen are resources shared between different workstations; on the other hand, all the workstations and journeymen are resources shared between the two projects.

Table 4.2. Fabrication activity list for girder line G1 of Bridge 1

ID	Task Name	Dur. (hrs.)	Precedence Relationships	Resources
	G1A Fabrication			
3	Cutting Top Flanges	8		2 JM, 1 flange cutting station
4	Cutting Bottom Flanges	8	3	2 JM, 1 flange cutting station
5	Straightening Top Flanges	8	4	2 JM, 1 flange straightening station
6	Straightening Bottom Flanges	8	4,5	2 JM, 1 flange straightening station
7	Splicing Top Flange	18	5	1 JM, 1 flange splicing station
8	Splicing Bottom Flange	18.	6,7	1 JM, 1 flange splicing station
9	Splicing Web	15.25.		2 JM, 1 web splicing station
10	Assemble Girder	20.25.	8,9	3 JM, 1 girder assembly station
11	Welding Girder	11	10	2 JM, 1 girder welding station
12	Welding Stiffener	54.1	11	2 JM, 1 stiffener welding station
13	Sandblast	10.5	12,25	2 JM, 1 sandblast station
	G1B Fabrication			
15	Cutting Top Flanges	8	4	2 JM, 1 flange cutting station
16	Cutting Bottom Flanges	8	15	2 JM, 1 flange cutting station
17	Straightening Top Flanges	8	15	2 JM, 1 flange straightening station
18	Straightening Bottom Flanges	8	16,17	2 JM, 1 flange straightening station
19	Splicing Top Flange	18	17	1 JM, 1 flange splicing station
20	Splicing Bottom Flange	18	18,19	1 JM, 1 flange splicing station
21	Splicing Web	15.25	9	2 JM, 1 web splicing station
22	Assemble Girder	20.25	20,21	3 JM, 1 girder assembly station
23	Welding Girder	11	22	2 JM, 1 girder welding station
24	Welding Stiffener	41.2	23	2 JM, 1 stiffener welding station
25	Splicing Girder G1A & G1B	13.75	12,24	1 JM, 1 girder splicing station
26	Sandblast	10.5	25,38*	2 JM, 1 sandblast station

4.4 Simulation Modeling

4.4.1 S3-SDESA Simulation Model

The S3 model was developed to schedule all the shop fabrication activities of Bridge 1 and Bridge 2 according to the resource use constraints and resource availability constraints; note by the algorithms underlying S3, activity start time is delayed until (1) the required resources are available, and (2) other specified logical constraints are satisfied. Execution of the S3 schedule simulation model under imposed resource constraints led to a total project duration of 2206 hours. Simulation logic was then verified by tracing step-by-step process details and the resulting schedule was further validated by domain experts involved in the partner company.

4.4.2 Simulation Model Variables and States

In a SDESA simulation model, resource entities are classified into non-disposable (manpower/machinery resources) and disposable resources, which are material or information units that are generated by one activity and requested by another as dictated by the logic of the problem being simulated (Lu 2003; Lu et al. 2007). Resources of both types constitute resource-availability constraints in matching resources for invoking activities in a SDESA simulation model. All resources are organized and dynamically updated in the resource-entity queue of the model (Figure 4.5). It is noteworthy that SDESA uses disposable resources to logically connect multiple workflows in a construction system. SDESA also initializes the type and quantity of resources available in the resource pool of the simulation model. Each resource has the attributes of the resource entity's ID (automatically assigned by the simulation executive); resource name, serving activity, ready to serve time (RTS), begin and end time of serving, and description. Figure

4.5 shows relevant resources and their attributes for the first forty-two hours of two-bridge girder fabrication.

The SDESA model also shows flow entities associated with each workflow in a diamond block (note a workflow consists of one or multiple activities), as shown Figure 4.7. In contrast with resource entities, flow entities do not have physical attributes to define and distinguish them. A flow entity is associated with a time stamp to track their attributes of begin, end and waiting times at activities. For the case of the two-bridge project, Figure 4.6 shows the flow entities and their attributes for the first one hundred and sixty hours of the two-bridge girder fabrication process. The attributes of the “ready to serve” time, “begin” and “end” time of the resources reflect the status of the system, which is continuously traced and dynamically updated as simulation proceeds. In short, by managing the two dynamic queuing structures (namely, the flow entity queue and the resource entity queue), the SDESA executive program advances the simulation clock and executes activities that have satisfied the logical and resource-availability constraints as specified by the modeler in the network diagram model.

Run	ResID	Resource	Ac...	Activity	RST	Begin	End	Idle
1	1	Journyman_1	1	G1A-CTF-Br1	0.00	0.00	8.00	0.00
1	2	Journyman_2	1	G1A-CTF-Br1	0.00	0.00	8.00	0.00
1	7	Flange cutting Station_1	1	G1A-CTF-Br1	0.00	0.00	8.00	0.00
1	22	G1A-CTF-Br1-Finish	2	G1A-Cutting Bottom Flanges-Br1	8.00	8.00	16.00	0.00
1	3	Journyman_3	2	G1A-Cutting Bottom Flanges-Br1	0.00	8.00	16.00	8.00
1	4	Journyman_4	2	G1A-Cutting Bottom Flanges-Br1	0.00	8.00	16.00	8.00
1	7	Flange cutting Station_1	2	G1A-Cutting Bottom Flanges-Br1	8.00	8.00	16.00	0.00
1	23	G1A-Cutting Bottom Flanges-Br1-Finish	3	G1A-Straightening Top Flanges -B...	16.00	16.00	24.00	0.00
1	5	Journyman_5	3	G1A-Straightening Top Flanges -B...	0.00	16.00	24.00	16.00
1	6	Journyman_6	3	G1A-Straightening Top Flanges -B...	0.00	16.00	24.00	16.00
1	8	Flange Straightening Station_1	3	G1A-Straightening Top Flanges -B...	0.00	16.00	24.00	16.00
1	24	G1A-Cutting Bottom Flanges-Br1-Finish	4	G1A-Straightening Bottom Flange...	16.00	24.00	32.00	8.00
1	25	G1A-Straightening Top Flanges -Br1-Fi...	4	G1A-Straightening Bottom Flange...	24.00	24.00	32.00	0.00
1	1	Journyman_1	4	G1A-Straightening Bottom Flange...	8.00	24.00	32.00	16.00
1	2	Journyman_2	4	G1A-Straightening Bottom Flange...	8.00	24.00	32.00	16.00
1	8	Flange Straightening Station_1	4	G1A-Straightening Bottom Flange...	24.00	24.00	32.00	0.00
1	26	G1A-Straightening Top Flanges -Br1-Fi...	5	G1A- Splicing Top Flange -Br1	24.00	24.00	42.00	0.00
1	9	Flange Splicing Station_1	5	G1A- Splicing Top Flange -Br1	0.00	24.00	42.00	24.00
1	3	Journyman_3	5	G1A- Splicing Top Flange -Br1	16.00	24.00	42.00	8.00

Figure 4.5. Resource entity queue for the first forty-two hours of the two-bridge fabrication process.

Run	EntID	Entity	ActID	Activity	Arrival	Begin	End	Wait
1	1	F-G1A-CTF-Br1_1	1	G1A-CTF-Br1	0.00	0.00	8.00	0.00
1	2	F-G1A-Cutting Bottom Flanges-B...	2	G1A-Cutting Bottom Flanges-Br1	0.00	8.00	16.00	8.00
1	3	F-G1A-Straightening Top Flanges ...	3	G1A-Straightening Top Flanges -B...	0.00	16.00	24.00	16.00
1	4	F-G1A-Straightening Bottom Flan...	4	G1A-Straightening Bottom Flange...	0.00	24.00	32.00	24.00
1	5	F-G1A- Splicing Top Flange -Br1_1	5	G1A- Splicing Top Flange -Br1	0.00	24.00	42.00	24.00
1	6	F-G1A-Splicing Bottom Flange -B...	6	G1A-Splicing Bottom Flange -Br1	0.00	42.00	60.00	42.00
1	7	F-G1A-Splicing Web-Br1_1	7	G1A-Splicing Web-Br1	0.00	32.00	47.00	32.00
1	8	F-G1A-Assemble Girder-Br1_1	8	G1A-Assemble Girder-Br1	0.00	60.00	80.00	60.00
1	9	F-G1A-Welding Girder-Br1_1	9	G1A-Welding Girder-Br1	0.00	80.00	91.00	80.00
1	10	F- G1A-Welding Stiffener-Br1_1	10	G1A-Welding Stiffener-Br1	0.00	91.00	145.00	91.00
1	12	F-G1B-Cutting Top Flanges-Br1_1	12	G1B-Cutting Top Flanges-Br1	0.00	91.00	99.00	91.00
1	13	F-G1B-Cutting Bottom Flanges-Br...	13	G1B-Cutting Bottom Flanges-Br1	0.00	99.00	107.00	99.00
1	14	F-G1B-Straightening Top Flanges-...	14	G1B-Straightening Top Flanges-Br1	0.00	107.00	115.00	107.00
1	15	F-G1B-Straightening Bottom Flan...	15	G1B-Straightening Bottom Flange...	0.00	115.00	123.00	115.00
1	16	F-G1B-Splicing Top Flange-Br1_1	16	G1B-Splicing Top Flange-Br1	0.00	123.00	141.00	123.00
1	17	F-G1B-Splicing Bottom Flange-Br...	17	G1B-Splicing Bottom Flange-Br1	0.00	141.00	159.00	141.00
1	18	F-G1B-Splicing Web-Br1_1	18	G1B-Splicing Web-Br1	0.00	145.00	160.00	145.00

Figure 4.6. Flow entities and their attributes for the first hundred and sixty hours of two-bridge fabrication process.

The SDESA model for the girder fabrication of Bridge 1 and Bridge 2 consists of two hundred forty-six activities, and three of them are given as sample in Figure 4.7. G1A- Br1 is a girder of type A in girder line 1, Bridge 1; JM refers to journeyman, FSS means Flange Splicing Station and FStS is Flange Straightening Station.

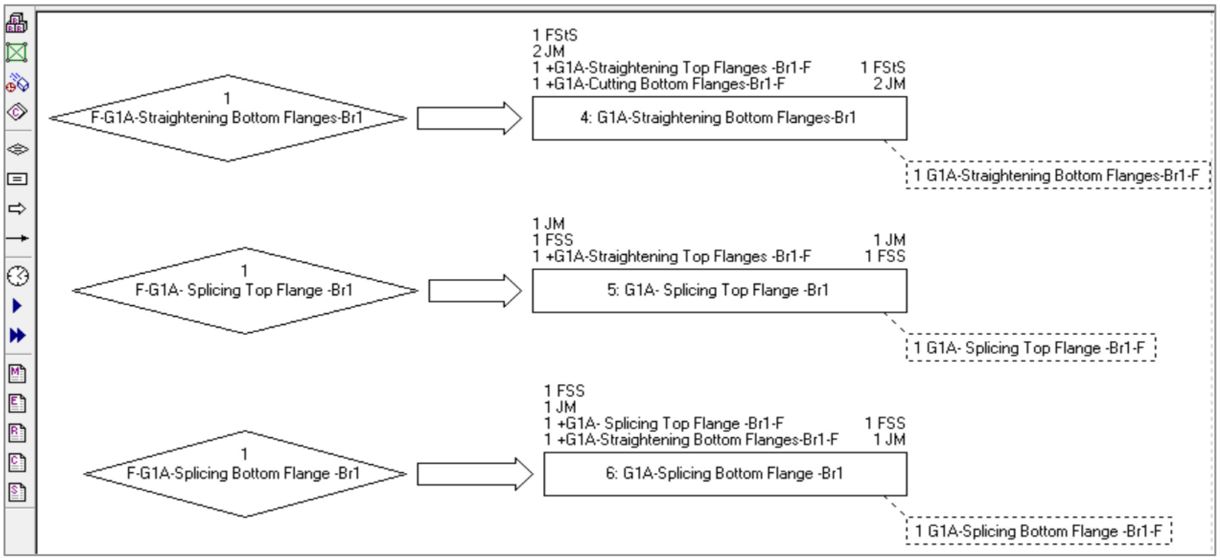


Figure 4.7. Three activities of SDESA simulation model for Girder1A Bridge 1.

Activity "G1A-Straightening button flange-Br1" requires two types of non-disposable resources (two journeymen and one flange straightening station) and two disposable resources (namely: one unit of G1A-straightening top flange-Br1 and one unit of G1A cutting top flange-Br1). This implies the logic: for performing the "G1A-Straightening button flang-Br1", the two activities "G1A-straightening top flange" and "G1A cutting top flange" need to be completed prior to executing the activity "G1A-Straightening button flang-Br1"; while two journeymen and one flange straightening station need to be available to execute this activity. SDESA also allows for visualizing and analyzing the utilization of individual resources on specific activities over the project duration. Resource-activity allocation scheme, total productive, semi-productive hours that resources have spent over the project execution can be found in the resource summary report. The main features of the S3-SDESA tool that is used in this study include the journeyman activity allocation bar chart and the total productive and semi-productive hours for the journeyman, as shown in Figure 4.8.

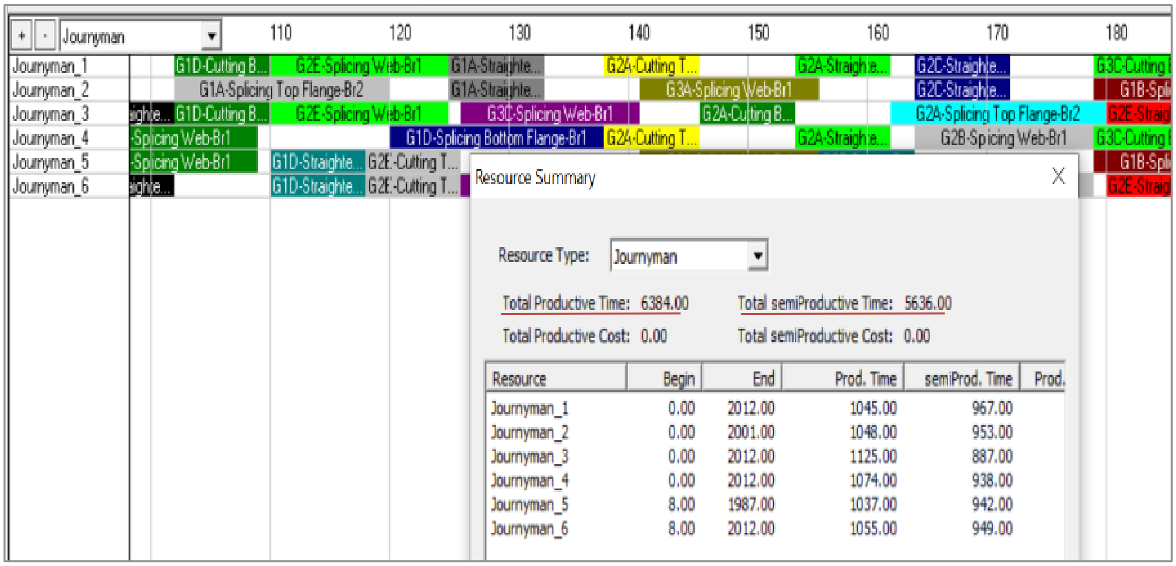


Figure 4.8. Journeymen activity allocation scheme and resource summery window for all journeymen in two-bridge fabrication process.

4.5 Discussion of Simulation Results

When allocating the limited number of journeymen to girder fabrication processes, resource activity allocation sequencing could differ dependent on the journeyman allocation order, given no technological or logical constraints are violated. In other words, given the same Activity-On-Node (AON) network, different activity sequencing for individual workers could be developed for the two-bridge project. Figure 4.9 illustrates three different sequencings for the ninety hours of the case study.

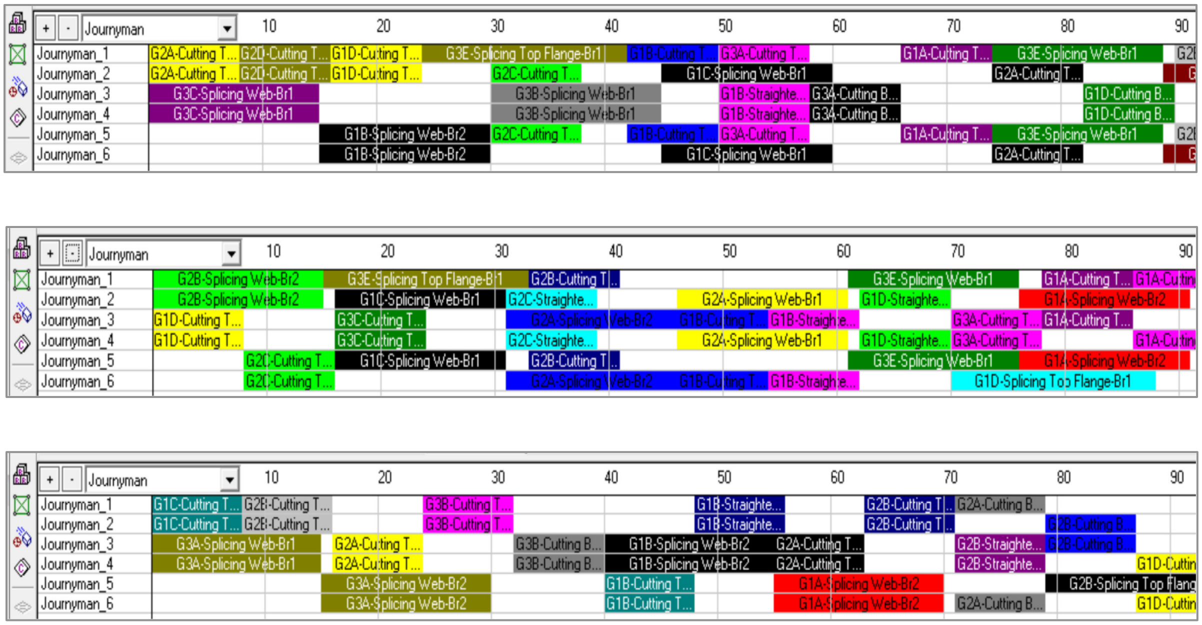


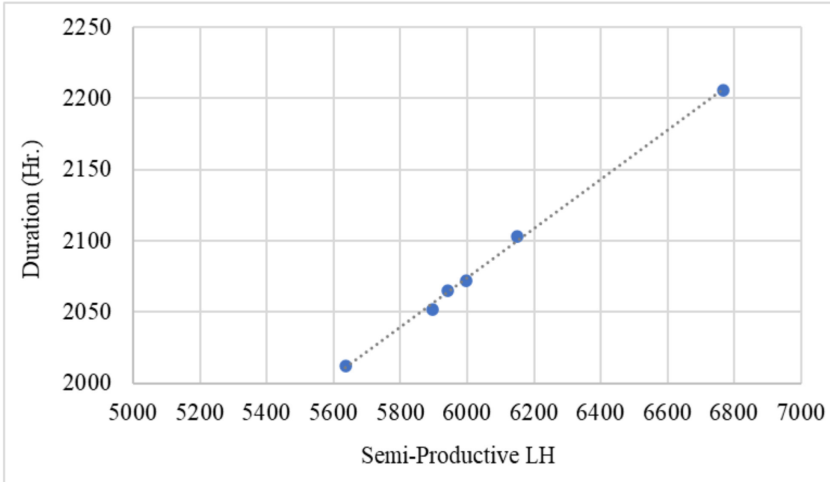
Figure 4.9. Different activity sequencing examples for the first ninety hours of the two-bridge project.

Six different resource activity allocation sequencing options of the two-bridge project (given the same AON network) are simulated, and the results of project duration, journeymen semi-productive hours, semi-productive versus productive hours ratio and total cost (labour-hours) presented in Table 4.3.

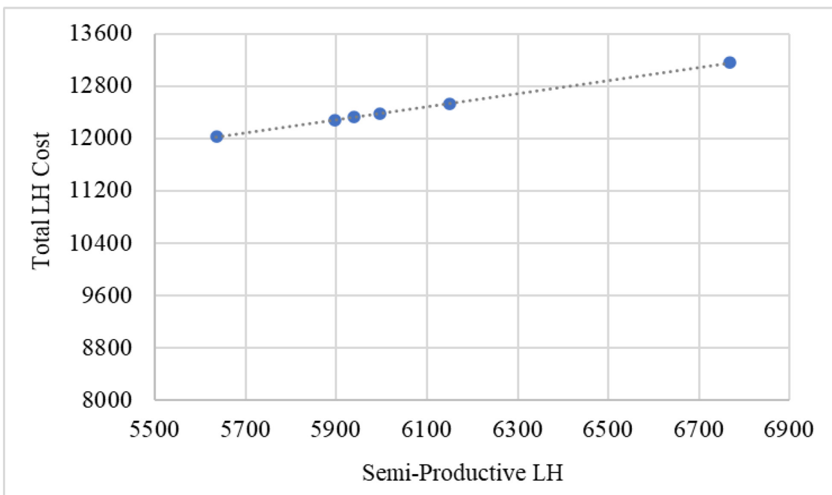
Table 4.3. Journeyman utilization rate in different scenarios for the crew size of six journeymen.

Scenario	Sequencing Option	Duration (Hr.)	Semi LH	Semi-Prod. Vs Prod. Ratio	Total LH Cost
1	6 (Seq. 1)	2206	6768	52: 48	13152
2	6 (Seq. 2)	2103	6150	49: 51	12534
3	6 (Seq. 3)	2072	5996	48.4: 51.6	12380
4	6 (Seq. 4)	2065	5940	48.2: 51.8	12324
5	6 (Seq. 5)	2052	5896	48: 52	12280
6	6 (Seq. 6)	2012	5636	47: 53	12020

To examine the research hypothesis, semi-productive work hours against the total project duration and cost are plotted as a scatter diagram in Figure 4.10. Fitting a trending line to the results shows the semi-productive hours are positively correlated with total project labour-hour cost and project duration, respectively (as seen in Figure 4.10).



(a)



(b)

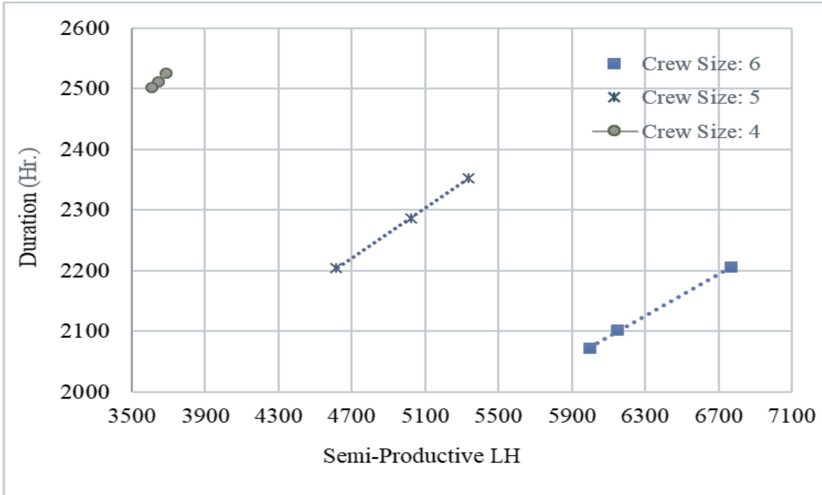
Figure 4.10. Positive correlation between the semi-productive hours and (a) project duration; (b) project total LH cost for Table 5.3 Scenarios.

Given certain resource activity allocation sequencing constraints, changing the number of journeymen (crew size) also results in different simulation scenarios. Results from simulation experiments for various crew sizes and different sequencing options are summarized in Table 4.4.

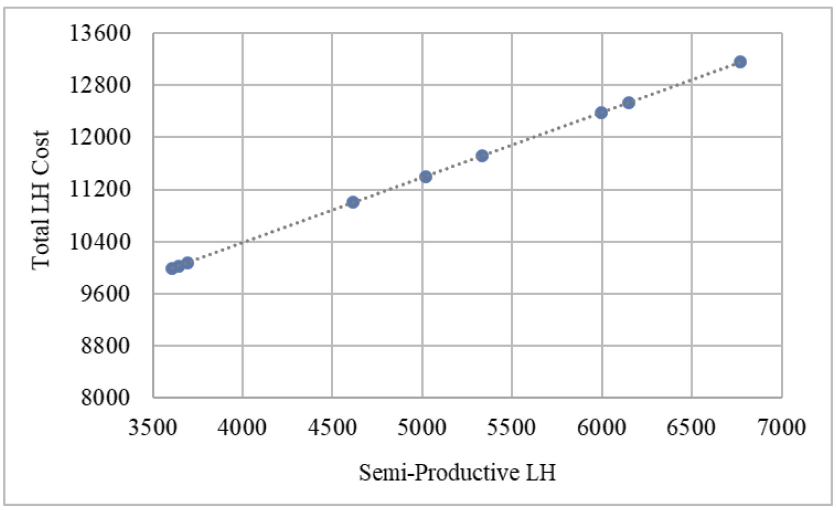
Table 4.4. Journeyman utilization rate in different scenarios.

Scenario	No. Journeyman (Crew Size)	Duration (Hr.)	Semi LH	Semi-Prod. Vs Prod. Ratio	Total LH Cost
1	6 (Seq. 1)	2206	6768	51:49	13152
2	6 (Seq. 2)	2103	6150	49:51	12534
3	6 (Seq. 3)	2072	5996	48:52	12380
4	5 (Seq. 1)	2352	5333	46:54	11717
5	5 (Seq. 2)	2286	5020	44:56	11404
6	5 (Seq. 3)	2205	4615	42:58	10999
7	4 (Seq. 1)	2526	3690	37:63	10074
8	4 (Seq. 2)	2511	3644	36:64	10028
9	4 (Seq. 3)	2502	3608	36:64	10002

The semi-productive hours are plotted against the total project duration and total labour-hour cost respectively, as presented in Table 4.4. It is found the semi-productive hours are positively correlated with the total labour-hours cost for all combinations of crew size and resource activity allocation sequencing scenarios for the two-bridge fabrication projects. It is also observed that the project duration increases as the semi-productive hours increase given different crew sizes (as seen in Figure 4.11).



(a)



(b)

Figure 4.11. Positive correlation between the semi-productive hours and (a) project duration; (b) Project total LH cost for Table 4 Scenarios.

Based on the simulated results in Table 4.3 and Table 4.4, it comes to the observation that as the semi-productive labour time to productive labour time ratio descreases, it results in better time and cost performances of the two-bridge project. In other words, the lower the semi-productive labour versus productive labour ratio, the more productive works are performed during labour working hours, meaning project performance improvement. By conducting this research, it is inferred semi-productive work hours can be lowered from about half of the total working time to a third by fine-tuning the crew size and work on the simulation model, which ultimatiely yields higher productivity, shorter project duration and a decrease in project cost.

CHAPTER 5

Optimization of Labour Flow Efficiency in Steel Fabrication Project Planning

This study considers projects that employ multiskilled labour resources in performing different tasks aimed at improving labour utilization efficiency. Based on field observation, the journeymen employed in a steel girder fabrication shop for bridge construction exemplify multiskilled labour resources in a practical setting. In particular, the need for crew transferring and waiting between various workstations on the shop floor gives rise to the bulk of semi-productive labour time. Unpredictable and unnecessary semi-productive working hours are considered a kind of waste as per lean principles. Increasing labour flow efficiency by properly allocating limited labour resources to project activities would reduce the semi-productive labour-hours while enhancing the labour flow reliability, leading to better productivity and leaner processes. *The Labour Flow Waste Index* (LFWI) is defined based on the determination of the semi-productive worker hours using resource-constrained project scheduling analysis. Further, the optimization problem of minimizing LFWI is formulated. A case study was conducted Utilizing Microsoft Excel Solver, resulting in significant decrease on the waste in labour resource flow.

5.1 Introduction

The cost escalation and low productivity are partially attributable to significant non-value-adding activities during construction processes, which are also categorized as *non-physical wastes* as per lean principles (Turner and Townsend 2019). Reducing non-physical wastes, therefore, is regarded as one essential task in the management of construction projects. In this regard, the lean concept is conducive to planning a production system so as to minimize or decrease waste in materials, time and effort (Koskela et al. 2002).

The application of lean construction is focused on avoiding various types of waste while emphasizing the importance of value creation. In essence, waste in lean construction is associated with the use of resources that do not add value to the final product (Khanh and Kim 2015; Bajjou et al. 2017). This implies that the efficiency of resource utilization and allocation in the flow of resources between activities for processing multiple jobs from different projects is associated with the amounts of non-value-adding efforts by resources involved.

In productivity studies, total labour efforts are classified into productive, semi-productive and non-productive activities (Dozzi and AbouRizk 1993). From the lean perspective, productive time is directly counted as value-adding activities in completing a specific scope of work (Hanna 2010), while the semi-productive labour time is considered as the value-enabling effort, which is indispensable in order to make it possible to perform value-adding activities (Moujib 2007). It is notable that semi-productive labour-hours do not directly add value to making the components but are generally required in support of the operation. In a fabrication shop, semi-productive hours are essentially associated with crews spending time in checking instructions, confirming specifications and drawings, reassuring safety measures, and getting ready prior to executing upcoming activities, which also include crew waiting time for matching resources like collaborating crew members or materials in process (Dozzi and AbouRizk 1993; Haas et al. 2017). The non-productive time (also known as the non-working time) in general represents worker's resting time, coffee breaks, and lunch breaks. Non-productive time is required to adjust physical and mental states of workers prior to resuming work which is vital to maintain productivity and safety over working time (Folkard and Tucker 2003; Dababneh et al. 2001). In industrial construction such as steel girder fabrication that requires frequent labour transfer between different workspaces, semi-productive time tends to occur irregularly during the operation time. Such irregular, unpredictable workers' hours give rise to non-value-adding efforts by causing operation interruptions and entailing frequent adjustment in crew makeups.

Previous studies emphasized the importance of labour productivity and efficient resource allocation on construction projects in addressing scheduling problems involving work efficiency. The majority of such research assumes activities are performed using single-skilled labour resources for a specified activity type, while neglecting multiskilling flexibility in assigning tasks in practice (Liu and Wang 2012). Multiskilling is defined as a labour utilization strategy in which workers possess a range of skills that are appropriate for more than one task to improve productivity, lower indirect costs and reduce turnover in construction (Burleson et al. 1998; Gomar et al. 2002). Research results also show that multiskilling can potentially increase productivity, resource work continuity, and quality of work (Burleson et al. 1998). Moreover, success in multiskilling depends on the foreman's ability to effectively form crews and assign multiskilled labour resources to proper tasks (Gomar et al. 2002). Therefore, this study considers projects that employ multiskilled labour resources in performing different tasks aimed at improving labour utilization efficiency. Based on field observation, the journeymen employed in a steel girder fabrication shop for bridge construction exemplify multiskilled labour resources in a practical setting.

In this research, considering the non-productive hours are relatively fixed (e.g., 10 minutes in an hour), the objective is to mitigate the semi-productive labour-hours in an attempt to reduce the non-value-adding labour efforts resulting from crew matching and transferring in employing multiskilled labour resources. In order to enhance productivity and resource utilization efficiency in a construction project, it is necessary to improve the labour resource allocation, which is closely correlated with the concept of *labour flow* between different activities in lean construction in terms of reducing cost, time, or waste of resources during construction processes (Koskela 1992). Therefore, with more effective labour allocation and activity sequencing, semi-productive hours will become more predictable and labour flow reliability will be improved. The result of this research will help project managers to comprehend the concept of *labour flow* easily and take effective measures to improve labour flow reliability. This will ultimately contribute to improving productivity while materializing lean construction in practice.

More specifically, the resource utilization efficiency associated with semi-productive labour-hours resulting from crew matching and labour resource allocation is generally ignored in current resource scheduling methods and project management software such as Primavera P6 and MS project. Hence, this study represents an attempt to quantitatively analyze the unnecessary semi-productive time in connection with the inefficiency in labour flow between consecutive activities due to crew matching, defining it as Labour Flow Waste Index. By taking advantage of Excel Solver, the research formulates an optimization model to decrease the non-value-adding worker hours, resulting in a practical labour-activity allocation plan and activity sequencing scheme from the lean perspective.

5.2 Literature Review

Different approaches have been used to formulate and find the optimal allocation of the limited number of resources to activities in order to reduce the total cost or the project duration. Lee and Gatton (1994) presented integer programming formulation to combine construction scheduling and resource planning by prioritizing resources. Other researchers developed artificial intelligence techniques to optimize and level the resource allocation and produce shorter project duration with a more levelled resource allocation scheme (Chan et al. 1996; Hegazy 1999). Senouci and Adeli (2001) used a nonlinear constrained optimization model to minimize project cost while levelling resources simultaneously. Later, resource-constraints scheduling was combined with dynamic programming to optimize resource utilization and minimize project cost and duration in scheduling activities (El-Rayes and Moselhi 2001). In addition, researchers have combined optimization techniques with simulation modeling to evaluate the optimization objective function based on simulated construction processes and operations and find the best configuration leading to the best operation performance (Feng et al. 2000; Salimi et al. 2018). Nonetheless, running a simulation model generally provides answers to the "what-if" questions, while simulation-based optimization analysis is short of the theoretical basis to generate optimum solutions, as it is deemed as "the process of finding the best input variables value from among all possibilities without explicitly evaluating each possibility" (Carson and Maria 1997).

Moreover, the lean approach delivers value within project constraints at *project planning level* through better workflow management aimed to improve the project cost and schedule performance. Ballard and Howell (1998) focused their attention on controlling project planning reliability as the means to improve workflow reliability; the concept of flow reliability from project planning perspective underpinned the *Last Planning Technique* proposed by Ballard (2000). Furthermore, Thomas (2002) proposed the necessity of treating labour the same as workflow and concluded that *labour flow* is an important component of lean flows in both project and production planning. Thomas (2002) suggested that for the sake of productivity improvement in construction, the flow in terms of both work flow and labour flow should be studied. He argued that workflow had been extensively addressed by lean thinking, but labour flow had received very limited attention. The result of his studies also showed that labour performance was determined by workforce management practices in labour intensive works and managing labour flow was essential for good performance in terms of project time and cost. 58% of the total inefficient work hours were attributed to ineffective flow management, particularly the ineffective labour flow. The results also suggested that more effort should be devoted to improve the reliability of labour flow in construction projects. Labour flow is distinct from the workflow in that it involves the allocation of the labour resource to various tasks (or work assignments) in connection with processing different jobs from different projects. Also, the interaction of the crew member with others and the precedence relationships with other tasks are relevant to describing labour flows (Thomas et al. 2003).

This research is mainly concerned with improving the cost and time performance of project delivery by efficiently utilizing labour resources and executing deadline-driven projects. Through solving a resource-constrained project scheduling problem and examining different activity sequencing, the efficiency of labour flow will be improved and unnecessary movements, non-value-adding activities and unutilized labour resources, known as wastes in lean construction, will be decreased from the perspective of project planner and scheduler in the context of planning the execution of labour intensive projects such as steel fabrication.

5.3 Demonstration Case

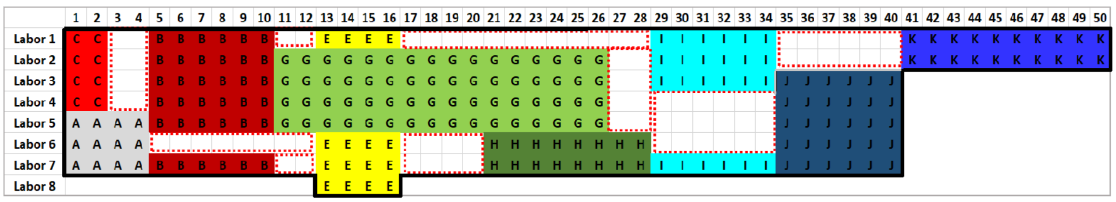
In labour intensive projects, when allocating limited labour resources to activities, activity sequencing could differ based on resource allocation order while still not violating any technology or logical constraints. In other words, given the same Activity-On-Node (AON) network (illustration of a project as a network diagram, consisting of nodes representing projects or tasks, linked by vectors (directional lines) representing dependencies in the project (mvorganizing 2021), different activity sequencing gives rise to a different labour allocation schedule. To elucidate this, Figure 5.1 shows two different activity sequencing options for Table 1 case. Note that the proposed case study is adopted from a Critical Path Method (CPM) example in Hegazy (1999).

Table 5.1. Duration, resource requirement and, predecessors of each activity

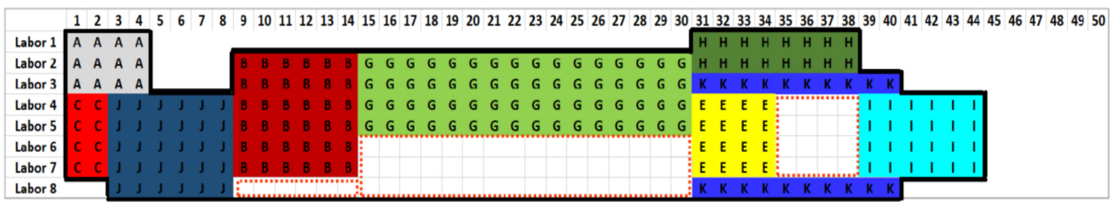
Activity	Predecessors	Duration (hr.)	Resource requirement
A	-	4	3
B	-	6	6
C	-	2	4
D	A	8	-
E	D	4	4
F	B	10	-
G	B	16	4
H	F	8	2
I	E, H	6	4
J	C	6	5
K	G, J	10	2

Figure 5.1 also shows two graphical representations of productive and semi-productive labour resource time based on two labour allocation plans for the case study. The total allocation of labour resources in the project is denoted with the total area delimited with a black frame. In other words, the black frame represents how each labour resource is allocated from the start of the first activity involved to the end of the last activity involved in a project. The colored areas marked with Activity ID symbolize productive utilization of particular resources allocated to the project activities while

semi-productive resource time blocks resulting from crew matching and transitioning efforts are highlighted with blocks in slashed red lines. Essentially, Figure 5.1(a) is a detailed resource work schedule subject to technological constraints and resource availability constraints. Figure 5.1(a) shows out of the total labour allocation of eight labourers to activity A to K, 78 hours spent as semi-productive labour-hours to match the resources and facilitating the flow of labourers between activities while in Figure 5.1(b) this effort is 70 labour-hours for the same case study of table 5.1.



(a)



(b)

Figure 5.1. Different labour allocation of the sample case of Table 5.1

As it can be observed different labour allocation and activity sequencing requires various crew matching efforts and labour flow between executive consecutive activities results in different semi-productive labour-hours.

Once the work content in labour-hours is fixed on each work item in the work activity of a fabrication of construction project, how to allocate the value of labour-hour to the different labour resources makes different value of semi-productive labour-hours (Zahedi and Lu 2021a). To examine different labour allocation aimed at minimizing the semi-productive time and optimizing the labour flows, an optimization model is developed and solved using the Excel Solver. Therefore, by minimizing the semi-productive labour-hours, and optimizing the labour allocation, the non-value-adding activities will be decreased leading to elimination or reduction of labour-hour wastes and production of a more reliable labour flow. By lean production, improvements result from increasing proportions of value-added work by reducing the content of waste (Thomas et al. 2003). In this regard, *the Labour Flow Waste Index* (LFWI) is introduced and formulated in this research to facilitate a quantitative analysis of semi-productive labour-hours associated with crew matching as Eq. 5.1.

$$\mathrm{LFWI} = \frac{\text{Semi\_Productive Labourhours}}{\text{Total Labourhours}} \tag{5.1}$$

Therefore, it can be deduced that the lower the LFWI is, the more efficient the labour resources flow between different activities resulting in a higher labour inter-activity utilization efficiency (Zahedi and Lu 2021b). On real projects, project duration is long enough, so, the jagged ends at start and end of total labour allocation (see Figure 5.1) become less significant. As such, the project completion time multiplied by the size of the crew deployed gives the total supply of crew resource in man-hours for completing the project. Hence, Eq. 5.1 is mathematically formulated as Eq. 5.2.

$$\mathrm{LFWI} = \frac{(\,\mathrm{D}_{project} \times \mathrm{L}_{availabile}\,) - (\,\sum_{i=1}^{i=n} \mathrm{D}_i \times \mathrm{L}_i\,)}{\mathrm{D}_{project} \times \mathrm{L}_{availabile}} \tag{5.2}$$

Note, D_i is the duration of activity (i), (n) is the number of activities of the project, L_i is the required number of labour resources to perform activity (i), $\mathrm{L}_{availabile}$ is the availability of the labour resources throughout the project and $\mathrm{D}_{project}$ is the total duration of the project as the project is scheduled.

Considering the $\mathrm{L}_{availabile} = 8$ labour resources , $\mathrm{D}_{project} = 50\ hr.$ and $\mathrm{D}_{project} = 44\ hr.$ for the two labour resource allocation alternatives of Figure 1(a) and 1(b) respectively, the LFWI is calculated as 43% (174/400) for Figure 1(a) scenario and 36% (126/352) for Figure 1(b). D_i and L_i are also given as Table 5.1. As can be inferred, given the same technological constraints as Table 5.1, different labour resource allocation plans and crew matching of Figure 5.1 results in different efficiency in labour flow.

5.4 Optimization Model

The main objective of this model is to optimize the labour flow and activity sequencing of labour intensive work in order to decrease non-value-adding activities delineating as waste in lean construction and improve the labour productivity and enhance project time and cost performance. In order to achieve this objective, the model is designed to identify the main decision variables of early start time of each activity(ES_i), which affects the early finish time of each activity and consequently the project duration which means the total duration of labour resource involvement.

The objective function of optimization model is to minimize the Labour Flow Waste Index as:

$$\text{Min } \frac{(\mathrm{D}_{project} \times \mathrm{L}_{availabile}) - (\sum_{i=1}^{i=n} \mathrm{D}_i \times \mathrm{L}_i)}{\mathrm{D}_{project} \times \mathrm{L}_{availabile}} \qquad (5.3)$$

The constraints of the model are defined in a way that the feasible solutions meet the technological and resource availability constraints. The optimization solution needs to ensure a time lag constraint between A and E, at least 8 hr. (i.e., D's duration). So, D is equivalent to a finish-to-start relationship with lag time. Similarly, there exists a time lag constraint between B and H with at least 10 hr. delay (i.e., F's duration). Accordingly for the proposed case study the constraints are defined as Table 5.2.

Table 5.2. Optimization model constraints

Technological constraints:		
$\mathrm{ES}_A \geq Sart$	$\mathrm{ES}_G \geq \mathrm{ES}_B$	$\mathrm{ES}_K \geq \mathrm{ES}_G$
$\mathrm{ES}_B \geq \mathrm{ES}_A$	$\mathrm{ES}_J \geq \mathrm{ES}_C$	$\mathrm{ES}_K \geq \mathrm{ES}_J$
$\mathrm{ES}_C \geq \mathrm{ES}_A$	$\mathrm{ES}_E \geq \mathrm{ES}_D$	$\mathrm{ES}_D \geq \mathrm{ES}_I$
$\mathrm{ES}_D \geq \mathrm{ES}_A$	$\mathrm{ES}_H \geq \mathrm{ES}_F$	$End \geq \mathrm{ES}_I$
$\mathrm{ES}_F \geq \mathrm{ES}_B$	$\mathrm{ES}_I \geq \mathrm{ES}_E$	$End \geq \mathrm{ES}_K$
	$\mathrm{ES}_I \geq \mathrm{ES}_H$	
Labour resource availability constraints:		
$\mathrm{L}_{availabile} - Resource\ Allocation_t \geq 0$		
Integer and non-negativity constraints:		
$\mathrm{ES}_i = integer$		
$\mathrm{ES}_i \geq 0$		

Solving the model by Excel Solver 2013 (Shardt 2015) results in decision variables of ES_i as shows in Figure 5.2(a). Accordingly, the results return the minimized LFWI of 29% which represents 32% improvement in labour flow and crew matching efficiency against the 43% LFWI of the project plan under the initial sequencing shown in Figure 5.1(a). The duration of the project is also reduced from 50 hours in Figure 5.1(a) and 44 hours in Figure 5.1(b) to 40 hours as the result of labour flow improvement through the optimization model solution. As such, for executing the project in 50 hours, 400 labour-hours should be budgeted while this budget is reduced to 320 labour-hours for 40 hours project executing time in optimized scheme.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Labor 1					A	A	A	A	B	B	B	B	B	B	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G															
Labor 2					A	A	A	A	B	B	B	B	B	B	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	K	K	K	K	K	K	K	K	K	K					
Labor 3					A	A	A	A	B	B	B	B	B	B	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	K	K	K	K	K	K	K	K	K	K					
Labor 4	C	C	J	J	J	J	J	J	B	B	B	B	B	B	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G			I	I	I	I	I	I							
Labor 5	C	C	J	J	J	J	J	J	B	B	B	B	B	B			E	E	E	E					H	H	H	H	H	H	H	H	I	I	I	I	I	I							
Labor 6	C	C	J	J	J	J	J	J	B	B	B	B	B	B			E	E	E	E					H	H	H	H	H	H	H	H	I	I	I	I	I	I							
Labor 7	C	C	J	J	J	J	J	J									E	E	E	E													I	I	I	I	I	I							
Labor 8			J	J	J	J	J	J									E	E	E	E																									

Figure 5.2. Activity sequencing from the optimization results using Excel Solver

5.5 Summary

Despite significant research in the literature concerning lean construction, few studies have attempted to investigate the impact of labour flow on generating waste and non-value-adding labour efforts. This research mathematically models the impact of activity-specific factors upon labour semi-productive time, crew matching and labour flow efficiency between different activities.

Possessing trades' know-how and management skills to lead, motivate and engage the labour resources is indispensable to successfully minimizing labour flow wastes in allocating multiskilled labourers to various tasks from the lean perspective. As such, a new waste index, namely Labour Flow Waste Index, is defined to quantify labourers' unnecessary movements and non-value-adding activities resulting from crew matching efforts and different activity sequencing. An optimization model is developed to optimize the regular allocation of labour resources and activity sequencing in an attempt to minimize the frequent labour transferring between different activities. The result from this study shows by examining different labour allocation plans which results in changes in activity sequencing the labour flow wastes could be reduced by 32 %, resulting in 20 % (50 hr. to 40 hr. and 400 LH to 320 LH) improvement in project time and cost performance. As such the hypothesis that time and cost performances of the whole project are enhanced by improving labour flow efficiency is validated.

CHAPTER 6

Conclusions and Future Directions

By investigating the current practice of prefabrication in construction and performing a comprehensive literature review on impact of multiskilling workforces in the production environment of prefabrication, the thesis has proposed a methodology based on discrete-event-simulation modeling for planning and scheduling prefabrication project involving multiskilled labour resources. The simulation-enabled methodology allows for the definition and determination of the utilization efficiency of labour resources associated with labour transfers between different workspaces in a typical prefabrication facility. The research has extended the theory and application of Critical Path Method (CPM) scheduling by integrating it with productivity performance measurements so as to obtain a more reliable labour-hour budget on typical prefabrication projects in construction. Further to the "what-if" scenario-based simulation analysis, optimization analysis is introduced in an attempt to enhance the utilization of multiskilled labour resources to the largest extent, leading to decreasing the labour utilization inefficiency –which is also recognized as motion and waiting waste according to the waste classification in Lean construction. This chapter recapitulates the thesis research, restates the academic and practical contributions, and finally addresses the limitations of this research and the further research.

6.1 Research Summary

To build a solid foundation of the research, a study in the current practice of prefabrication in construction is performed to elucidate the distinctive characteristics of prefabrication against manufacturing that could have hampered the implementation of high-level of modularization in facilities such as steel girder fabrication shop. Later, a comprehensive literature review to investigate the application and impact of shifting from single-skilling to multiskilling in labour employment in typical prefabrication facilities is conducted. A quantitative analysis of multiskilled labour utilization based on the proper understanding of the level of multiskilling and a sufficient modeling of resource use schedules identifies that a downsized crew consisting of skilled labourers, each trained with multiple skills to work on various semi-automated workstations, would provide a more cost-effective strategy for labour employment at off-site prefabrication facilities. The extra cost resulting from multiskilling training can be potentially compensated by the direct cost saving from implementing multiskilling in practice.

It should be noted that given the same number of labourers, activities completed by single-skilled labourers may take less time than those completed by multiskilled labourers due to their higher level of skill and productivity. However, in this research, variations in activity time subject to single-skilled or multiskilled labourers are ignored as objective assessment methods on skill levels and productivity data are not available in practice -which will be worthy of further research in the future.

Employing multiskilled labour resources as the main type of finite resources in performing the scope of work on prefabrication and off-site projects, this research extends the commonly used Critical Path Method (CPM) scheduling technique by integrating productivity notions and labour flows in order to improve the accuracy of labour-hour cost estimating of such projects. In general, when applying CPM scheduling under resource constraints, the derived budget does not consider the efficiency of crew formation, as CPM is not able to account for resource schedule details such as labour resource waiting to be assigned to an activity. At best, seasoned schedulers would apply a budget scale factor based on experience in order to compensate for such impact, which is essentially to follow the “rule of thumb” falling short of scientific rigor.

Aimed at advancing the current practices of planning, estimating, and budgeting for prefabrication projects in industrial construction at a semi-automated prefabrication facility, utilizing multiskilled labour resources, this research takes advantage of a simulation-based scheduling approach to formally define a new efficiency factor — resource inter-activity utilization efficiency—to quantitatively investigate the semi-productive time resulting from crew scheduling and labour allocation on the activity level in a resource-constrained environment. The newly developed efficiency factor is then utilized by estimators to characterize the impact of semi-productive labour-hours and derive a more reliable labour cost budget on the project level.

In contrast with CPM-based solutions, the simulation model is capable of accounting for a sequence of executed activities for each individual resource. By conducting the whole scope of this research, it is concluded that if the semi-productive percent is reduced, inter-activity utilization efficiency will increase, leading to an improvement of the total labour-hour budget and project duration. In this research, S3—which had been developed from research, verified, and validated (see Lu et al. 2008 for details) — is selected and applied as the resource scheduling simulation tool, since it provides an effective means for analyzing each labourer’s allocation to different activities over project time, which is not possible when using existing CPM-based tools (such as Primavera P6). By running the simulation model and examining the results for different what-if scenarios, the effect of different crew matching, activity sequencing and crew size on project labour cost budget is revealed in an analytical way. A conceptual optimization model of minimizing the semi-productive labour-hours leading to enhanced inter-activity utilization efficiency, improved labour flow and project cost and time performances is formulated.

Furthermore, implementing Lean construction principals and taking advantage of Excel Solver, an attempt to minimize the frequent labour transferring between different activities and inefficiencies in labour flows— namely the *Labour Flow Waste Index*, has resulted in an optimization model along with a simple case to demonstrate the effect of optimization upon regular allocations of labour resources and activity sequencing in planning a prefabrication project. As such it further validates the hypothesis that the time and cost performances of the whole project are significantly enhanced by improving labour flow efficiency.

The study utilizes separate optimization formulations to incorporate the distinct Lean and productivity concepts, leading to a consistent and united solution. It is concluded that a leaner labour flow results in increased productivity of labour resources. The Lean optimization model maximizes labour flow efficiency, which in turn leads to the maximum labour productivity and minimum semi-productive time. This was demonstrated in the specific context of multiskilled labour in construction manufacturing or fabrication, where both objectives were aligned and the concepts were unified, ultimately leading to an improved in resource utilization.

A real-world case study of steel girder fabrication projects in Alberta, Canada was carried out in collaboration with the partner organization. The research methods were implemented, and the simulation results were verified through comparison with Primavera P6 as described by Sargent (2009) in the verification by comparison to other models. The proposed framework was also verified by manually checking the detailed simulation results to ensure satisfaction of constraints, such as finite resource availability and proper sequencing of activities. The validity of the results was confirmed through an independent validation process, as described by Sargent (2010) in the face validation process. The model and labour cost estimate were evaluated by experienced project planning experts to determine their reasonableness and validity.

In the case study, semi-productive work hours can be lowered from about 50% of the total working time to 30% by fine-tuning the crew size and work sequencing based on the simulation model, leading to higher productivity, shorter project duration and a decrease in project cost.

6.2 Academic Contributions

The accomplished research outcomes have resulted in following academic contributions:

- Performing a comprehensive literature review to generalize and contrast features of traditional construction, manufacturing, and off-site construction environment and proposing a framework to investigate the application and impact of shifting from single-skilling in regards to multiskilling in labour employment subject to production environment of a prefabrication and off-site facility.
- Extending the theory and application of AON/CPM-based project planning and labour cost budgeting by developing a discrete-event-simulation-based framework to model the labour utilization efficiency in connection with multiskilling and dynamic crew formations in prefabrication and off-site construction.
- Introducing novel approaches by integrating productivity concepts with project planning, scheduling and budgeting to improve the accuracy of labour-hour cost estimating in prefabrication and off-site construction in a multiprojects-multiskilling-fabrication-shop environment.
- Formulating an optimization model to improve the simulated allocation of labour resources and activity sequencing in an attempt to reduce the frequent labour transferring between

different activities, which ultimately results in an improvement to project cost and time performances.

- Integrating lean construction principles, simulation techniques and productivity concepts with project scheduling and budgeting to streamline labour flow between different activities by proposing an analytical means to reduce the frequent unnecessary labour movement, which is also recognized as motion and waiting waste according to the waste classification in lean construction.

6.3 Industrial Contributions

Industrial contributions that have arisen out of collaborative research efforts with the construction industry include:

- To deliver a methodology based on discrete-event-simulation modeling for planning and scheduling prefabrication project involving multiskilled labour resources. The simulation-enabled methodology allows for determination and improvement of the utilization efficiency of labour resources associated with labour transfers between different workspaces in a typical prefabrication facility.
- To assist project managers in comprehending the concept of labour flow and taking effective measures to improve labour flow predictability, while developing a more realistic labour cost budget in an analytical way so that the generated cost budget would be more closely aligned with the actual project labour cost.

- To lend the project management practitioners an analytical decision support to produce sufficient and realistic cost budgets in planning labour intensive projects in the early stage of project development.

6.4 Research Limitations

Although the research findings in the above chapters support the developed approaches, certain limitations of this research should be noted and explored.

- The accuracy and reliability of the developed simulation model largely depends on the quality and availability of the data available in the current project planning and scheduling systems.
- The assumption that multiskilled labour resources are identical in terms of expertise and proficiency in each skill can provide a simplified framework for the analysis and calculation of task completion times. However, it is imperative to recognize that this assumption may not accurately reflect the reality of the situation. In actuality, workers may exhibit different levels of proficiency and expertise in different skills, as well as varying levels of productivity.
- While the research framework is expected to be applicable—in its current form—to all labour intensive prefabrication construction projects using multiskilled labour resources, applicability of the framework to other labour intensive construction projects has yet to be implemented and confirmed using actual project data in the real world.

6.5 Future Directions

This section points out possible future directions based on this doctoral research work, which include:

- The development of workface planning algorithms and computer tools to enable labour/ subassembly fabrication schedule analysis based on the formalized subassembly workflow model.
- Agile project management based on the proposed planning and scheduling framework is yet to be realized in the prefabrication industry. Agile project management requires dynamic plan updating and optimization for project execution control in response to all the changes in the project environment (Hopp and Oyen 2004). Lack of agile capabilities is identified as the key barrier to realizing the full potential of the proposed simulation and optimization-based research. Future research is intended to overcome this limitation.
- Integration of the proposed methodology with (1) Building Information Modeling (BIM) 3D product models, (2) activity time estimate based on labour skill assessment (3) real time work allocation app to individual labourers (which workstation to go, what's next job, whom to team up with), and (4) regulations on Occupational Health and Safety (OHS), multiskilled labour training and employment condition

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APPENDIX I

1. Introduction

To assist in construction project planning and resource scheduling, the simulation tool of Simplified Simulation-based Scheduling (short for S3) is developed within the SDESA platform (Simplified Discrete-Event Simulation Approach) allowing for modeling, simulation analysis, and optimization of the project scheduling plan. Note that a Particle Swarm Optimization (PSO) based optimizer underlies the S3 to automatically find the best resource provisions so as to achieve the optimization goal of the shortest project duration or the least project cost in both deterministic Critical Path Method (CPM) and stochastic (PERT) settings (Lu, M., The Hong Kong Polytechnic University 2006).

1.1 About the User's Guide

This user guide explains how to use the S3 Project Detail Manager and the S3 platform for (1) initializing a project scheduling plan and specifying activity details, (2) generating and executing a S3 network model, (3) collecting and analyzing simulation results, and (4) searching the optimum solution based on a simulation model. The following flow chart maps out the procedures of applying S3.

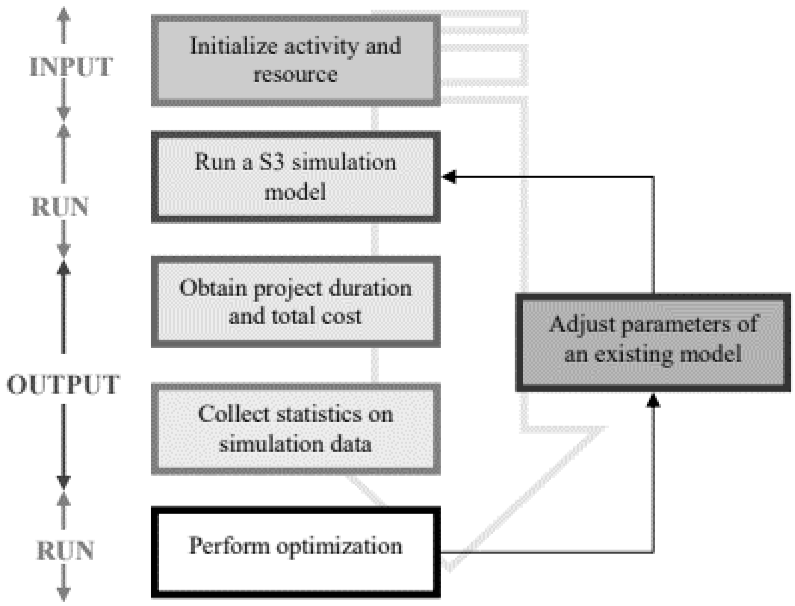


Figure A1. S3 flow chart map

2. Input S3 Project Details

Before executing the S3 model analysis, general settings such as activity details, resource information, and cost data should be defined first. The tool of "CPM Database Manager" provides the user with an easy-to-use interface for inputting the general project details. An input screen is designed for users to specify the details of activities and resource requirements as well as the resource availability and interruption constraints. To start this tool, click Start, Programs, SDESA, and then select CPM DB Manager. The menu provides three functions related to S3 database, namely, building a new model, opening a user-specified model and closing the currently opened model. Files in the "CPM Database Manager" format use the MDB extension. This chapter will introduce you to the menus and options you will use to key in your data and organize your scheduling plan.

2.1 Initialize Resource Details

As shown in the figure A2, the tab pages available are “Resource List”, “Task Schedule”, “Interruption Settings” and “Indirect Cost”. The first step is to define the resource details by selecting the Resource List page. Manpower, equipment and space blocks could also be tracked as a resource. To add a new resource, click the “plus” button or click the blank space adjacent to the field descriptions. The Resource window has four input areas: Resource Code, Description, Limit and Cost. This allows the user to specify the details (i.e. name, available quantity & daily cost) of a specific resource for a given time period.

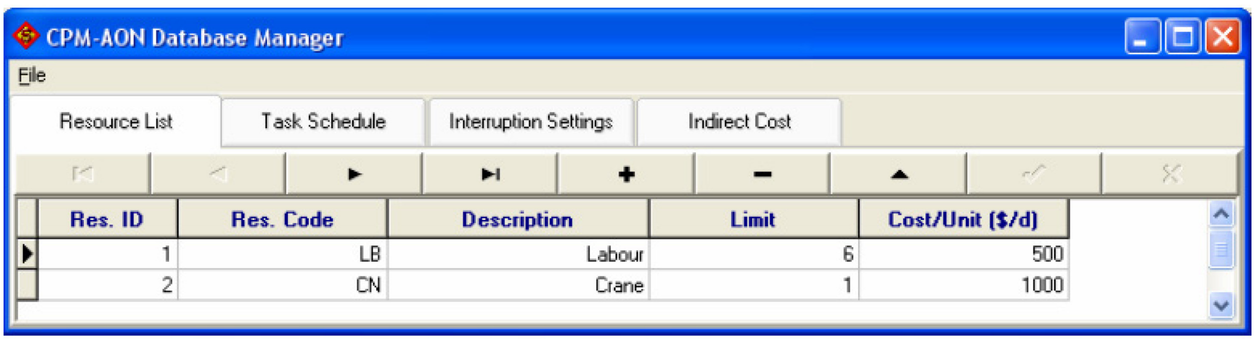
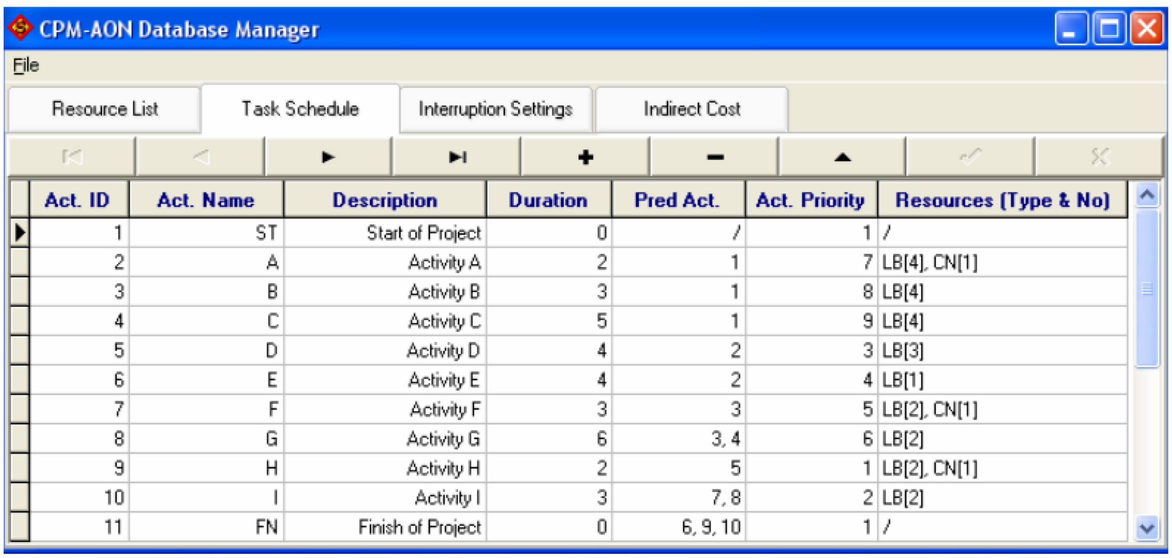


Figure A2. Initializing resource list

Above the Resource List table is a navigation bar for easily handling the input record table. There are nine buttons on the navigation bar from the left to right, which are “First record”, “Prior record”, “Next record”, “Last record”, “Insert record”, “Delete record”, “Edit record”, “Post edit”, and “Cancel edit”.

2.2 Initialize Activity Details

The second step is to define the activity details by selecting the Task Schedule tab. To add a new activity, click the plus button or click the blank space adjacent to the field descriptions. S3 automatically assigns a unique ID to each activity you add. The Task window has six input areas: Activity Name, Description, Duration, Preceding Activity, Activity Priority and Resource Required. This allows the user to specify the details (i.e. description, duration, preceding activities & resource quantity) of a specific activity.



Act. ID	Act. Name	Description	Duration	Pred Act.	Act. Priority	Resources (Type & No)
1	ST	Start of Project	0	/	1	/
2	A	Activity A	2	1	7	LB[4], CN[1]
3	B	Activity B	3	1	8	LB[4]
4	C	Activity C	5	1	9	LB[4]
5	D	Activity D	4	2	3	LB[3]
6	E	Activity E	4	2	4	LB[1]
7	F	Activity F	3	3	5	LB[2], CN[1]
8	G	Activity G	6	3, 4	6	LB[2]
9	H	Activity H	2	5	1	LB[2], CN[1]
10	I	Activity I	3	7, 8	2	LB[2]
11	FN	Finish of Project	0	6, 9, 10	1	/

Figure A3. Initializing activity list

The priority is relative index to indicate the importance of activities as regarded by the project manager. When there is more than one activity requesting for one resource, S3 always allocates the resource to the one with the highest priority. The default priority value is 1, and a larger number stands for a higher priority. And if multiple activities have the same priority, the resource will serve the one with smallest activity ID first.

2.3 Define Interruptions to Activity & Resource (Activity/Resource Calendars)

Switching to the Interruption Settings tab gives the input settings of activity/resource interruptions. S3 allows user to add any regular interruptions (i.e., labour holiday, equipment maintenance period, etc.) into the model. Prior to entering the interruption, the user should set the project start date by using the calendar input interface. During the interruption period, the selected activity stops, and every resource involved remains idle until the end of the interruption. Note the S3 algorithm automatically handles the overlapping of multiple activity or resource interruptions.

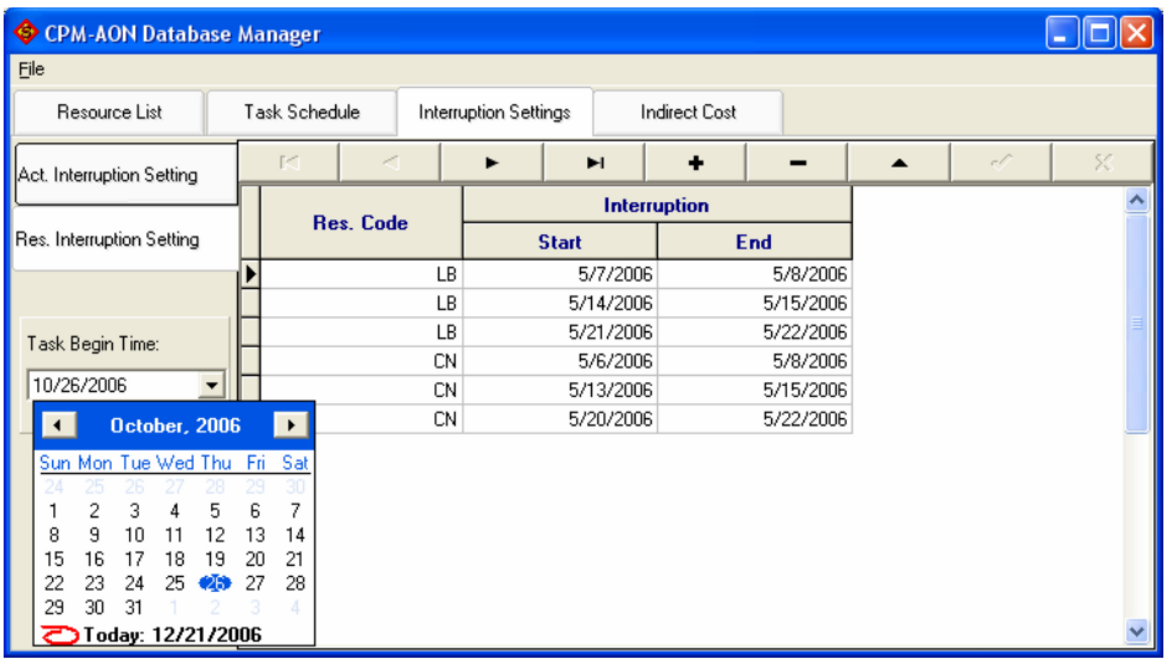


Figure A4. Project details setting in S3.

2.4 Initialize Cost Details

The final step is to define the project cost details by selecting the Indirect Cost tab. The Tab window has two input areas. This allows the user to specify the cost details (i.e. initial fixed indirect cost and daily indirect cost) of a specific project.

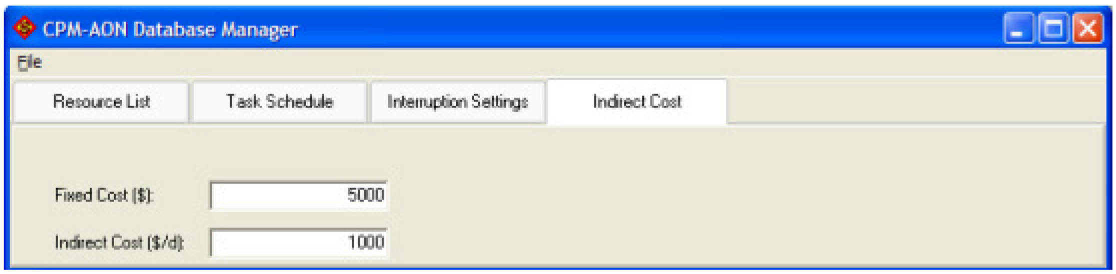


Figure A5. Initializing cost details.

Upon confirming all the details of project scheduling, pressing the Close menu will automatically export the project details into a Microsoft Access file with an extension name of MDB. Then, it is ready to create a S3 simulation model. To close and exit the program, user can click the "X" button at the top-right corner of the window or select Exit menu.

3. Generate S3 Model

After creating the S3 data file by running through related modules (i.e. activity details, resource information and cost data) and saving it into a MS Access file, the user can input the data file to S3 within the SDESA simulation platform. To start S3, click Start, Programs, SDESA, and then select SDESA.

3.1 S3 Menu

The S3 drop down menu located on the menu bar contains options for importing data, executing Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT) analysis, and carrying out the optimization.

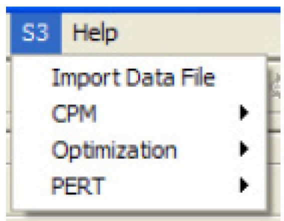


Figure A6. S3 menus

Table A1. Description of S3 menu

Each of the selections available on the S3 menu is explained below.

Import Data File	Select and import MS Access data file previously created in CPM Database Manager.
CPM	Allow the user to carry out deterministic CPM analysis (i.e. single-run simulation, float analysis, cost and resource summary) for the current model.
Optimization	Define the PSO optimization settings and perform the optimization for the current model.
PERT	Allow the user to carry out stochastic PERT analysis (i.e. multiple-run simulation, duration/cost summary and optimization) for the current model.

3.2 Convert Data File to a S3 Model

The S3 data file about project information can be loaded directly from any existing MDB file in SDESA platform by selecting Import Data File from S3 menu. Upon confirming the database file entry, pressing the "Open" button will automatically generate the S3 simulation model. A resource pool (a rectangle block holding corresponding input data) will be shown on the right-hand side of the screen in S3 model.

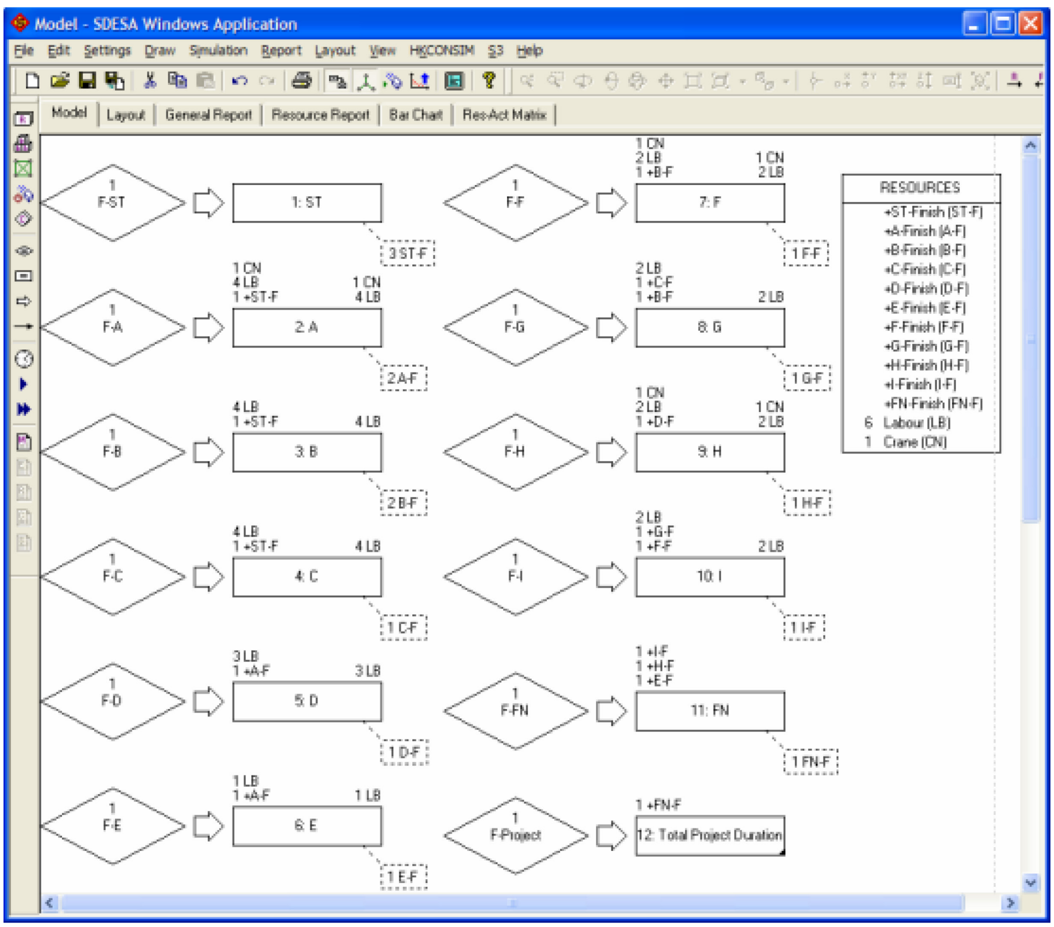


Figure A7. S3 model representing fabrication activities, precedence relationships, plus imposed resource constraints.

According to the input details of Activity-On-Node (AON) network of a project (Figure A8), the simulation model will be created in the SDESA computer platform as Figure A7 resource pool (a rectangle block holding corresponding input data) will be shown on the right-hand side of the screen in S3 model then. Firstly, each activity in the Activity-On-Node (AON) network is represented with one Flow Entity linked with one Activity Block, ensuring each activity is executed once only. Secondly, the Disposable Resource Entity in the SDESA substitutes for the arrows in the Activity-On-Node (AON), as shown in Figure A7 as an information unit to enforce the precedence relationship in Activity-On-Node (AON). An activity generates Disposable Resource Entities (marked on the bottom right corner of the activity rectangle), which are requested to initiate its successors. When all its preceding activities are finished, as a result, all the required Disposable Resource Entities become available to trigger the start of the current activity (marked on the top left corner of the activity rectangle). Thirdly, we can specify the resource requirements in each activity. The Reusable Resource Entities requested by each activity, such as manpower and equipment, are also marked on the top left corner of the activity rectangle, while the Reusable Resource Entities to be released at the end of the activity are marked on the top right corner.

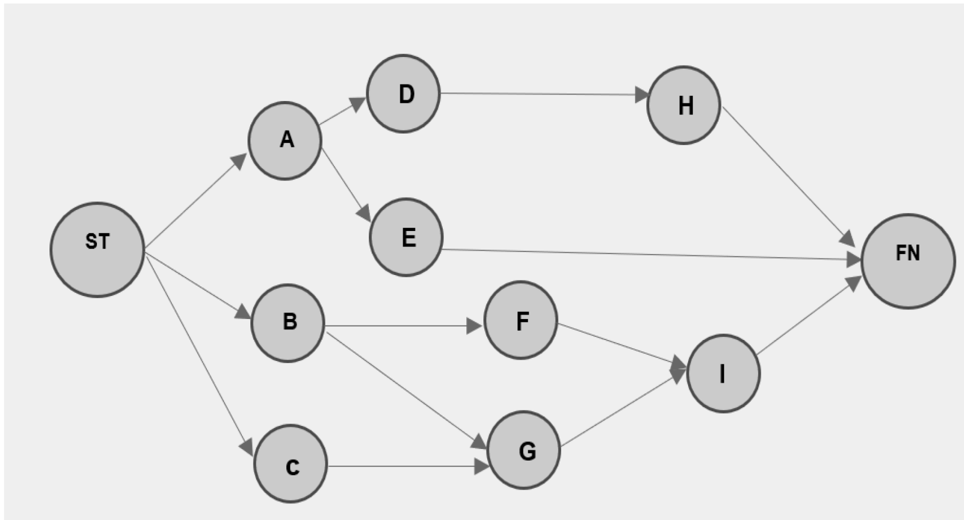


Figure A8. Activity-On-Node (AON) for model in Figure A7

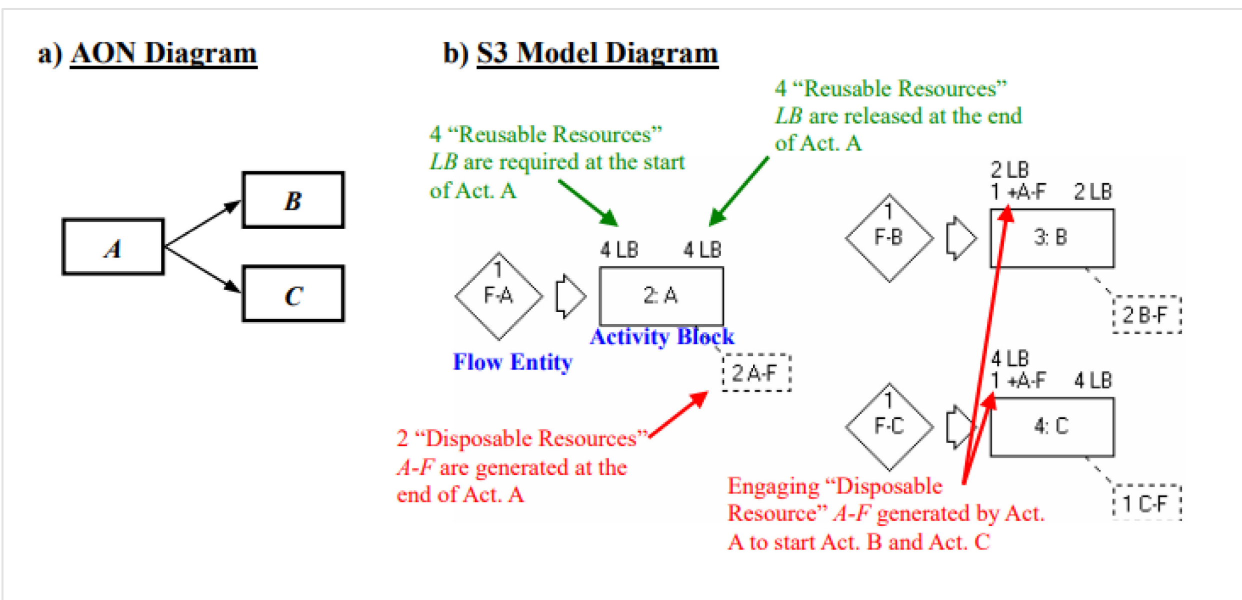


Figure A9. AON conversion to S3

S3 will automatically convert the database file into a SDESA simulation model; however, the Flow Entity and Activity Block are often compactly placed and maybe difficult to read. In case of crammed activity placement on screen, the user can reposition the activities by using the mouse to pick up and actually move an activity to a new location on the window page. One and only one Start node is allowed in the network, which earmarks the milestone of the total project start. The user specifies the project start time, the default value of which is 0. One and only one End activity is allowed in the network, which earmarks the milestone of the total project completion time.

3.3 Modify Activity Duration of the Current S3 Model

By using CPM-AON Database Management, all activity durations are defined in constant values for deterministic analysis. If the users want to carry out PERT analysis, it is suggested to modify the activity duration of the current S3 model. In order to edit the attributes of the activity, double-click the corresponding Activity Block to access the Activity Properties entry box. Change the Activity Duration to any probability distributions using the Expression Editor. In the Expression Editor, user is allowed to select different distribution type in a list box and key in the parameters.

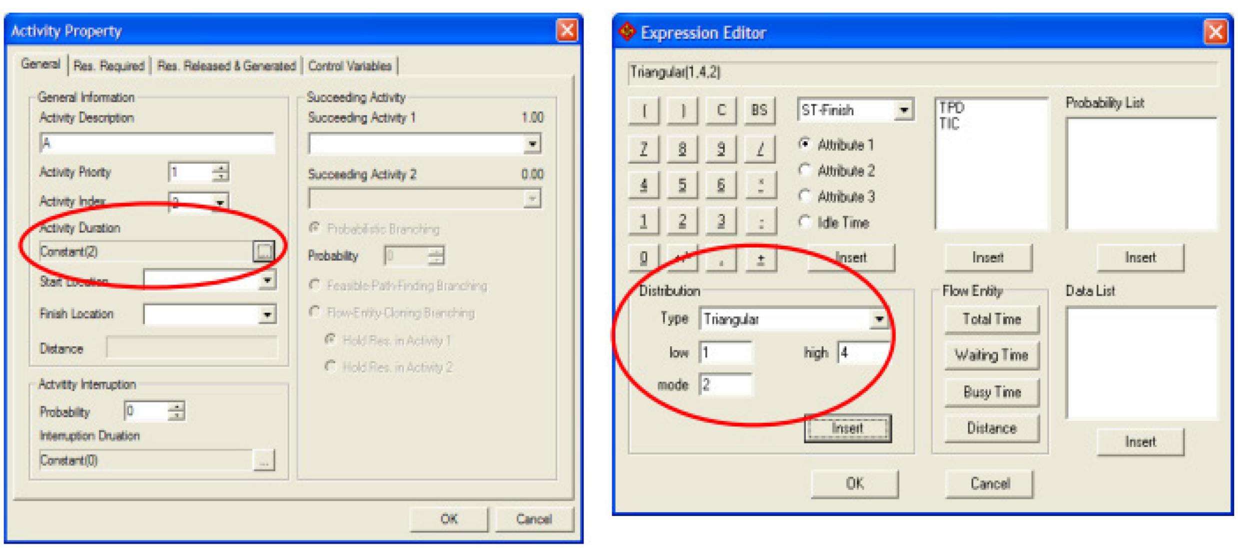


Figure A10. Defining activity duration in S3

4. Start S3 Simulation

The S3 tool provides the user with two options to run the simulation (i.e. deterministic CPM analysis and stochastic PERT analysis) for different requirements.

4.1 Critical Path Method (CPM) Analysis

4.1.1 Start Single-Run Simulation

S3 allows user to run a single simulation run in order to produce the utilization rates and work schedules for the corresponding resources. When a model has been well setup, user can start the dynamic simulation model experiment by clicking S3> CPM> Start Simulation. After the single-run simulation is complete, there will be a message box popping up, showing the number of Flow Entities (activities) processed and the total analysis time taken.

4.1.2 Collect Simulation Results

Report Output in S3 includes the summary report of the model, and the detailed figures of model processing data for both activity and resource.

Early Schedule Bar Chart

Bar charts are relatively easy to read and frequently used in project management presentations. The “Bar Chart” tab in the SDESA gives the project schedule in the Gantt chart format. It shows the working sequence and early start/finish times of each activity, as well as the project completion time.

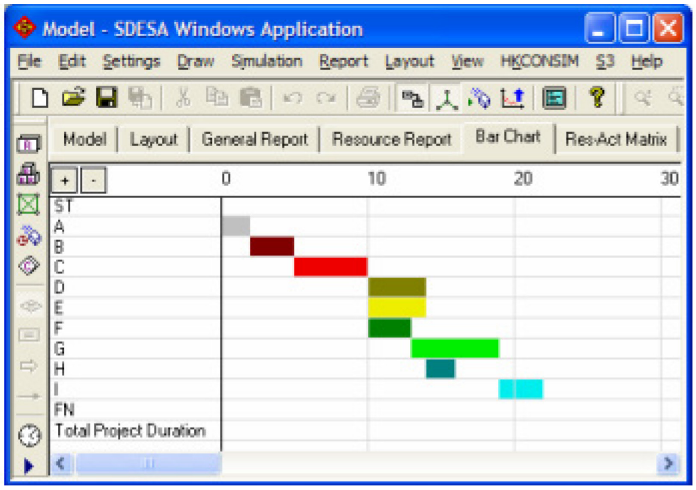


Figure A11. S3 early schedule bar chart

Resource Bar Chart

Switching to the "Res-Act Matrix" tab in the SDESA gives the resource-activity interaction matrix in a color scheme that is consistent with the previous bar chart. Individual resources with specific name/ID are listed in the left-hand side column.

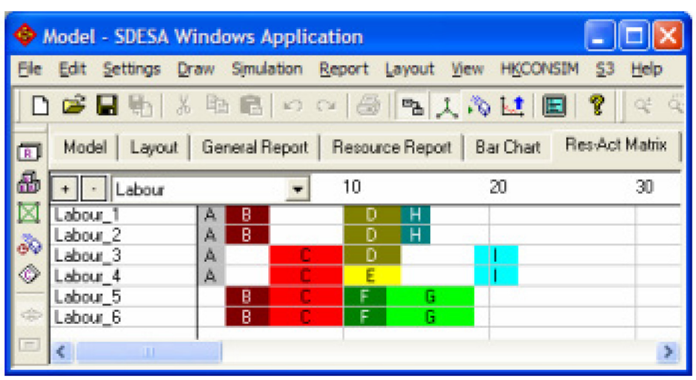
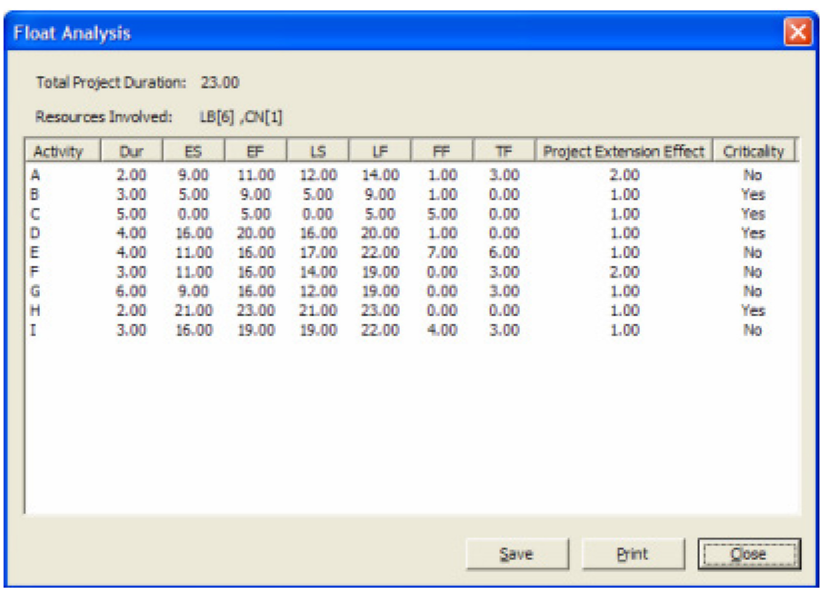


Figure A12. S3 resource bar chart

For deterministic analysis, S3 also specially develops three main analysis reports including float analysis, resource summary and cost summary. The data in these reports can be saved in a text file for backup or further reporting.

Float Analysis

Through the Float Analysis, the user can obtain total project duration and scheduling details of each activity. To start float analysis, select S3, CPM, and then Float Analysis. The activity times (Early Start, Early Finish, Late Start, Late Finish, Free Float and Total Float) are displayed to the user for each activity. In addition, S3 explicitly defines the project extension effect which is the magnitude of extending the total project duration due to delaying the completion of an activity by one day beyond its late finish time (LF). This effect is also summarized in the Float Analysis result table.



Float Analysis

Total Project Duration: 23.00

Resources Involved: LB[6] ,CN[1]

Activity	Dur	ES	EF	LS	LF	FF	TF	Project Extension Effect	Criticality
A	2.00	9.00	11.00	12.00	14.00	1.00	3.00	2.00	No
B	3.00	5.00	9.00	5.00	9.00	1.00	0.00	1.00	Yes
C	5.00	0.00	5.00	0.00	5.00	5.00	0.00	1.00	Yes
D	4.00	16.00	20.00	16.00	20.00	1.00	0.00	1.00	Yes
E	4.00	11.00	16.00	17.00	22.00	7.00	6.00	1.00	No
F	3.00	11.00	16.00	14.00	19.00	0.00	3.00	2.00	No
G	6.00	9.00	16.00	12.00	19.00	0.00	3.00	1.00	No
H	2.00	21.00	23.00	21.00	23.00	0.00	0.00	1.00	Yes
I	3.00	16.00	19.00	19.00	22.00	4.00	3.00	1.00	No

Save Print Close

Figure A13. Float analysis in S3

Resource Summary

Resource Summary includes the details of all reusable resources. To review the Resource Summary, click S3>CPM> Resource Summary in the top menu. Users can obtain overall productive time/cost and non-productive time/cost for the whole resource group as well as for each individual resource. For each individual resource, the working start time and end time are also determined.

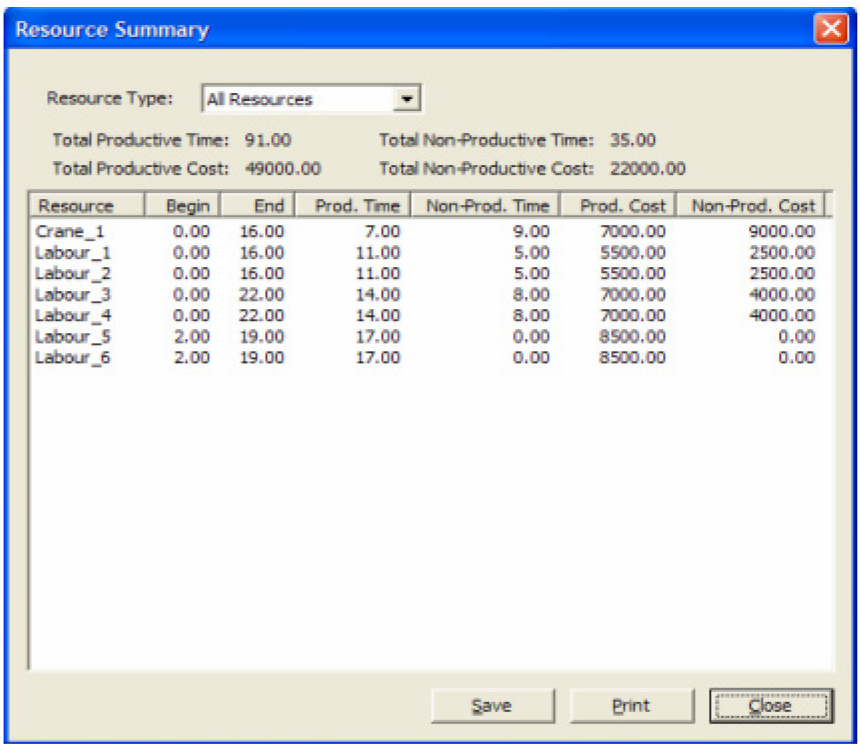


Figure A14. Resource summary analysis in S3

Cost Summary Cost Summary includes total indirect cost, total productive/non-productive resource cost and total project cost.

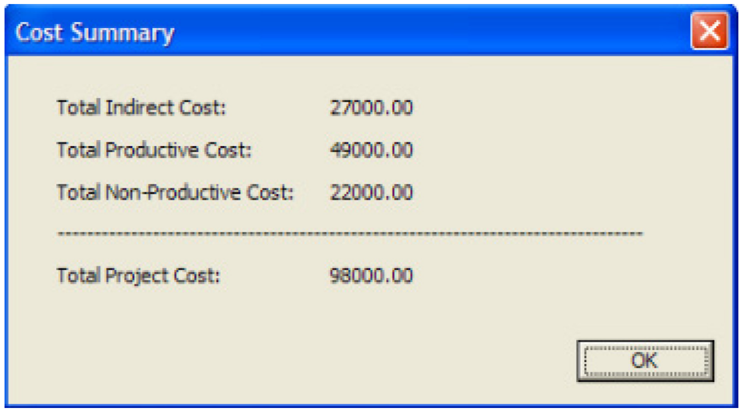


Figure A15. Cost summary analysis in S3

5. Start S3 Optimization

Project managers intend to use simulation tools to predict and improve the system performances by modeling the actual operations. Users can freely set up and try out different scenarios, but it is difficult to seek the optimal activity sequences or optimal combination of resource provisions, which leads to the optimal system performance. The S3's PSO-based optimization function provides the user with two options (i.e. deterministic CPM analysis and stochastic PERT analysis) to improve the project performance. In dealing with the deterministic S3 simulation models, there are two objective options for optimization analysis, namely, the "optimize total project duration" and "optimize total project cost". By using the PSO technique to search for an optimum set of resources and activity priorities, we can optimize the project schedule in terms of attaining the shortest project duration ("resource allocation") or the least project cost ("time/cost tradeoff"). To use the optimizer, select S3> Optimization> Start Optimization. In "Optimization Settings" dialog box, user can have various options to setup the optimization constraints and the objective.

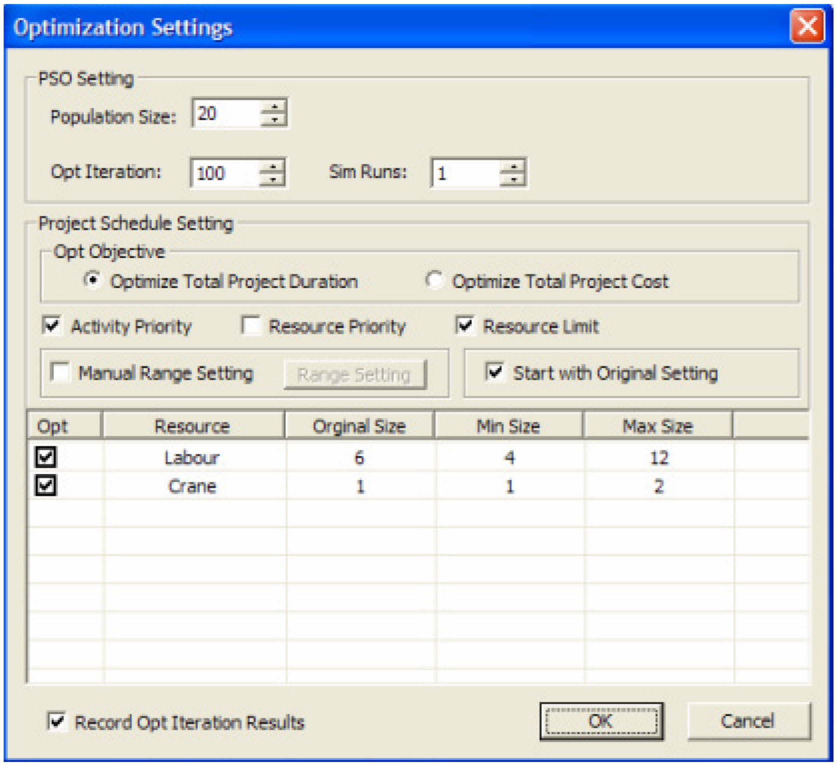


Figure A16. Optimization setting in S3.

Table A2. S3 optimization parameter description

PSO Parameters Setting	
Population size, optimization iteration & simulation run	The number of particles that are stored in optimization process; the criteria for controlling the number of iterations to find the optimum result; and number of simulations runs in each iteration
Optimization Objectives	
Optimize total project duration / Optimize total project cost	The objective function can be set to either minimize the total project duration (resource allocation) or minimize project cost (time/cost tradeoff)

Optimization Variables	
Activity priority	It is index to indicate the relative importance of activities when there is more than one activity requesting for one resource (the larger the number, the higher the priority for allocation)
Resource priority	It is index to indicate the relative importance of resource when there is more than one resource of the same type ready at the same time (the larger the number, the higher the priority for allocation)
Resource limit	User can set two boundary values for each resource group

Once the optimization process starts, the program will remain in running state until an optimization result window pops up. The window shows the processing time, the optimal objective value, the optimal activity priority, and the optimal combinations of resources. The optimal scenario as identified is already stored in the current S3 model, so user can save this scenario as a new model file in SDS extension format.

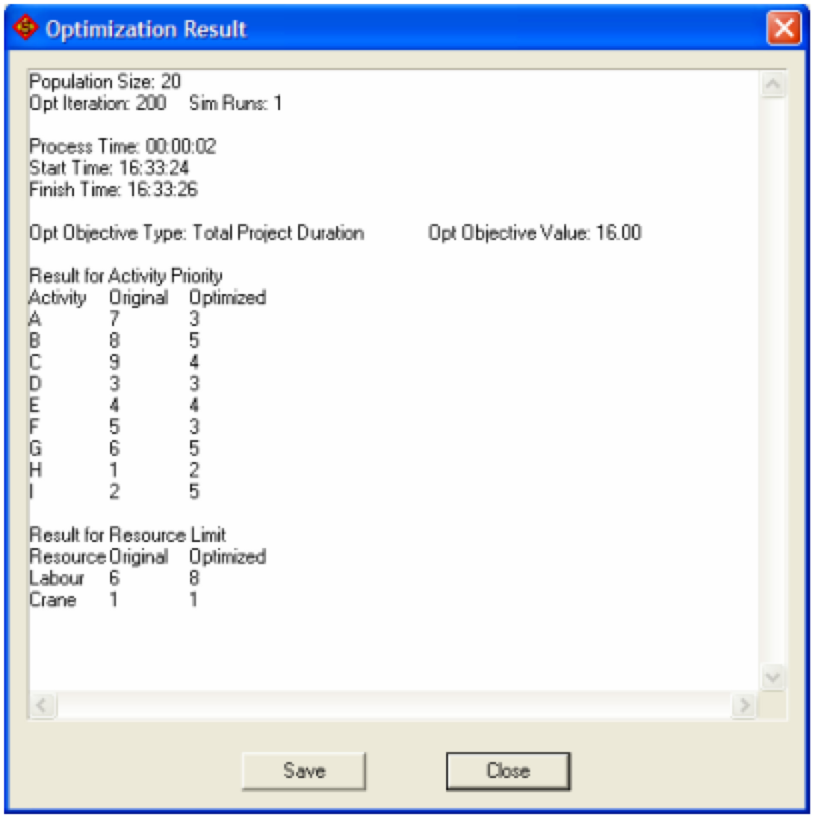


Figure A17. Optimization results in S3

Another objective option is the “optimize total project duration” for dealing with the stochastic PERT simulation models. Similar to deterministic cases, we can optimize the project schedule in terms of attaining the shortest project duration by using the PSO technique to search for an optimum set of resources and activity priorities. Most settings are the same as these settings for deterministic case. The main difference is that the optimization process is divided into two steps (step 1 for initialization of optimization search; step 2 for fine-tuning). Users can define different simulation runs and the number of iterations in two optimization steps. The user can use more simulation runs to avoid simulation output distortion due to sampling errors, however, it requires much longer processing time. The default setting is a good compromise. In general, all default values are recommended.

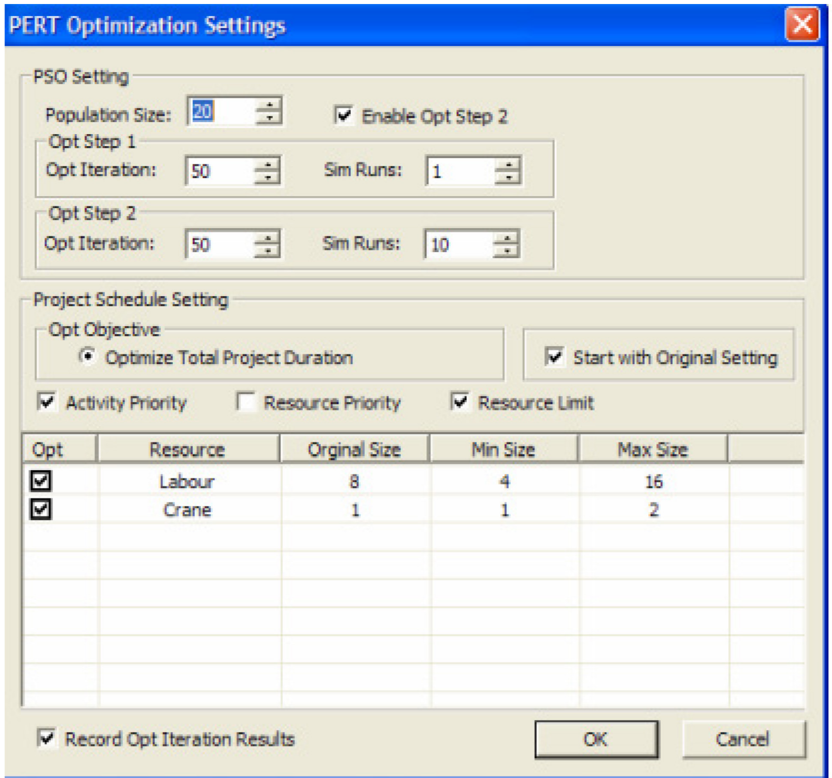


Figure A18. PERT optimization setting in S3.

Note that the processing time is highly dependent on the number of population size, the total number of activities and the computer power.

APPENDIX II

Excel Solver

Solver is a Microsoft Excel add-in program you can use for what-if analysis. Use Solver to find an optimal (maximum or minimum) value for a formula in one cell — called the objective cell — subject to constraints, or limits, on the values of other formula cells on a worksheet. Solver works with a group of cells, called decision variables or simply variable cells that are used in computing the formulas in the objective and constraint cells. Solver adjusts the values in the decision variable cells to satisfy the limits on constraint cells and produce the result you want for the objective cell.

Put simply, you can use Solver to determine the maximum or minimum value of one cell by changing other cells. For example, you can change the amount of your projected advertising budget and see the effect on your projected profit amount. To define and solve a problem (Microsoft Excel Support (online), Shardt 2015).

1- On the **Data** tab of excel software, click Solver to see Figure A.19.

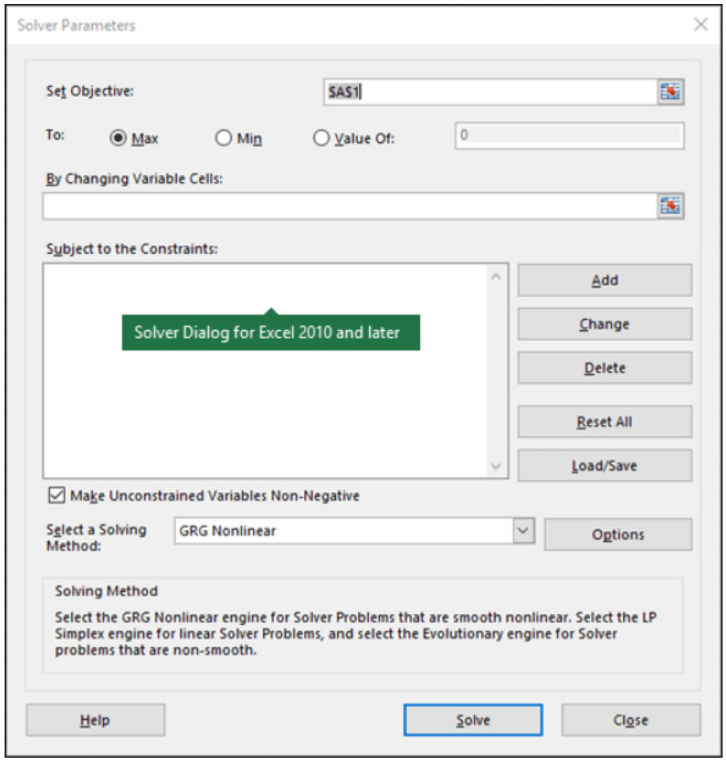


Figure A.19. Solver parameter definition

2- In the **Set Objective** box, enter a cell reference or name for the objective cell. The objective cell must contain a formula.

3- Do one of the following:

- If you want the value of the objective cell to be as large as possible, click Max.
- If you want the value of the objective cell to be as small as possible, click Min.
- If you want the objective cell to be a certain value, click Value of, and then type the value in the box.

- In the By Changing Variable Cells box, enter a name or reference for each decision variable cell range. Separate the non-adjacent references with commas. The variable cells must be related directly or indirectly to the objective cell. You can specify up to 200 variable cells.

4- In the **Subject to the Constraints** box, enter any constraints that you want to apply by doing the following:

- In the Solver Parameters dialog box, click Add.
- In the Cell Reference box, enter the cell reference or name of the cell range for which you want to constrain the value.
- Click the relationship (<=, =, >=, int, bin, or dif) that you want between the referenced cell and the constraint.If you click int, integer appears in the Constraint box. If you click bin, binary appears in the Constraint box. If you click dif, alldifferent appears in the Constraint box.
- If you choose <=, =, or >= for the relationship in the Constraint box, type a number, a cell reference or name, or a formula.
- Do one of the following:

✓ To accept the constraint and add another, click Add.

✓ To accept the constraint and return to the Solver Parameters dialog box, click OK. You can apply the int, bin, and dif relationships only in constraints on decision variable cells.

You can change or delete an existing constraint by doing the following:

- In the Solver Parameters dialog box, click the constraint that you want to change or delete.
- Click Change and then make your changes or click Delete.

5- Click **Solve** and do one of the following:

- To keep the solution values on the worksheet, in the Solver Results dialog box, click Keep Solver Solution.
- To restore the original values before you clicked Solve, click Restore Original Values.
- You can interrupt the solution process by pressing Esc. Excel recalculates the worksheet with the last values that are found for the decision variable cells.
- To create a report that is based on your solution after Solver finds a solution, you can click a report type in the Reports box and then click OK. The report is created on a new worksheet in your workbook. If Solver doesn't find a solution, only certain reports or no reports are available.
- To save your decision variable cell values as a scenario that you can display later, click Save Scenario in the Solver Results dialog box, and then type a name for the scenario in the Scenario Name box.

To examine different labour allocation aimed at minimizing the semi-productive time and optimizing the labour flows of a simple case given in chapter 6, an optimization model is developed and solved using the Excel Solver. Figure A20 and A21 shows the screenshot of the Excel Solver Model.

In order to achieve this objective, the model is designed to identify the main decision variables of early start time of each activity(ES_i), which affects the early finish time of each activity and consequently the project duration which means the total duration of labour resource involvement.

The constraints of the model are defined in a way that the feasible solutions meet the technological and resource availability constraints. The optimization solution needs to ensure a time lag constraint between A and E, at least 8 hr. (i.e., D's duration). So, D is equivalent to a finish-to-start relationship with lag time. Similarly, there exists a time lag constraint between B and H with at least 10 hr. delay (i.e., F's duration). Accordingly, to the proposed case study the constraints are defined as Table A3. Objective function is given as Eq. A1:

$$\text{Min } \frac{(D_{project} \times L_{availabile}) - (\sum_{i=1}^{i=n} D_i \times L_i)}{D_{project} \times L_{availabile}} \qquad \text{Eq. A1}$$

Table A3. Model constraints of simple case study of chapter 6

Technological constraints:		
$ES_A \geq Sart$	$ES_G \geq ES_B$	$ES_K \geq ES_G$
$ES_B \geq ES_A$	$ES_J \geq ES_C$	$ES_K \geq ES_J$
$ES_C \geq ES_A$	$ES_E \geq ES_D$	$ES_D \geq ES_I$
$ES_D \geq ES_A$	$ES_H \geq ES_F$	$End \geq ES_I$
$ES_F \geq ES_B$	$ES_I \geq ES_E$	$End \geq ES_K$
	$ES_I \geq ES_H$	
Labour resource availability constraints:		
$L_{availabile} - Resource\ Allocation_t \geq 0$		
Integer and non-negativity constraints:		
$ES_i = integer$		
$ES_i \geq 0$		

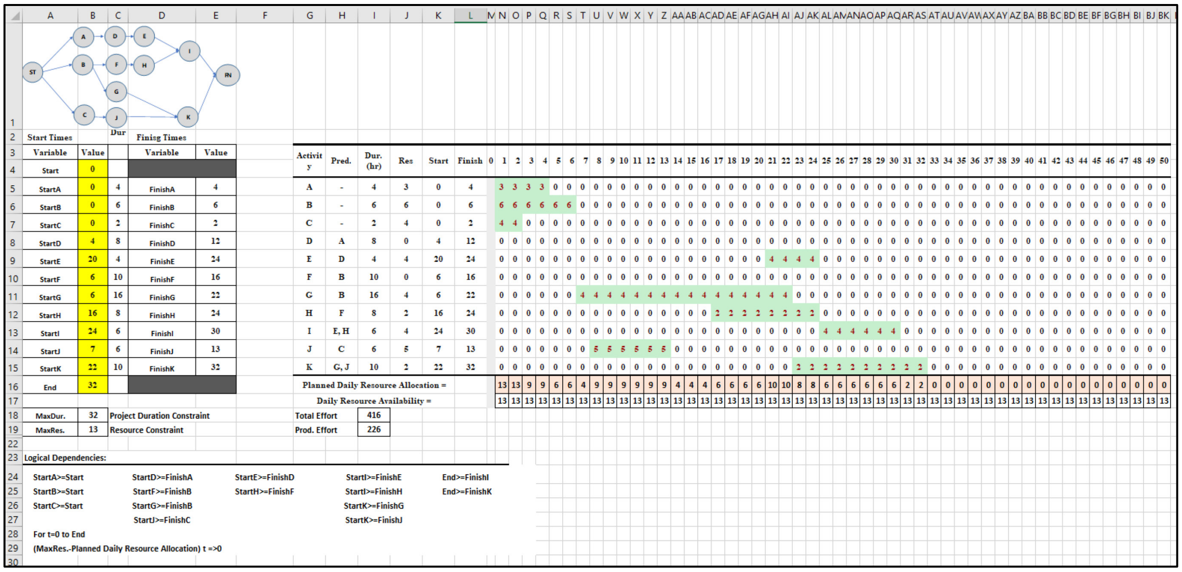


Figure A20. Screenshot of Excel Solver model of chapter 5

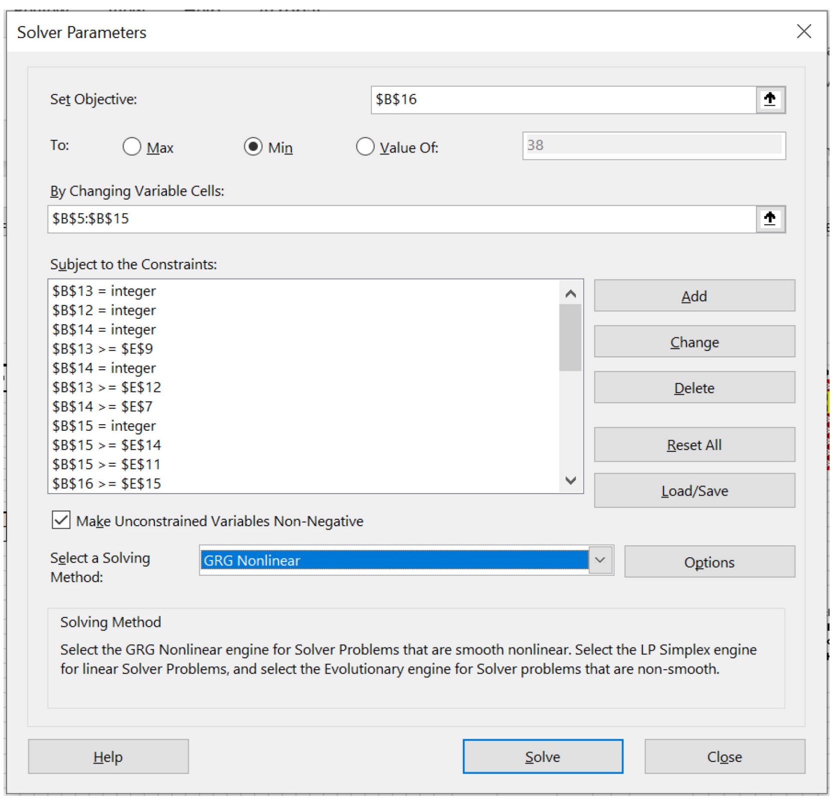


Figure A21. Screenshot of Excel Solver parameter of chapter 5