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# ANALYZING IMPACT OF SEMI-PRODUCTIVE WORK HOURS IN SCHEDULING AND BUDGETING LABOR-INTENSIVE PROJECTS: SIMULATION-BASED APPROACH

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## ABSTRACT

This research investigates labor 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 laborer (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 labor 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.

## 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, labor productivity is defined as the ratio between completed earned work hours and expended work hours to execute a labor-intensive project. Measurement of labor 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 labor-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. Laborer’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 labor 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 laborer’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 repetitive tasks that require frequent labor transferring between different work stations 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-

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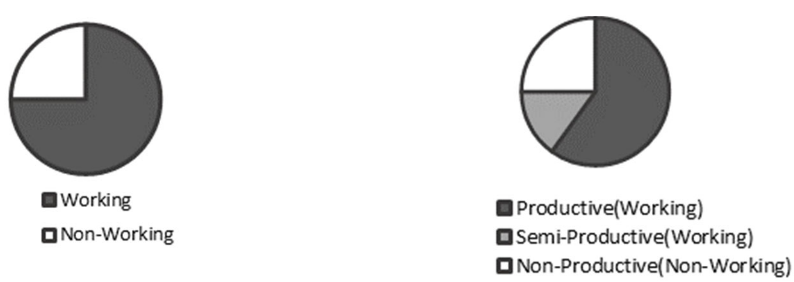
productive labor time from productivity labor time based on actual job cost data is too cumbersome to be practical in labor-intensive operations. In this study, steel girder fabrication projects subject to resource availability and transfer constraints are modelled by a simulation tool in order to logically undertake project execution processes in sufficient details, while enabling quantitative analysis of the semi-productive labor 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 labor productivity by minimizing the semi-productive time. Ultimately, the present research is to prove the hypothesis that a reduction on the semi-productive labor time enhances time and cost performances in delivering the whole project at the end.

## 2 LITERATURE REVIEW

### 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 labor efficiency (Dozzi and AbouRizk 1993). Hanna (2010) defined productive time as value-added operation time. Accordingly, the more productive the laborers are, the more value-added operation time generated out of the total time the laborers are involved in an operation, which results in higher labor productivity.

In general, workers' operation time classifies into working and non-working time [Figure1(a)]. As per Figure 1(b), working time consists of productive (direct work) and semi-productive time (support work). In labor-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 laborers 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, lunch breaks, etc. The non-working time can be interpreted as the 10 min or 15 min time in an hour [as shown in Figure. 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).




(a) (b)

Figure 1: (a) Working vs. Non-working; (b) Productive, Semi-productive vs. Non-productive work hours.

A significant body of labor productivity research has been conducted in the past, which attempts to increase the productive labor time. Thomas (2000) analyzed how productive labor time was affected by the disruption of workflow resulting from schedule acceleration, and proposed matching of the labor resource to the amount of work available to perform, so as to maximize labor productivity. Gong et al. (2011) applied labor time utilization assessment methods, such as work sampling and five-minute rating, and found that there is a statistically significant difference in crew utilization efficiency across different types of activities as well as on 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 labor 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 labor productivity in construction (Thomas et al. 1984; Smith 1999; Fayek and Oduba 2005; Lu et al. 2000; Nasirzadeh and Nojedehi 2013). These models take advantage of a wide range of 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 labor time, few studies have attempted to quantitatively model the impact of activity-specific factors upon semi-productive labor time, including number of crew size, crew matching and labor 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 labor time percent proportion (dark grey) by reducing the semi-productive labor time percent proportion (light grey) [Figure 1(b)]. Particularly, by examining various numbers of crew size and different labor 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 labor time is validated in the end.

## 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 serving 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 laborers' work steps, aimed to generate a well-structured workface plan. In contrast, this research is mainly concerned with improving the cost and time performances 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 the 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 labor availability and transfer constraints, facilitating the determination of productive and semi-productive work hours in the application context of labor-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 labor 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 labor work hours by examining the implications of different crew sizes and labor allocation schemes subject to inter-activity technological constraints.

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

## 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 2012). Figure 2 depicts a typical girder finished with key features annotated.

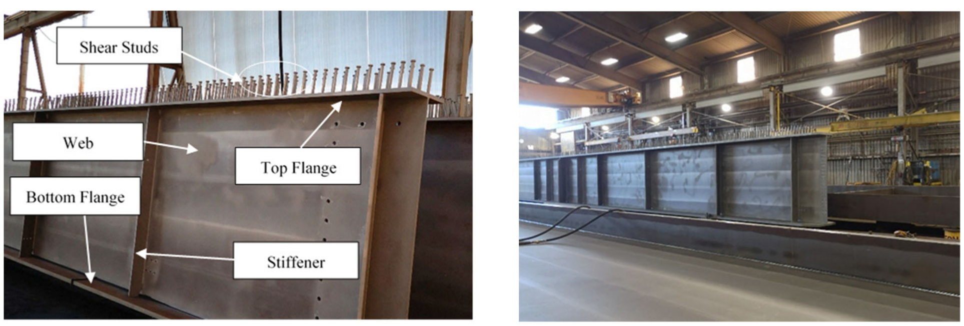
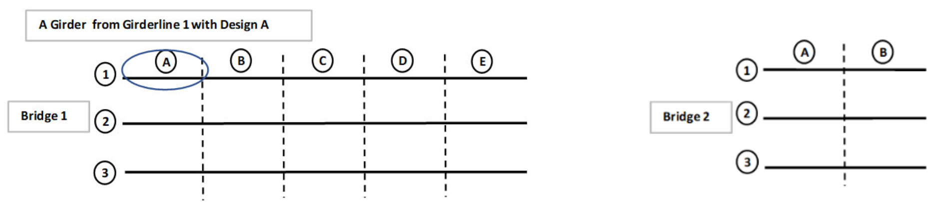



Figure 2: Finished girder ready for shipping.

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). 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 3. Resource limit, workstation-based fabrication activities, duration of each activity, precedence relationships, and required resources are given in Table 1 and Table 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 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 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. 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.

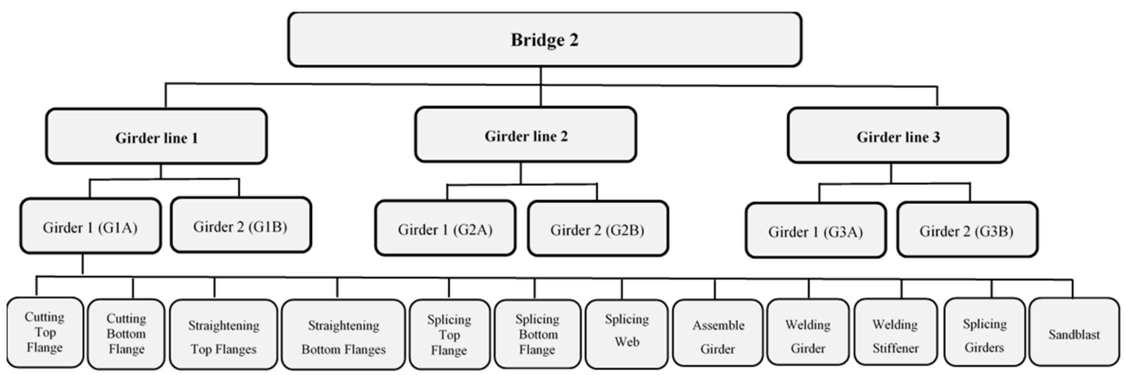



Figure 4: WBS of Bridge 2 project.

Table 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 work stations; on the other hand, all the work stations and journeymen are resources shared between the two projects.

Table 2: Fabrication activity list for girder line G1 of Bridge 1 (JM refers to journeyman).

| 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 SIMULATION MODELING

### 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.

### 4.2 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 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 serves time (RTS), begin and end time of serving, and description. Figure 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 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 6 shows the flow entities and their attributes for the first one hundred and sixty hours of 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 5: Resource entity queue for the first forty two hours of 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 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 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.

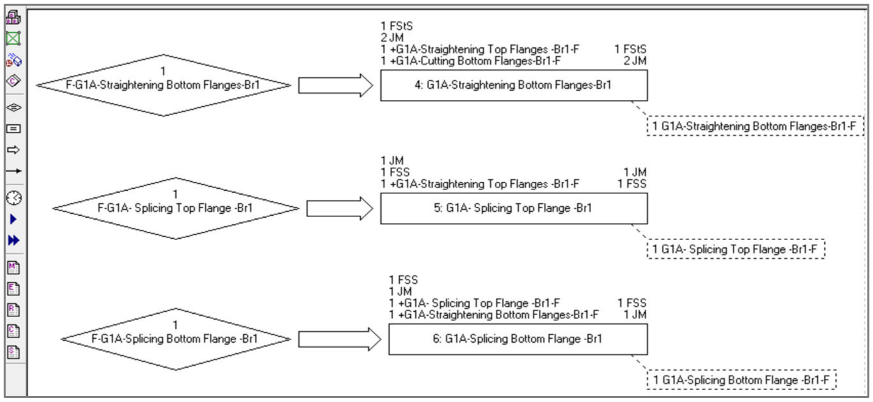



Figure 7: Three activities of SDESA simulation model for Girder1A Bridge 1.

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 8.

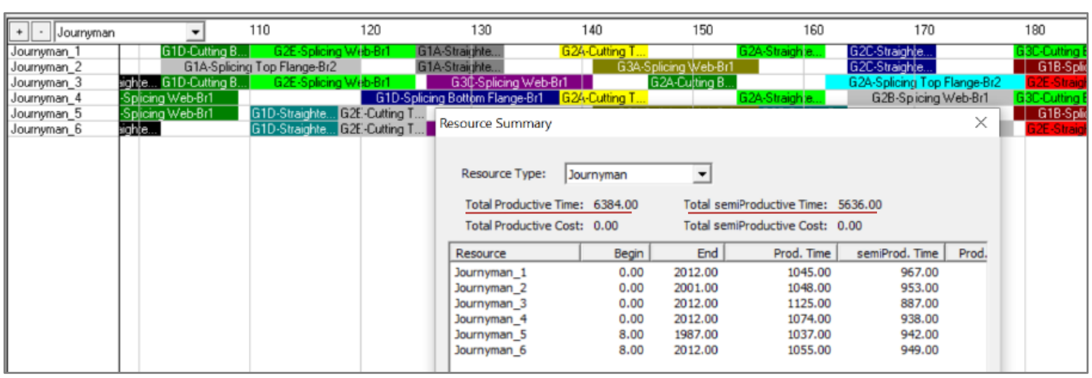



Figure 8: journeymen activity allocation scheme and resource summery window for all journeymen in two-bridge fabrication process.

## 5 DISCUSSION OF SIMULATION RESULTS

When allocating the limited number of journeymen to repetitive 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 AON network, different activity sequencing for individual workers could be developed for the two-bridge project. Figure 9 illustrates three different sequencings for the ninety hours of the case study .

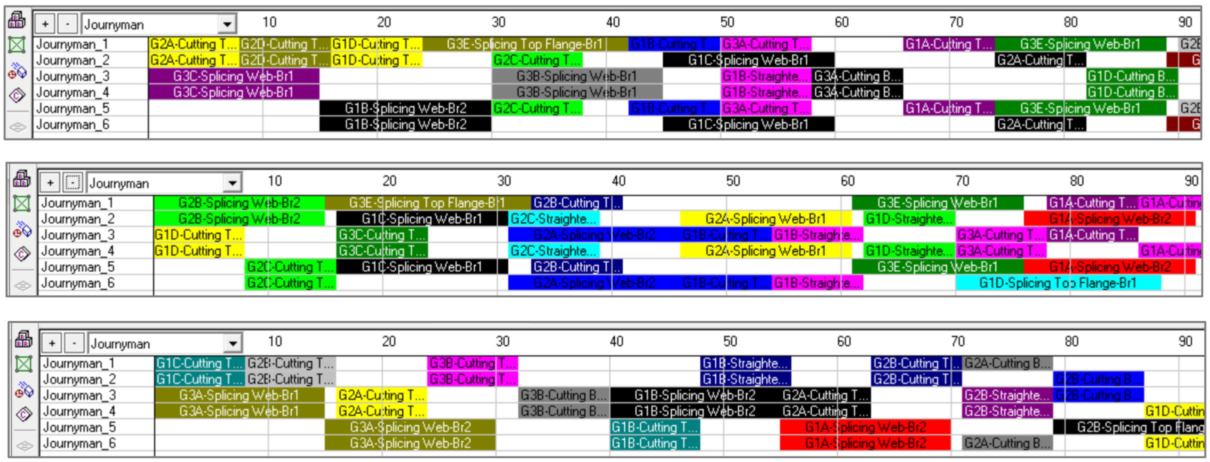



Figure 9: Different activity sequencing examples for the first ninety hours of two-bridge project.

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 (labor hours) presented in Table 3.

Table 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 10. Fitting a trending line to the results shows the semi-productive hours are positively correlated with total project labor-hour cost and project duration, respectively (as seen in Figure 10).

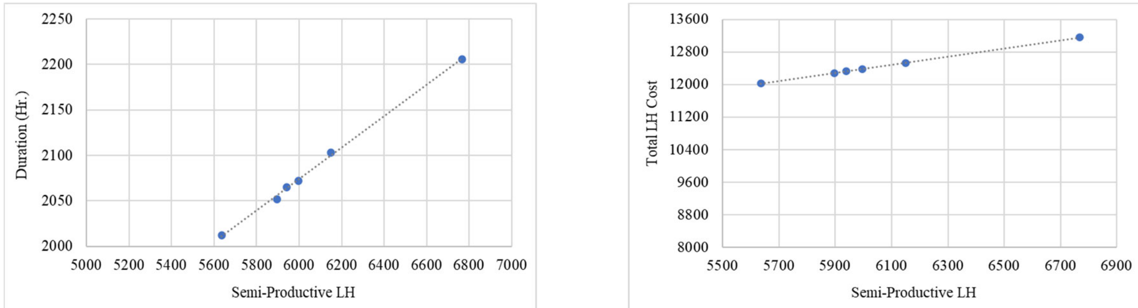



Figure 10: Positive correlation between the semi-productive hours and (a) project duration; (b) Project Total LH cost for Table 3 Scenarios.

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.

Table 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 LH cost respectively, as presented in Table 4. It is found the semi-productive hours are positively correlated with the total labor 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 11).

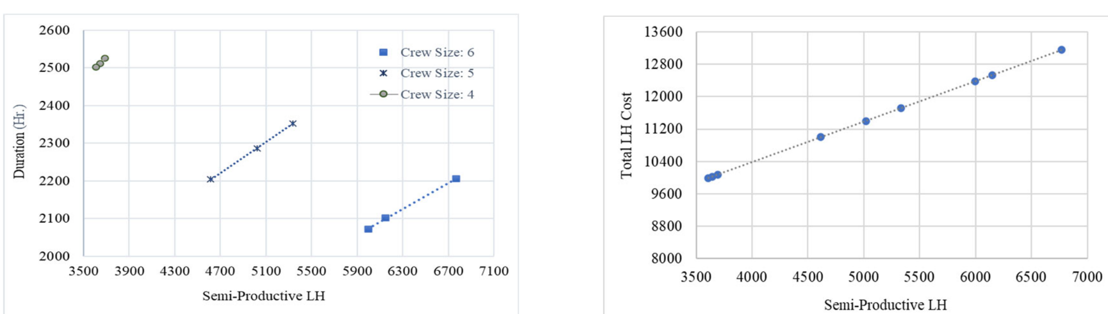



Figure 11: Positive correlation between the semi-productive hours and (a) project duration; (b) Project Total LH cost for Table 4 Scenarios.

Based on the simulated results in Table 3 and Table 4, it comes to the observation that as the semi-productive labor time to productive labor 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 labor ratio, the more productive works are performed during labor 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.

## 6 CONCLUSION

In this research, shifting the uncertainty in project planning and scheduling from activity time variations to different crew sizes and labor-activity allocation schemes, an attempt is made to investigate impact of semi-productive work hours in delivering labor-intensive projects. In a labor-intensive environment of industrial construction, changes in labor-activity allocation plans and crew sizes result in different amounts of semi-productive labor time, thereby affecting labor productivity. The semi-productive time (locating materials, confirming drawings, checking safety) does not directly add value to the production components but they are essential to support the productive time. In contrast with non-working time, which is considered non-productive operation time, semi-productive time is regarded as part of the working time required to execute the operation. In a dynamic fabrication facility, differentiating the semi-productive from productive time is practically infeasible to carry out without using simulation tools. Semi-productive time could impair a laborer's morale by causing work interruptions, adjustments in crew makeup and "stop-and-go" operation (Hanna et al. 1999). Analysis of the irregular semi-productive work hours based on a sufficient resource scheduling simulation would also reduce the negative impacts of high unpredictable semi-productive hours on laborer's morale, thus preventing further productivity loss. This research has proven that as the semi-productive labor time to productive labor time ratio decreases, it results in better time and cost performances of the two-bridge project. In other words, the lower the semi-productive labour versus productive labor ratio, the more productive works are performed during labor working hours, meaning project performance improvement. 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, which ultimatiely yields to higher productivity, shorter project duration and a decrease in project cost.

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