Enhancing Activity-on-Node Network Diagramming Technique for Modeling Interdependent Workflows in Planning Fabrication Projects

by

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Abstract

Fabrication operations produce made-to-order structural components (such steel elements or precast concrete) for multiple construction projects, which require crews to repeat their work at a number of workstations or locations in a special manufacturing facility. Scheduling these interdependent concurring workflows often requires maximizing work continuity for these crews while minimizing resource idle time and crew interruptions. Many attempts have been made in the past to account for the complexities and uncertainties inherent in these complex construction environments and many tools and techniques have been developed to facilitate modelling and analysis. However, these existing scheduling approaches fail to address the extensive resource links among projects, thereby negatively impacting the stability and feasibility of resultant project schedules and increasing management difficulties in different stages of the project. Hence, the workface operation realities often deviate away from the actual planning bringing down the overall productivity. Unless the changes and variations (e.g., material logistics) during operations can be sufficiently and cost-effectively reflected in the planning, the project team would only encounter misleading and unachievable plans and schedules throughout a project.

This research explores a novel resource-constrained scheduling framework named Activity-on-Node Plus (AON+), which fills these gaps by facilitating communication and finding solution to workface planning problems by Discrete Event Simulation or Optimization. The proposed methodology is capable of (1) generating robust resource use plans for multiple interdependent concurring workflows, (2) interconnecting and synchronizing schedules while accounting for both technological and resource constraints, (3) analyzing crew performance in regard to

resource use, productivity, and 'lean' at various levels of granularity, and (4) considering crew interruption duration while adjusting production capacity to generate proper schedules with reduced waste. These advantages are illustrated and demonstrated through an in-depth literature review, two example problems (Bridge deck reinforcement and Bored pile concreting), and one real-life project based on the fabrication of bridge girders in collaboration with a partner company in Edmonton, Canada. SDESA is the DES (Discrete Event Simulation) platform selected for these case studies; however, any other DES platform can be applied to establish this proposed scheduling framework.

The academic contributions of this research are identified as (1) identifying the practical challenges and constraints associated with scheduling and control of different phases of repetitive construction projects based on an in-depth literature review of the current practices; (2) proposing an Enhanced Activity-on-Node (AON+) network diagramming method to account for project complexities and uncertainties while circumventing the aforementioned limitations in the existing models; (3) enabling construction managers to represent details in workflows in a streamlined network diagram by sufficiently factoring in logical constraints imposed by both technology and resource; (4) improving resource utilization efficiency while maintaining modelling simplicity and transparency to improve communication efficiency at different levels of project management, which is crucial to civil engineering applications; (5) analyzing the 'mura' (variations) inherent in product design and reducing the 'muda' (waste) in typical or nontypical repetitive projects of any size or complexity, which is instrumental in planning a lean environment. This developed job-shop production scheduling approach can be applied beyond the steel fabrication productivity modelling and scaled up for typical prefabrication projects of practical size and complexity in construction.

Preface

I, Badhon Das Shuvo, declare that this thesis titled, "Enhancing Activity-on-Node Network Diagramming Technique for Modeling Interdependent Workflows in Planning Fabrication Projects" and the work presented in it are my own. The content is based on the following research papers, which have been reorganized for the thesis in order to streamline the logic and be pertinent to the theme of this thesis:

1) Shuvo, B.D. and Lu, M. (2020). "Lean construction planning subject to variations in detailed features of fabricated bridge girders." *Proc. 28th Annual Conference of the International. Group for Lean Construction (IGLC28),* Berkeley, CA, USA, pp. 1–12. DOI: https://doi.org/10.24928/2020/0115
2) Shuvo, B.D. and Lu, M. (2022). "Enhanced Activity-On-Node Network Diagramming Method for Construction Planning and Scheduling Applications." *Proc. CSCE 2022 Annual Conference*, Whistler, BC, Canada. (Accepted)

I confirm that:

- I am the sole author of this thesis; the work was done wholly while in candidature for a master's degree at the University of Alberta.
- This is a true copy of the thesis, including any required final revisions, as accepted by the examiners.
- The thesis may be made electronically available to the public.

Acknowledgments

At the completion of my dissertation, I would say that this long journey of my MSc study would not be possible without the solid support of my advisor, committee members, and family throughout my studies.

I would like to first express my deepest gratitude to my supervisor, Dr. Ming Lu. The years I spent learning from him are the years I will continue to cherish for the rest of my life. His support, advice, constructive guidance, and encouragement have often been indispensable and is something I dearly treasure.

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Chapter 1: Introduction

1.1 Overview

Repetitive construction projects consist of a number of identical or similar units, where construction crews repeat similar sequential activities at particular workstations in a fabrication facility or moving from one location to the next in the same project. A unit can simply be a typical girder in a bridge or a typical floor in a high-rise building. Repetitive projects can be divided into typical and non-typical repetitive projects (Vorster and Bafna 1992, Hyari and El-Rayes 2006). Typical repetitive projects consist of activities having identical duration in each unit and utilize resources with the same productivity. Non-typical repetitive projects have varying durations for each unit for the same activity, and/or utilize resources (crews, equipment etc.) operating with varying productivity. An example of this category can be the fabrication of girders in a bridge project, where the processing duration may change from one girder to another because of possible variations in their structural properties and resource requirements.

During the linear repetitive construction projects, occurrences of interruptions of deterministic or probabilistic nature are inevitable because of unavailability of resources or human and management factors, thereby causing high variability in activity duration and lower labor productivity. Since the crew assigned to an activity in a number of repetitive units is often required to move from one unit to another, scheduling is to be done in a way to ensure maximum crew work continuity by avoiding unnecessary crew idle time. Traditional scheduling tools and techniques for scheduling repetitive construction projects, such as LOB (Line of Balance), RSM (Repetitive Scheduling Method), AON (Activity on Node) or CPM (Critical path method) have been proved ineffective and widely criticized due to their inability to maximize work continuity for the crews on these projects (Kavanagh 1985; Russell and Wong 1993; Adeli and Karim, 1997; El-Rayes and Moselhi 1998; Fan and Tserng 2006; Hegazy and Kamarah 2008). The fragmented nature of current scheduling practice coupled with lack of effective communication makes it difficult for project managers to make effective and efficient production schedules at the workface facility in line with project goals and constraints (Han et al. 2007; Shokri et al.

2015). This calls for research to ensure maximum crew work continuity with minimum project duration based on the available multiple crews allocated to different repeating activities. AON+ is proposed in this research with the goal of improving repetitive process scheduling by representing the dynamic resource allocation and facilitating productivity level estimation for complicated processes. AON+ is platform neutral; it represents the planning problem in a structured format that is much more streamlined than AON. Although SDESA is the DES (Discrete Event Simulation) platform selected for this research, any other DES platform can be applied to establish this proposed scheduling framework.

1.2 Motivation

With the growing implementation of prefabrication and off-site construction in practice, the focus of job shop scheduling shifts from manufacturing to the practical application context in construction. Due to this trend, significant labor-intensive works have transferred from construction sites to off-site fabrication facilities, where various types of customized components are prefabricated. In a typical shop facility, laborers of specialized skills are allocated to work on different tasks for multiple concurrent projects from time to time. As a consequence, inter-project resource transfers are unavoidably imposed, giving rise to undesired labor work discontinuity (Lee et al. 2015). Scheduling the construction operations for these repetitive projects thus needs to be resource-driven and should entail excessive communication among management teams to maximize the efficiency of resource utilization.

Traditional network techniques such as AON or CPM have been widely criticized in literature for their major drawbacks when applied to scheduling of repetitive projects. One of the biggest challenges with AON or CPM is that it is not oriented towards providing work continuity, making it vulnerable to address or sequence changes of work between the repetitive typical units (Reda 1990). As a result, the uninterrupted utilization of resources from unit to unit cannot be assured, making resource continuity constraints unpresentable directly in CPM networks. Therefore, there is a pressing need for a novel method for scheduling repetitive construction projects that is capable of overcoming these limitations of existing models. The enhanced version of AON (AON+) proposed in this thesis is not to reinvent the wheel from scratch but only to add necessary features to its current format so as to embrace flexibility and account for practical factors commonly encountered during repetitive construction projects.

1.3 Research Objectives

The main goal of this study is to produce an integrated scheduling methodology for managing different phases of repetitive construction projects while accounting for project complexity and uncertainty. In order to achieve this general objective, the following research sub-objectives are accomplished:

- Conducting a comprehensive literature review of the current practices for scheduling of scattered repetitive projects in order to identify the practical challenges and constraints associated with scheduling and control of those projects.
- Proposing an AON+ based scheduling framework, capable of circumventing the aforementioned limitations and research gaps in the existing models.
- Illustrating the model formulation and applications to derive practically feasible solutions for real-world typical (e.g., Bridge deck reinforcement, Bored pile concreting) and non-typical repetitive projects (e.g., Bridge girder fabrication).
- Performing extensive inter-unit resource transfers and synchronizing schedules for various management functions in an attempt to improve management efficiencies without compromising crew work continuity.
- Revealing the 'mura' inherent in project management and production processes and addressing the inherent variations in girder fabrication time and inter-girder lag to facilitate applying lean concepts with a simplified discrete event simulation approach.

1.4 Research Methodology

To achieve the abovementioned objectives, this research proposes an enhanced Activity-On-Node network diagramming method (named AON+) to enhance the construction planning and scheduling practice for repetitive workflows in fabrication projects. The research methodology of this thesis is shown in Figure 1.

The literature on previous related research is first reviewed to investigate the tools and techniques tailored for production planning and scheduling and the limitations in their applicability for managing repetitive construction projects. A novel resource-constrained scheduling framework named AON+ is formalized against AON-CPM, LOB and RSM in an attempt to bridge the identified gaps in the existing models. Detailed explanation and description of the proposed framework is given in Chapter 3. A 'Virtual Plant' was analyzed for aligning with AON+ and streamlined in a Discrete Event Simulation (DES) platform, where the proposed project network diagramming technique was implemented in real world applications to derive the crew performance KPIs in regard to resource use, productivity, and 'lean' at various levels of granularity. It is worth mentioning the Virtual Plant had been developed for the bridge shop of the partner company involved by the Collaborative Research Development (CRD) research team 2016-2020; and had been validated in collaboration with industry partners but not yet formally structured as AON+. The feasibility and capabilities of this validated "Virtual Plant" simulation model are illustrated and demonstrated in Chapter 4, Chapter 5, and Chapter 6 by conducting different case studies. The final part of this research (Chapter 7) sheds light on the effect of variations due to product design features and workflows in bridge girder fabrication, and how lean concepts can be applied for planning field construction operations in practice.

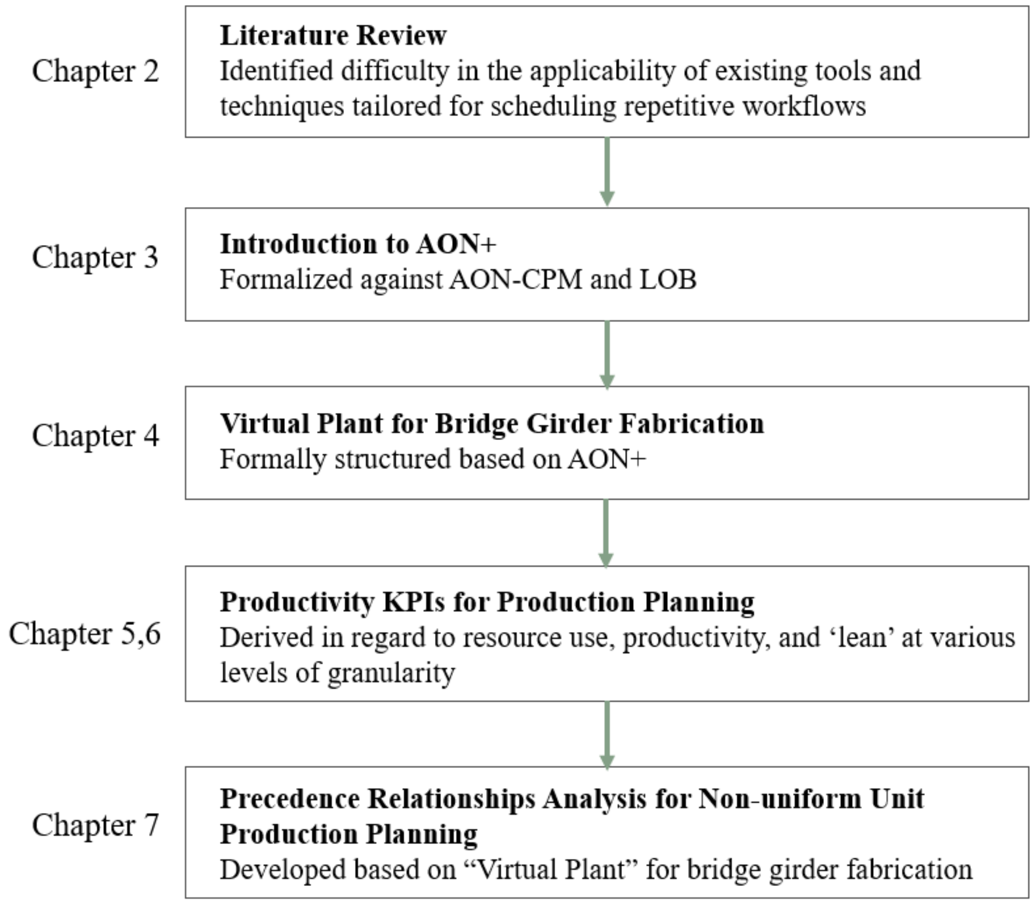


Figure 1. Research Methodology.

In this research, uncertainties in activity duration (in some cases) and shop processing capacity are taken into account when scheduling projects since uncertainty and construction are inseparable. It is noteworthy at a given moment, multiple girders can be processed concurrently in the fabrication shop, making it essential to determine the maximum number of concurrently processed girders in the bridge girder fabrication shop as the shop production capacity. In addition to job processing plans and resource allocation plans, the proposed methodology enables shop managers to customize different useful plans in connection with various management functions by extracting relevant data from simulation results.

1.5 Thesis Organization

This thesis consists of eight chapters. Chapter 3, 4 and 7 are composed based on two conference papers produced during the author's MSc study. To stay pertinent to the theme of the thesis, some contents in these papers have been reorganized. The remainder of the thesis is organized as follows:

- Chapter 2 presents a comprehensive literature review in order to determine the unique characteristics of repetitive projects. It investigates the capabilities and limitations of the existing scheduling tools and techniques for scheduling of repetitive projects.
- Chapter 3 proposes a novel resource-constrained scheduling framework named AON+ in an attempt to illuminate why a planning problem with repetitive workflows does not lend it well to existing solutions to formulate the production schedules.
- Chapter 4 emphasizes the capability of AON+ with two case studies to facilitate communication and devise analytical decision support for workface planning problems by further applying DES or optimization.
- Chapter 5 describes the capabilities of the proposed virtual plant by addressing a practical planning problem in bridge steel girder fabrication.
- Chapter 6 derives the crew performance KPIs for the bridge girder case study in regard to resource use, productivity, and 'lean' at various levels of granularity, which are cross checked against actual data available.
- Chapter 7 exploits a discrete event simulation approach based on the AON+ model to illuminate on 'mura' (variations in product design and production process) inherent in girder fabrication and address the variations in designing the girder-by-girder production plan with SS and FF lags.
- Chapter 8 summarizes the research works, highlights the research contributions, and recommends future research directions.

Chapter 2: Literature Review

2.1 The Project Complexity Puzzle

Project Complexity refers to the measurement of the number of elements and interfaces, or a relative comparison of difficulty to what an organization had previously accomplished (Kermanshachi et al. 2016). A complex project demonstrates interrelatedness and difficulty in cooperation between the functional areas to a degree, or level of severity, that makes it difficult to predict project outcomes or manage the project (Remington et al. 2009). Additionally, it typically begets project difficulty, which in turn makes the project harder to complete and requires special effort to keep project risks in check. Throughout the last few decades, there has been an increasing tendency to draw attention to the particular challenges posed by complex projects. However, most of the references to low or high complexity are often made by intuition and may often represent a relative assessment of complexity by comparison to other types of projects or to similar projects within an industry sector. Thus, in most projects, complexity and uncertainty influence project planning, coordination, and control criteria, impede clear identification of major project goals and objectives, influence the selection of project inputs, affect the project objectives related to scope, time, expense, and quality (Baccarini 1996).

Job shop scheduling problems (JSSP) are considered “one of the hardest combinatorial optimization problems” (Lawler et al. 1982); and over the past few decades, numerous algorithms have been developed for solving JSSP defined in the manufacturing sector. Manufacturing processes in general involve a lesser amount of resource-constrained relationships between activities, where the variation in different pieces of a product is insignificant (Lu and Wong 2007). In contrast with manufacturing, construction is a project-oriented business endeavor producing bespoke products, where more resources are involved, and more interrelationships exist between activities due to space, resource, and technology constraints (Ortega and Bisgaard 2002, Lu and Wong 2007). With the growing implementation of prefabrication and off-site construction in practice, the focus of job shop scheduling has been shifting from manufacturing to the practical application context in construction. A fabrication shop, servicing construction projects generally produces made-to-order products featuring significant variations in product details, fabrication processes, and required shop processing times due to the limited resource availability constraints (e.g., shared crane, shared workspace, and shared journeymen.) In addition, the size and weight for the product are larger and heavier, making it not flexible and not safe to move them around and store them at a temporary storage or a laydown place in and out of the shop. The more complex a project, the greater the number of project elements that must be addressed in order to achieve the project goals. Hence, greater and more comprehensive attention to the project complexity attributes can be expected from the project managers to lower a project's initial risk profile. Well understanding project complexity and creating a complexity management strategy can influence how efficiently and economically projects are planned, executed, and managed.

2.2 Measuring and Managing Labor Productivity

The decline in labor productivity has remained an issue of great concern in the construction industry all over the world. Since labor is more variable and unpredictable than other project-cost components, it is critical to understand the effects of different factors on labor productivity. Highly productive labor is a crucial factor for success in construction projects due to the fact that a major part of the construction budget is allocated to the labor expenses (Hanna et al. 2005, Sonmez et al. 2007). Therefore, productivity improvement becomes a common objective of all the construction companies to offer better value against minimum on-site labor costs, since it is among the most profit-influencing factors (ranges between 33% to 50% of total project cost) (Rowlinson et al. 1999). To reduce the labor cost, it is crucial to enhance labor productivity by identifying and addressing the areas of high and low productivity. This will not only offer strategic advantages to the construction companies, and add to the overall performance management and monitoring, but will also highlight the potential areas of improvement to achieve overall organizational goals resulting in cost efficiency and better resource management (Sheikh et al. 2017).

Past studies and research identified numerous factors affecting productivity. Adrian (1987) in a study, classified the productivity factors causing low productivity as industry related factors, labor-related factors, and management-related factors. Industry-related factors, essentially, indicate the uniqueness of construction projects, varied locations, adverse and unpredictable weather. Labor-related factors include the rework, overtime and lack of motivation. Management-related factors usually refer to the lack of management for tools or techniques (Olomolaiye et al. 1998). According to their perspectives, the nature of the industry, usually the complexity and uniqueness of different construction functions have been affecting construction productivity through delay in drawings, design changes, and following rework.

In the management literature, there is a saying that “what cannot be measured, cannot be managed” (Waal et al. 2013). Although productivity management has such a significant financial influence, the measurement of labor productivity has been a puzzling issue faced by the industry throughout the years. The involvement of complex operations and relationships throughout the life span of a project makes it difficult for the project managers to assess the performance of labor in order to address the productivity issues. One specific approach to measuring labor productivity, which is very popular in the construction industry is called Work Sampling. Work sampling implies a series of instantaneous observations, or “snap shots,” of work in progress taken randomly over a period of time (Jenkins et al. 2003). It classifies all the construction activities into 3 types:

1. Productive (Effective work): Directly related to the construction process that contribute directly to final result.
2. Semi-productive (Essential contributory work): Does not directly influence the outcome but generally required in running an operation.
3. Non-productive (Ineffective work): Not directly related to the work performed.

Mctague et al. (2002), McDonald and Zack (2004), Choy and Ruwanpura (2006) conducted the work sampling analyses, reiterated the findings and concluded that the composition of productive time on a construction site generally falls between 40% and 60% of the total work time. The studies also tracked the individual activities that a laborer spends his time on and revealed that a considerable amount of time is spent mostly on the nonproductive activities, such as idling, waiting for instructions, and searching for material. Although work sampling has been proven far less expensive to perform than other existing assessment methods, which provides a quantitative estimate of the amount of time spent in each category rather than a subjective estimate, there are several limitations that cannot be ignored (Sane et al. 2016):

- Work sampling only allows one to draw conclusions about the average behavior of the group, it does not measure individual's strengths and weaknesses, nor the quality of the work performed.
- If more than one observer is being used, inter-observer difference regards to fundamental details of the work sampling method can invalidate the study's results. Specifically, it should be ensured that: 1) Each observer makes instantaneous observations at the prearranged times, 2) The work categories are being sufficiently well described to ensure that incorrect classifications are not made, and 3) Enough samples are made to reach the desired accuracy in the final estimates.
- Also, workers might change their work patterns upon sight of the observer. This so-called "Hawthorne effect" (Workers being motivated and productivity being increased in response to the increased attention brought on by the experimental set-up) can impact the documentation and assessment of the productivity data (Aboagye-Nimo et al. 2017).

Moreover, work sampling is not broadly implemented by industry because of the scarcity of standard guidelines on how to perform statistical validation of its effectiveness (Sittig 1993). In the end, it definitely identifies productivity issues, but does not determine the root causes or provide any improvement strategies (Gouett et al. 2011). To address this criticism, ‘Activity Analysis’ was proposed as a constant improvement process in order to streamline productivity measurement. It provides a convincing solution for monitoring the on-site operations and supports root cause analysis on the issues that adversely impact the productivity. Activity Analysis can be defined as “a continuous process of measuring and improving the amount of time that craft workers spend on actual construction referred as tool time, wrench time, or direct work time” (CII 2010). Activity Analysis extends the work sampling technique into a continuous improvement process, which includes two parts: (1) workface assessment and (2) continuous improvement process (Sheikh et al. 2017). The workface assessment portion of the Activity Analysis is the application of work sampling (Khosrowpour et al. 2014). According to the study, one of the primary advantages of Activity Analysis over work sampling is that this method includes significantly more detailed observations and results than work sampling.

2.3 Lean Implementation for Waste Elimination

Lean construction was championed by Koskela (1992), who described it as a way to design production systems to minimize waste of materials, time, and workforce, in order to generate the maximum possible amount of value. According to Koskela et al. (1992) and Thomas et al. (2002), the core concepts of Lean Construction is Just-in-time (JIT), which uses pull-driven scheduling to reduce the variability in process and waste, and where units should be available only when required. Eriksson (2010) studied how to increase the understanding of implementing various aspects of lean thinking in a construction project and how supply chain actors and their performance are impacted. Furthermore, the various aspects of lean construction were investigated and grouped into six core elements: waste reduction, process focus on production planning and control, strong user focus, cooperative relationships, continuous improvements, and systems perspective. Later, Marzouk et al. (2011), using a computer simulation tool, assessed the impact of applying lean principles to design processes in construction consultancy firms to aid in decision making at early stages of construction projects. The study concluded that applying lean construction principles to the design process resulted in improved process efficiency, in terms of increased resource utilization and reduced process durations.

From the beginning, the goal of lean construction has been to achieve the highest quality with minimal cost in the shortest time to make the customer satisfied, and this goal can be achievable by continuing eliminate the non value added activities (Nahmens et al. 2011). These non value added activities, otherwise referred to as 'Waste' have been accorded attention in construction management research endeavors in order to address construction productivity issues in general, and lean construction in particular. Koskela (1992), Alarcon (1994), and Love et al. (1997) concluded that all those activities that produce costs, direct or indirect, and use time or resources, but do not add value or progress to the product can be defined as non value adding activities or Waste. Alarcon (1994) gave examples of these activities in construction projects, which include work not finished, rework or unnecessary work, errors, stoppages, waste of materials, loss of labour, unnecessary material and people movement, excessive vigilance or supervision, unnecessary space, delays in activities, extra processing, and abnormal wear or tear of equipment. Research has revealed that although, non value added activities are considered to be a pure waste in the construction process (Ismail and Yusof 2016), most of the participants in construction projects do not have any tool to measure their impacts.

Han et al. (2007) produced a model based on system dynamics for the measurement of non-value-added activities in the construction production system and revealed that though they can be identified and quantified through a simulated model, they can be easily propagated into other related activities. As a result, rework in the form of ‘the rework cycle’ can occur either at the design stage or on construction sites and pervade the construction process regardless of project activities, types or locations (Han et al. 2007). The lean philosophy was introduced aiming at the removal of ‘muda’ (waste in material, time and space) (Womack and Jones 1997) through systematic planning; however, if the existence of ‘mura’ (variations in product design or production process) (Shingo and Dillon 1989) is not well understood and even ignored in planning and scheduling, muda would be impossible to be controlled, let alone to be reduced or eliminated. In reality, it is difficult to reach consensus on classification of value vs. waste, as its definition could vary among different stakeholders. It is not reliable to rely on "commonsense" about lean construction, as "the sense isn't common" in the real world (Howell et al. 1996). Thus, research contributing to common senses on lean construction is much needed.

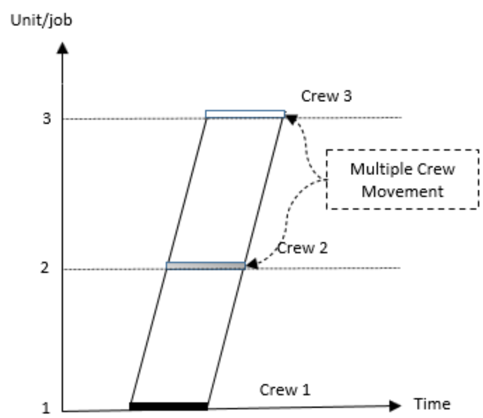
2.4 Scheduling of Repetitive Construction Projects

Construction projects often consist of several identical units, where a construction crew often repeats the same work of that activity, moving from one repetitive unit to another completing a set of work packages that are repeated sequentially at different locations. These activities usually maintain a technologically driven sequence and are continuously subject to resource constraints imposed by internal technological, managerial, or external causes holding true for the entire life span of the project (Kallantzis and Lambropoulos 2004). Projects of this type are thus considered high risk, which potentially causes delays in overall project completion and budget overruns, thus making the management of resources a very significant issue (Ipsilandis 2007). During the last decades a significant number of planning techniques have been proposed for scheduling repetitive construction projects. These techniques can be classified into two basic categories: Resource-driven methods (i.e., LOB, RSM) and Duration driven methods (i.e., CPM, PERT). A LOB (Line of Balance) or RSM (Repetitive Scheduling Method) schedule allows the balancing of operations such that each activity is continuously performed from one unit to the other (Hegazy 2002). A LOB schedule is presented graphically as an X-Y plot where the two axis represent units (or cycles) and time. For houses, stores, apartments, or floors in high-rise construction (vertical construction projects), the repetitive units are usually discrete entities, and work progress is generally measured in units completed (Harris and Ioannou 1998). As a resource-driven technique, LOB identifies a balanced mix of resources and synchronize the activities such that these resources are fully employed. The major advantage of a LOB scheduling is that it represents the duration and production rate information in such an easily interpreted graphical format (Yang and Ioannou 2004), it allows the planner to adjust the rates to meet project deadlines, while maintaining the work continuity of the resources (Hegazy and Kamarah 2008). In contrast to the LOB or RSM methodology, duration driven methods like CPM (Critical Path method) assumes the activity durations as functions of the resources required (rather than available) to complete each activity (Ammar 2013). When resource availability is not as required, the general assumption is to delay activity start till required resources are available; or productivity is lowered, and activity duration is prolonged.

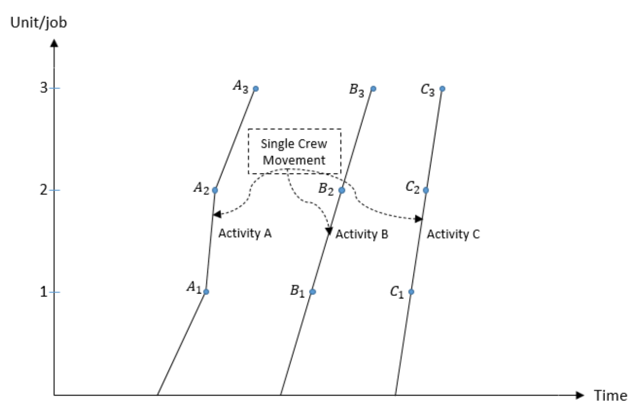
2.4.1 Basic LOB Representation

Planning and scheduling repetitive projects have a unique nature that justifies the utilization of the line-of-balance (LOB) technique. Line of Balance (LOB) encompasses the original form (constant slope), the flowline variation (changing slope instead of straight line) and later repetitive scheduling method (RSM) formalized for discretizing continuous space into spatially interconnected jobs (repetitive floors in high-rise building). LOB/RSM effectively represents crew-activity execution patterns on linear or repetitive projects. Trimble (1984) described the LOB as a resource-oriented scheduling tool and mentioned that scheduling with resources as the starting point may be more realistic than activity-dominated scheduling. The LOB chart (Fig. 1) provides a vivid overview of the project's overall status by quantitatively representing the cumulative completion of activities associated at a given point in time. It graphically reveals any imbalance that suggests a deviation from the plan due to the actual uneven progress of activities, and promptly enables management to focus on assessing the variation quantitatively (Khisty 1970).

Let's consider a scenario, where the project is divided into three repetitive units, with three discrete tasks, repeated at each unit. A specialist crew works on consecutive jobs continuously in time and space in executing a particular activity (say Activity B). The activity has technology constrained preceding and succeeding activities, entailing minimum space or time buffers in between: A precedes B; C succeeds B.



a) LOB representation



b) LSM representation

Figure 2. Basic representations of repetitive activities.

The sequence of work must be maintained by each crew at each location along the chainage on a linear project, or at each job in a predefined sequence of spatially interconnected jobs. The multiplicative complexity of the resulting LOB diagram for all the three units of the project, is shown in Figure 2. All task dependencies are finish to start as shown in the precedence network diagram in Figure 2 along with other constraints. The most common representation format of LOB is shown in Figure 2(a), in which each bar represents one activity, and each repetitive unit is represented by a horizontal line. This representation allows for multiple crew usage in the same activity, as shown in the Figure. The width of the bar is the activity duration of one unit, which is assumed uniform along all units. This assumption is not practically true but still realistic, especially in projects with a large number of repetitive units (Ammar 2013). Although variable duration at different units of an activity can be assumed, it is too difficult to model using this visualization.

Harris and Ioannou (1998) introduced another representation, in which a repetitive activity is represented by a single line instead of a bar. Horizontal segments on the progress line correspond to work breaks or resource idleness between the execution of a task in successive units. Two points represent each unit, for example the point A_1 denotes the unit start time of a particular job, whereas A_2 denotes the finish time for A_1 and start of another job, as shown in Figure 2(b). The horizontal difference between the two points is the activity duration for that unit. The slope of flowline denoting the crew production rate of the specific task at each unit. In this scenario, the crew production rate varies on certain construction activities (Activity A), which remains nearly constant on others (Activity B and C). For example, in road construction, the subgrade activity (A) entails cut and fill earthwork and the subgrade crew's production rate could broadly vary from section to section depending on the ground condition and the soil property. For the pavement activity (C), crew production rate can be generally maintained at a constant production rate given consistently suitable weather condition and a reliable asphalt mix supply. This visualization can easily handle variable activity durations (i.e., variable work quantities) along different units. However, multiple crew usage cannot be modeled using line representation; in addition, resource sharing between various activities is generally not accommodated in LOB. Thus, it would be infeasible to model the multi-skilling labor usage in a fabrication facility where a journeymen is involved in performing multiple activities. These shortcomings of both these cases indicate the inefficiency of LOB to model repetitive activities with variable activity durations (i.e., variable work quantities) and dynamic crew allocation that are commonplace in executing prefabrication projects.

2.4.2 Critical Path Method (CPM)

Both practitioners and researchers voiced their disappointment with CPM application on repetitive projects. One of the main reasons was CPM's vulnerability to sequence changes of work between the repetitive typical units, which is, on repetitive projects, caused by the unforeseen circumstances (Rahbar and Rowing 1992). Figure 3 shows the application of CPM in repetitive construction where technology-constrained relationships are imposed horizontally at each job location. The generalized project patterns in the format of AON are as follows:

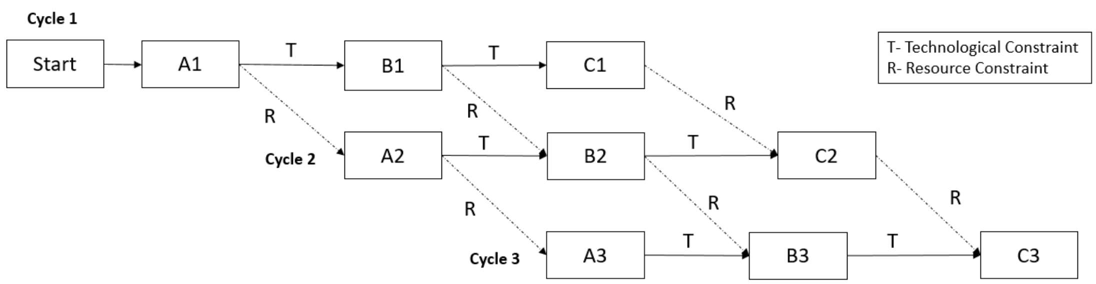


Figure 3. Sequence of jobs driven by Logical Relationships.

In the vertical direction of AON, only resource-constrained relationships are imposed represented by the dotted lines; where a particular activity crew completes the current job, then moves to start the next one in the spatial order. This assumes that a crew working on a typical activity, for example activity C1, is supposed to move from one unit to the other according to the sequence dictated by the management and represented by the dotted relationships. However, the crew often follow a different sequence and the need for revising the dotted relationships would be real and practical to maintain a meaningful and manageable schedule.

Figure 3 is a CPM network prepared for a project consisting of three repeating units of work, where each unit consists of three activities. The solid lines linking the activities within each unit define the technical precedence constraints in the network. For example, activities B2, C2, and A3 cannot be started until Activity A2 is completed. The dashed lines linking similar activities from one unit to another unit represent the resource availability constraints; for example, Activity C3 cannot start until the crew from Activity C2 is available. Now the units can differ in the number of activities each contains, and the individual activity durations can vary subsequently.

2.5 Limitations of Existing Scheduling Models

Despite the wide application of both RSM and CPM in construction management, various researchers have challenged their applicability in an attempt to prove their inadequacy for scheduling real world repetitive projects. The biggest limitation with the use of CPM is that it is not oriented towards providing work continuity for the crew of the repetitive activities, which is fundamental in repetitive construction. The revision of the dotted relationships becomes even more tedious if the planner has, realistically, deployed more than one crew to work on each typical activity. Scheduling without correcting this error produces mistaken schedules. Therefore, each time the sequence is changed, it becomes necessary to expend many work hours to correct the dotted relationships to keep the schedule meaningful and workable (Rahbar and Rowing 1992). As a result, the uninterrupted utilization of resources from unit to unit cannot be assured, making resource continuity constraints largely ignored in CPM networks.

According to Ipsilandis (2007), the objective of RSM or LOB is achieving work continuity leading to minimizing the overall project cost without considering the minimization of the project completion time. Although reduced cost is desired in most of the construction projects (Yang 2002), this assumption may not be true since extending the project duration may result in delay penalties and lost revenues. Kavanagh (1985) pointed out that the LOB techniques are designed to model simple repetitive production processes with a limited degree of complexity and, therefore, practically meaningless in a complex construction environment. CPM-based techniques have been criticized for its inefficiency to describe the repetitive nature of Linear Repetitive Project scheduling. Nonetheless, Network analysis has been characterized by its critics as insufficient to account for neither resource availability nor work continuity (Hegazy 2002). This methodology treats the piecewise execution across the project units as a set of distinct activities connected only through precedence relationships. However, for the Linear Repetitive Project scheduling, the size of the corresponding CPM network quickly explodes in size. Ammar et al. (2002) developed a CPM-based repetitive scheduling model to schedule repetitive activities in an easy nongraphical manner, where the model considered only the most significant resource for each activity and failed to acknowledge multiple crews used by an activity.

Simulation is considered an appropriate methodology to assess and model the non-deterministic nature of construction projects and the effect of uncertainties (Yang 2002). Ashley (1980) studied the planning of housing projects with the GPSS simulation language, which optimized the minimum project duration by altering inputs in the simulation. Kavanagh (1985) proposed a scheduling approach called SIREN (Simulation of Repetitive Networks) to solve repetitive project scheduling problems, which combined two concepts of the network scheduling technique and the queuing technique into a simulation system named GPSS. Lutz (1990) introduced MicroCYCLONE, where he focused on applying learning phenomenon, cycle monitoring, and buffer monitoring to solve similar scheduling problems. Nevertheless, all these studies could not control or eliminate idle times to achieve continuity in resource utilization (Yang 2002, Ioannou et al. 2005). Taghaddos et al. (2012) introduced a hybrid framework called simulation-based auction protocol (SBAP) to schedule the fast-track modular construction projects in consideration of limited resources and space in an assembly yard. Schramm et al. (2008) and Gupta et al. (2012) applied DES to assess the relationship between labor productivity and inventory buffer levels; and established work sequences to reduce non-value adding activities in the repetitive building projects. Mohsen et al. (2018) used Simphony.NET to analyze and simulate the floor operations at a cabinet manufacturing facility where different scenarios were investigated to reduce work-in-progress and decrease idle time. Irrespective of the DES platform used for resource scheduling simulation in hope of improving productivity or lean performances, the fundamental question is how to structure a complex system into activities and logical relationships and how to represent the resource workflows in the real world so that sufficient details of resource use and engineering processes in the system can be accounted for in a streamlined format. Both the last planner system (LPS) and the value stream mapping (VSM) share the same vision to improve workflows and detailed resource use planning in construction. Hamzeh (2016) used LPS to simulate real project conditions and ensure work continuity by removing constraints before and during execution. The VSM technique originated in lean production is valuable to map out processes and identify time or material wastes in the system (Masood et al. 2017); nevertheless, its effective implementation calls for a cost-effective and agile technique to make simulation models of the dynamic interdependent working processes.

Through this research, AON+ essentially is proposed to address this fundamental application need for productivity study or for lean construction. The resulting AON+ network model can be taken as work breakdown structure and project network diagram, which provides the basis for simulation modeling in any DES platform. In this research, SDESA (Simplified Discrete Event Simulation Approach) (Lu 2003) is selected because AON+ formalization has been inspired by and benefited from the modeling view and model element concepts of SDESA for streamlining the network diagram representing resource workflows and production processes, e.g., tracing the workflows of individual crews or workers in terms of repetitive work units being processed (called "flow entities" in SDESA); tracking the flows and critical events of individual resources (worker or equipment) in space and time; distinguishing repetitive work units with attributes feeding into activity time functions in scheduling; distinguishing disposable resource vs. non-disposable resource; use of disposable resource to impose on the resource constrained relationships between activities in various workflows. This is in contrast with using arrow connections to link interdependent activities in various workflows by other simulation modeling methods or established flowcharting techniques (such as AON for CPM), resulting in much simplified resource-constrained repetitive workflow models. In short, this research study formalizes a novel resource scheduling methodology termed as “AON+” based on activity definitions and process mapping in a simplified discrete-event simulation environment under practical constraints such as variations in attributes of repetitive work units (non-typical work units), limited resources, and activity interruptions. Two example applications and one real-world case study are presented afterwards to illustrate the implementation and features of the proposed model based upon the repetitive workflow patterns associated with non-uniform work units.

The proposed framework can be used with regression models to relate differences in features of the girder with the productivity in the virtual plant. This is done by selecting a proper set of input variables, each input variable contributing to accounting for the dependent variable. In steel fabrication, plates are used as stiffeners creating connections between structural elements. Groove welding is done to connect fabricated components permanently (Mohsenijam et al. 2019). Groove welding can be classified into two types: complete penetration welds and partial penetration welds. Since the complete penetration welds are thicker than the partial penetration welds, it requires more labour-hours compared to the partial penetration welds (Mohsenijam et al. 2019). Besides welding, bolted connections are also commonplace for splicing steel pieces to permanently connect steel pieces in the construction site. More efforts or manhours are required for drilling holes and handling pieces as the number of bolts increases.

AON+ uses linear regression models to predict crew size (permanent hire of multiskilled journeymen) required based on variation in girder design features (Hasan et al. 2019). Utilization of multi-skilled journeymen can enhance the flexibility of production planning against variations in design features and resource availability. Since every journeyman is capable of performing their primary activity as well as the next immediate activity in the workflow, resource idle time can be minimized while enhancing the crew productivity (Arashpour et al. 2017). The main variations in production planning in this research are not in activity time, rather in production sequence and crew size. The job sequencing and resource constraints were evaluated in collaboration with industry professionals based on design features of individual girders to predict the number of permanent multiskilled journeymen required. It is noteworthy at a given moment, multiple girders can be processed concurrently in the fabrication shop, making it essential to determine the maximum number of concurrently processed girders in the bridge girder fabrication shop as the shop production capacity. In addition to job processing plans and resource allocation plans, the proposed methodology enables shop managers to predict ideal crew size (multiskilled journeymen) and customize different useful plans in connection with various management functions by extracting relevant data from simulation results.

Chapter 3: Enhanced Activity-on-Node (AON) Network Diagramming Method for Fabrication Planning and Scheduling Applications

Repetitive construction projects undergo a set of activities that are repeated sequentially at different locations or units. However, among these activities there may exist both repetitive and non-repetitive jobs together in a construction project. For example, in a road basecourse construction project, multiple truckloads of aggregates need to be unloaded on one road section in the site before the road undergoes a workflow of grading, moistening, and compaction. Here, the truckloads follow a similar kind of activities for multiple times (repetitive part), whereas the grading, moistening, and compaction may happen only once (non-repetitive part). Vorster et al. (1992) divided the repetitive projects into typical and non-typical. Typical repetitive construction projects utilize resources (crews and equipment) having same productivity and consist of activities with same quantity of work needed for each repetitive unit. On the other hand, the non-typical projects have different quantities of work needed for each repetitive unit; utilize resources operating with different productivity. AON or Critical Path method is the most recognized and commonly used planning and scheduling technique for the graphical representation of project activities and their relationships in repetitive or non-repetitive construction projects (Galloway 2006).

3.1 Activity-on-Node (AON)

AON diagram is a graphical representation of project activities and their relationships and is the most recognized and commonly used planning and scheduling technique for construction projects (Galloway 2006). This precedence diagramming method uses nodes (or boxes) to represent the start and finish of each activity (Figure 4). These various nodes are connected from beginning to end with arrows to depict a logical progression of the dependencies between the scheduled activities. Each node is coded with a number or letter that correlates to an activity on the project schedule. The network diagram generally has many paths originating from one point and ending at another point. Each of these paths has a duration, and the one with the longest duration is called the Critical Path. The sum of all activity durations in the Critical Path equals to the project's duration; therefore, a delay to any critical activity results in a delay to the project completion date. Thus, this CPM based diagramming method can be used to provide a visual representation of the network logic of an entire project schedule. In an attempt to elaborate the method of AON, consider following activities with corresponding duration and resource requirements given in Table 1. This example is built upon on Fig. 9.3 presented by Ahuja et al. (1984).

Technology-constrained precedence relationships are:

- Activity A must precede D;
- E cannot be started until A is done;
- D is followed by H;
- F succeeds B;
- G's predecessor activities are B and C;
- Upon finishing F and G and B, activity I can start;
- Only 6 carpenters are available at any time.

Table 1. Duration and resource requirements for activities.

Activity	Duration (Days)	Resource
A	2	4L
B	3	4L
C	5	4L
D	4	3L
E	4	1L
F	3	2L
G	6	2L
H	2	2L
I	3	2L

The equivalent AON network based on the above technology-constrained precedence relationships is given below (Figure 4):

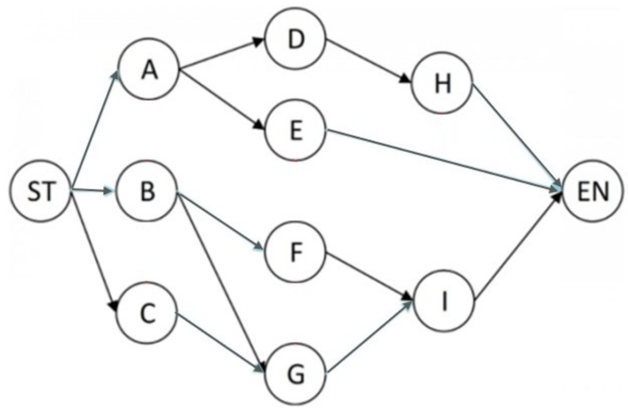


Figure 4. AON diagram without resource constraints.

Now the initial AON (technology constraints) needs to be imposed with extra resource constraints due to the resource availability limit; thus, resulting in the transformation of AON (Lu et al. 2003). For one current activity, its resource-constrained successor activities include the immediately following activities that in part or in total involve the resources shared or used in the current activity. The resource-constrained precedence relationships for this example are:

- Activity E and D follow A;
- A follows B;
- B and G follow C;
- H follows D;
- F follows E and G;
- I follow H.

When these new relationships (red) are added, the redundant relationships can be identified (light blue) in Figure 5.

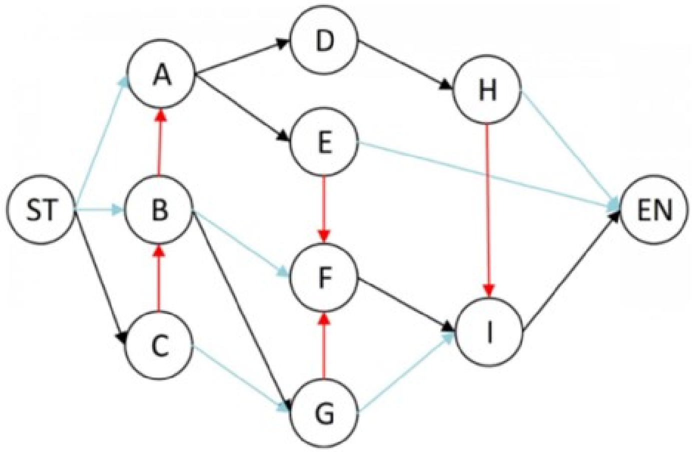


Figure 5. AON Diagram with resource constraints.

After the removal of the duplicate or redundant relationships from the diagram, the reconstructed AON can be found in Figure 6.

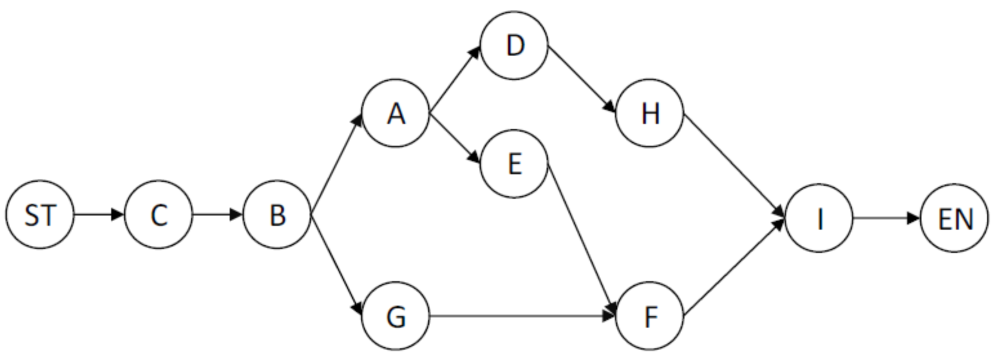
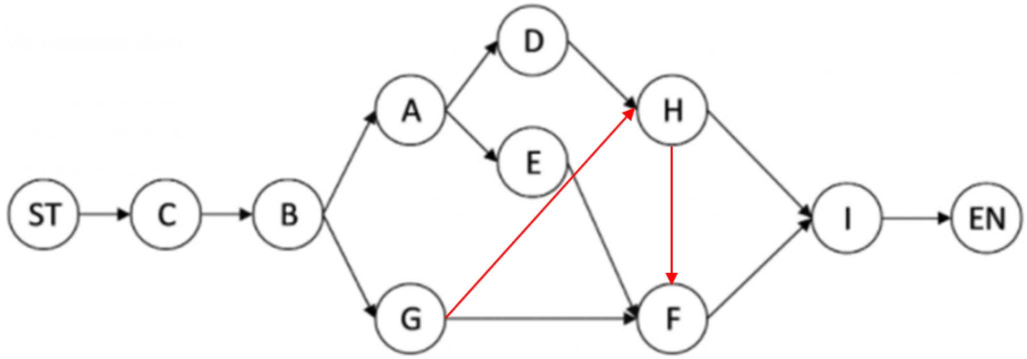
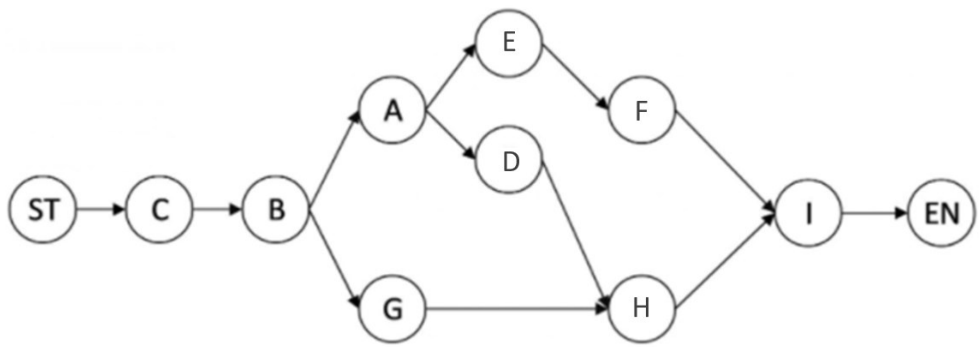


Figure 6. AON Diagram without redundant relationships.

However, in the final check of this work plan, it is revealed that Activity G and H will occur at a limited workspace so that workers can maintain adequate physical spacing, starting H follows the completion of G. Besides, activity F and H each will require the use of a special mobile crane in addition to the labor resource requirements. Hence, two new resource links (G to H; H to F) can be identified and added to the diagram given in the current problem (Figure 7).



a) New relationships added



b) Reconstructed AON Network

Figure 7. Reconstructed AON due to the extension of resource constraints.

One of the reasons why AON/CPM is still the most popular scheduling method in scheduling repetitive activities is that it provides well-established logic in the network analysis phase and permits further computerized applications. The network analysis method involves forward and backward pass calculation, which logically identifies the critical path and performs scheduling analysis to determine the total project duration. Also, the network can be rearranged and redesigned based on planner's intuition and experience to obtain the most desirable result. Although AON can be applied to represent a well-established logic, its analysis features are limited to tackle the repetitive construction projects. For the above example, the critical path depends on the transformation of AON, which continues to be updated with new constraints. For any real world workface planning scenario subject to technology and resource constraints, AON always keeps changing, transforming itself to such an extent that it can be intractable to keep up with changes in practice when the scale and complexity of AON turn overwhelmingly complicated due to the size and technology of the planning problem. When the number of repetitive details continues to increase, the resultant CPM schedule gets cluttered with the repetition of information posing it a complex challenge to interpret information for the practitioners. So, the question still remains how to make the AON network model tractable given these practical constraints and variations. It is desirable to have a sufficient, streamlined, while rather stable form of AON to represent the operations in workface planning. Besides, the CPM formulation often results in large daily fluctuation of resources, and therefore, individual resource-leveling efforts are required to improve resource utilization and avoid excessive hiring and firing of resources (Kamarah 2018). The limitations of AON become even more apparent when applied to projects of repetitive nature. When representing the CPM network for any repetitive project graphically, individual nodes or arrows are required for each repetitive activity, which results in a complex network and makes it difficult for the project team to visualize and understand the project schedule (Harris and Ioanno 1998, Ipsilandis 2007).

The limitations of AON and its inability to model repetitive projects has been widely recognized in the literature. Maintaining work crew continuity is essential in repetitive projects to minimize interruption or idle time for labor and equipment. In general, repetitive activities in the projects with repetitive nature have varied production rates. This imbalance in productivity rates can often hinder the project performance by causing inefficient utilization of the available resources. In AON diagramming method, each activity starts immediately after the completion of its predecessor activities without considering the production rate of each crew specific to the current job unit (such as special design and detailing features), and therefore, the work continuity becomes difficult to be maintained. A faster crew often has to remain idle until all its predecessor activities that utilize crews with slower production rates are complete, resulting in an inefficient and imbalanced utilization of resources (Fan and Tserng 2006, Kamarah 2018).

3.2 AON+

The enhanced version of AON (AON+) is not to reinvent the wheel from scratch but only to add necessary features to its current format. AON+ represents a construction system by:

- Delineating major activities and workflows;
- Defining individual activities within each workflow and the flow entities associated with each workflow; and
- Identifying resource entities involved in workflows.

In the AON+ model, resource entities are classified into disposable resources and non-disposable resources compatible with SDESA (Chan et al. 2006). Disposable resources represent material units or information units, generated by one activity, and requested by another which are associated with two different resource workflows. Disposable resources constitute part of resource-availability constraints in matching resources prior to starting activities. This is contrast with non-disposable resources such as manpower/machinery, or space block, commonly applied in construction. AON+ represents a construction operation by delineating major workflows, where a workflow consists of major activities (or work packages) logically connected with arrows to denote finish to start precedence relationships. Each workflow can handle a set of work units or cycles, each being easily identifiable and measurable unit of work that is processed by activities and easily identifiable and measurable. The work units, also called as flow entities in simulation terms (Chan et al. 2006), can also be likened to the materials takeoff in certain unit measures in estimating costs for construction activities. The associated flow entities are generally a certain quantities of material to be handled or production units (e.g., units of material, parts, and subassemblies). AON+ results in a cost-effective project network modeling methodology enabling engineers to capture details in construction operations in basic process dimensions. The resulting AON+ is essentially structured problem inputs ready for further simulation or optimization analysis.

3.3 Challenges with Applying AON Diagramming Method: Rebar Deck Case

The construction operation of repetitive nature considered here to showcase the complexities of AON and implementation of AON+ framework is the Rebar Installation on a Bridge Deck problem illustrated in literature (Lu et al. 2017). According to the example project, the Creek Deck is 57.5m in length and 11m in width. As per design drawings, rebars are placed in two layers and two perpendicular directions, namely: top and bottom layers, and short and long directions. Rebar stock will be processed in a rebar bending yard next to the site and then delivered to site as cut-to-length rebar segments. The installation operation of reinforcing steel is decomposed into two work packages (WP) as follows (Figure 8):

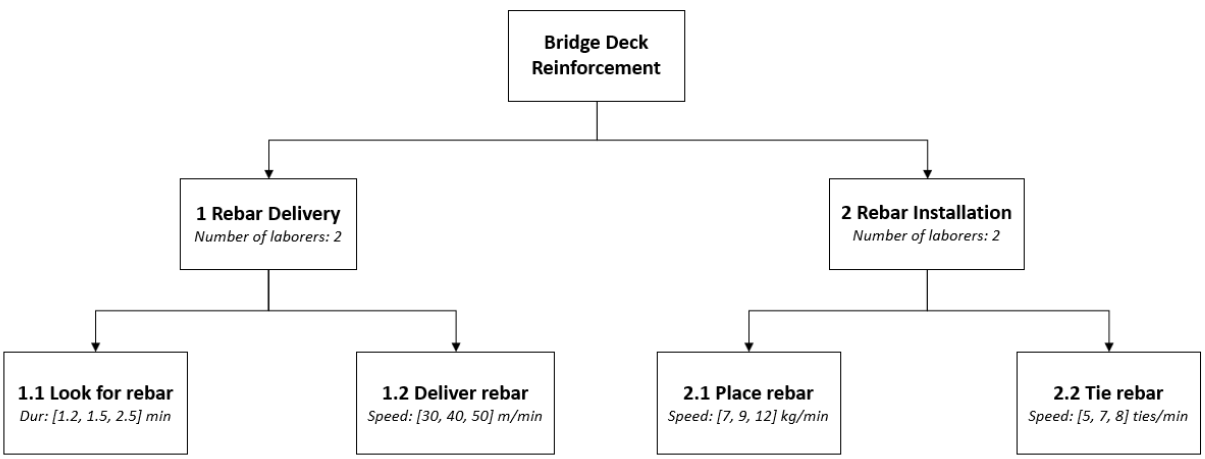


Figure 8. Work packages for Bridge Deck Reinforcement.

The first work package consists of looking for the appropriate bars and carrying them to the site. The time to look for the appropriate rebar is in the range [1.2, 1.5, 2.5] min (here, 1.2 is the minimum, 2.5 is the maximum, and 1.5 is the most likely duration). The speed to deliver rebar lies in the range [30, 40, 50] m/min. In work package 2, the rebars are placed on blocks at [7, 9, 12] kg/min and tied at intersection at a speed of [5, 7, 8] ties/min. Two labourers work as a team on WP1. They can carry 30 kg on each trip; the distance from the rebar bending shop to the site is 25 meters. Besides, two labourers also work on WP2. A total of four reinforcing labours are employed on-site for this job for a total takeoff of 21191.3kg steel. Based on the calculations, a total of 707 repetitive cycles/jobs are required to complete this project. AON representation of the planning patterns for this project is shown in Figure 9.

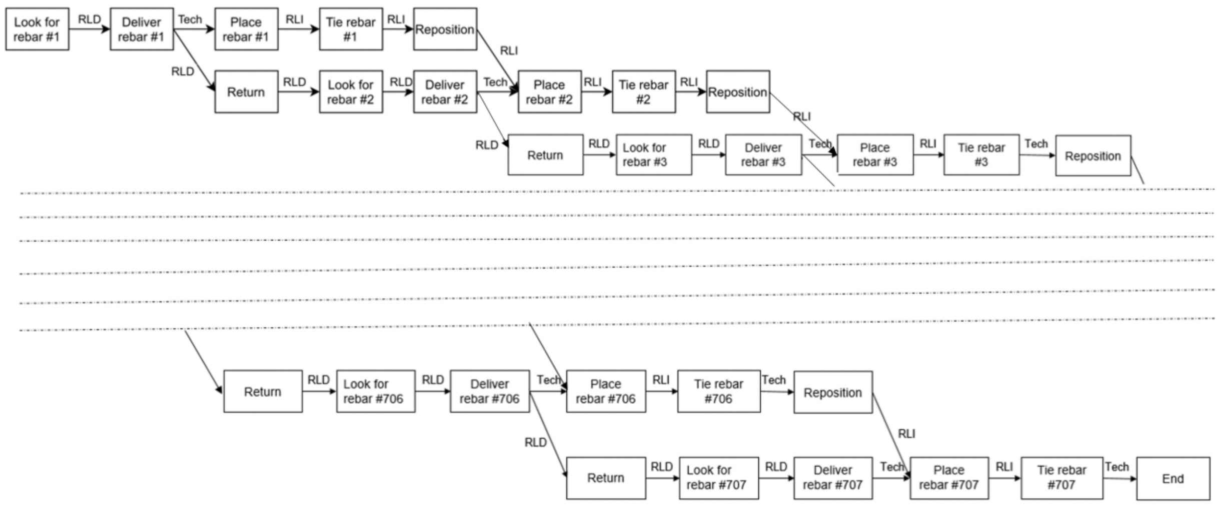


Figure 9. AON representation of the Rebar Case Study.

In Figure 9, the AON prepared for the project consists of 707 repeating units of work, where each unit consists of six activities (except first unit). The nature of the precedence relationship (resource involved or technology constraint) is marked on each arrow in AON. The solid lines linking the activities within each unit define the technical precedence constraints in the network. For example, activity “Tie rebar #2” cannot be started until activity ‘‘Place rebar #2’ is completed. The lines linking similar activities from one unit to another unit represent the resource availability constraints; for example, Activity ‘return’ cannot start until the crew from Activity ‘Delivery rebar’ is done with the current job and becomes available. RLD represents Rebar Delivery Labor, whereas RLI represents Reinforcement installation Labor. In the horizontal direction, there is a mix of resource constrained and technology constrained precedence relationships. For instance, in handling job #1, after delivering rebar by the RLD to the deck, a technology link exists between “Delivery rebar #1” and “Place rebar #1” by RLI. The ensuing activities (“Tie rebar #1” and “Reposition”) are connected by two arrows involving RLI. Based on previous studies (Harris et al. 1998, Arditi et al. 2002), resource links are not supposed to connect activities in the horizontal direction in LOB applications, but only links denoting technology constraints between activities. In short, this repetitive construction planning problem does not lend itself to LOB or RSM. The revision of the vertical relationships (resource constraints) becomes even more tedious if the planner has, realistically, deployed more than one crew to work on each typical activity. Thus, AON network model provides a process modeling solution but becomes unscalable for practical application and ineffective to lend decision support for planning. In larger and more complex applications, AON can become too cumbersome and complicated for process modeling and communication. Scheduling without correcting these errors can produce mistaken schedules. Without AON, CPM thus becomes pointless for scheduling analysis. The research inquiry is how to enhance AON so to keep its flexibility and ease of use while making it scalable and practical in construction applications. AON+ may not ensure continuity; but, if the process is correctly modeled, it helps with reducing gaps in crew work time, by squeezing the total project time. This research is intended to generalize an enhanced version of AON, inspired by the SDESA. The end result is a streamlined project network model to account for complexities in planning fabrication or workface at construction. One additional benefit is the AON+ model is compatible with SDESA and can be taken as structured input model for discrete event simulation analysis.

3.4 Development of AON+ framework

The key components and steps for AON+ process mapping based on the Rebar installation problem are as follows:

Step 1: Collect Project Data

The project information (Activity, Time, and Resource) is collected first to feed the AON+ model.

Table 2. Basic information (Duration and Resource requirements)

#	Activity Name	Time	Resource
1	Look for Rebar	[1.2,1.5,2.5] min	2 JM
2	Deliver Rebar	[30,40,50] m/min	2 JM
3	Place Rebar	[7,9,12] kg/min	2 JM
4	Tie Rebar	[5,7,8] ties/min	2 JM

The activity logical sequence for one travel is as follows (Figure 10):

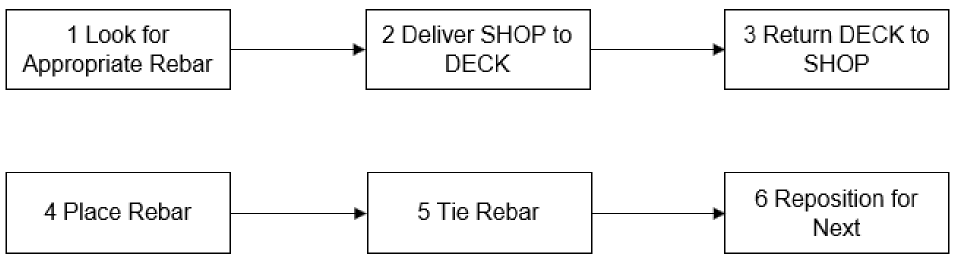


Figure 10. Logical Sequence of activities.

Step 2: Determine the Flow Entity

Since the target of the operation is to deliver all the rebars to rebar installation area and then install them, the first Flow Entity can be defined as “Rebar Delivery” and the second Flow Entity can be “Rebar Installation”. And it is convenient to set the quantity of the workflows to be “707 Rebar Delivery” and “707 Rebar Installation” as the number of cycles to repeat all activities in each of these workflows. The Flow Entity should be setup as follows (Figure 11):

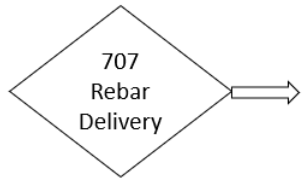


Figure 11. Flow entity of workflows.

Step 3: Combine the Flow Entity with the Activities chain

In this step, the Flow Entities are combined with the proper activity logical sequence chain. The process can be represented by the following diagram (Figure 12):

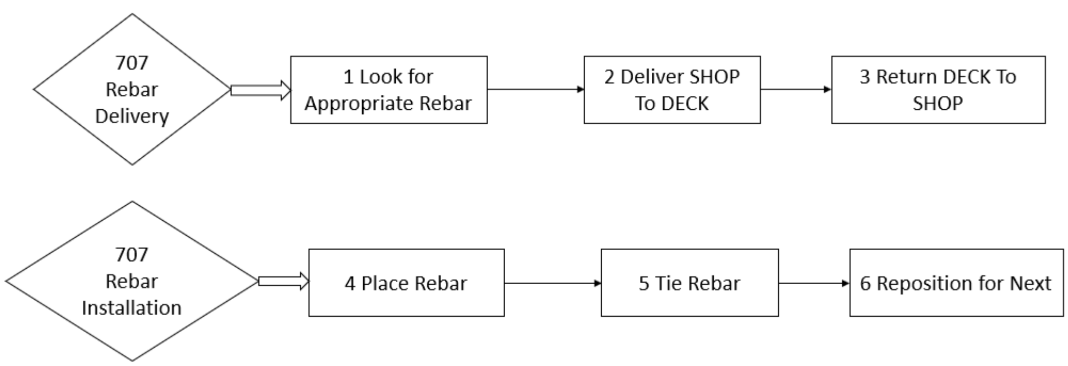


Figure 12. Schematic model before resource assignment.

Step 4: Distribute Resources to activities

Then the required resources are distributed to each activity according to the logic and the following diagram can be found (Figure 13):

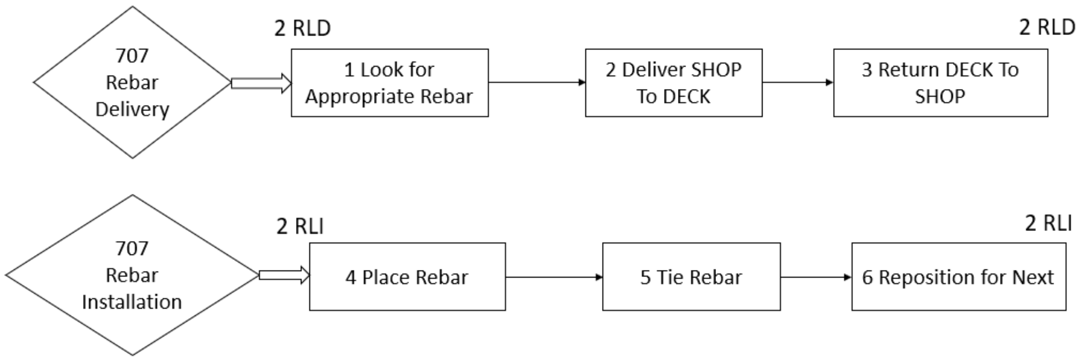


Figure 13. Schematic model without Disposable resources assignment

In Figure 13, "RLD" represents the Delivery Labor and "RLI" represents the Installation Labor. In the first flow workflow, "RLD" is required to start the activity "Look for Appropriate Rebar" and is disposed after the last activity of this workflow "Return DECK To Shop". For Rebar installation, "RLI" is required by its first activity "Place Rebar" and is disposed by the ending activity "Reposition".

Step 5: Add Disposable Resource Entity

Finally, the interdependent relationship between the Delivering rebar and Placing rebar activity is established by a Disposable Resource Entity (Figure 14). It can be noticed that the use of the disposable resource entity can activate the placement of rebar once there is a "Rebar" that has been delivered to the Rebar Installation area (Deck). There is a plus sign before the description of a disposable resource to differentiate it from non-disposable resources.

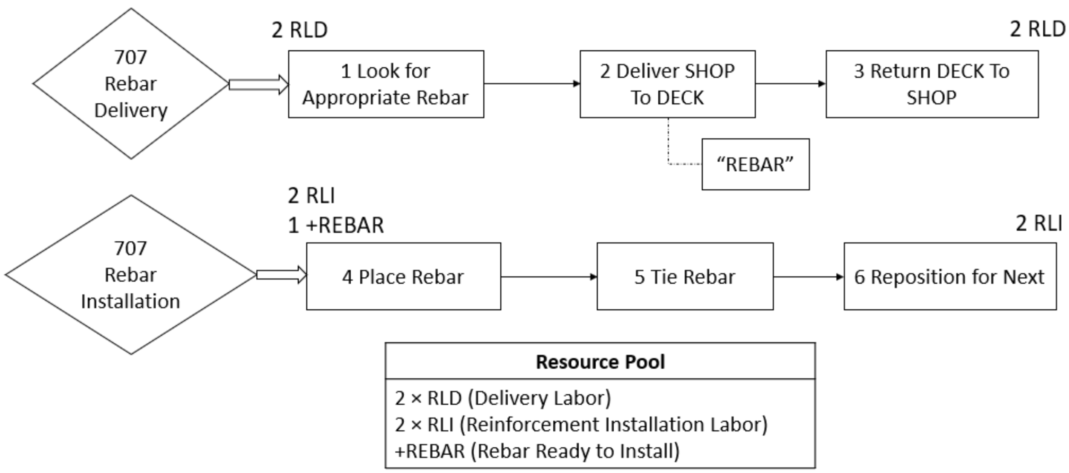


Figure 14. AON+ process mapping for the Rebar Case Study.

The activity duration depends on the shape, complexity of the bar segments, the position on the jobsite, so the same activity can take longer or shorter in processing different batches of rebar. These variations exist in reality and exert significant influence upon the project duration. The impact of such variations cannot be overlooked or avoided in project planning and scheduling; instead, they need to be identified first, clearly specified in the production plan, and analytically modeled to assess their impact on shop scheduling. In the rebar case, the formulated AON+ model (Figure 14) sets triangular distribution (Low, Mode, High) based on the likely duration of all the four activities provided in the WBS (Figure 8) and linkup the parallel crew workflows logically. Thus, AON+ mimics the common logic and practice of AON-CPM; the scheduling accuracy can be obtained by performing discrete event analysis on AON+ -analogous to performing critical path analysis on AON in current practice.

AON+ can be taken as the process mapping model compatible with the Simplified Discrete Event Simulation Approach (SDESA) and can feed into SDESA as input model to generate a process simulation model. AON+ vs. SDESA simulation analysis is analogous to AON vs. CPM scheduling analysis (Lu 2003). As per SDESA, a central resource pool holds the definitions of all the resources relevant to construction planning, regardless Non-Disposable Resources or Disposable Resources. The resource pool is dynamically managed to control resource availability status in simulation. The time-event scheduling engine underneath the

SDESA computer platform marshals two dynamic queuing structures namely, the flow-entity queue and the resource entity queue on first-in-first-out basis, so as to advance the simulation clock and execute activities that satisfy the logical and resource-availability constraints as specified by the modeler in the AON+ network diagram model. To be specific, AON+ will add a counter to control the number of repetitions for each resource workflow; and a "disposable resource" definition to link various resource workflows, keeping the simplicity and flexibility of the original AON.

Chapter 4: Case Study

Construction-applied materials can be categorized into bulk materials and engineered materials, which are termed as permanent resources in project management because of staying as part of the facility being built after they are handled and placed in the field (Tatum 2012). According to Tatum (2012), the bulk materials (e.g., ready-mix concrete, stock lengths of rebar, masonry concrete blocks etc.) are commonly available in stocks of a supplier, manufactured in large quantities, and generally can be procured in a short lead time. In contrast, engineered materials (e.g., fabricated steel beams, process pipe spools etc.) are prefabricated in specialized fabrication facilities in accordance with detailed design catering for specific project needs, which demands for special engineering expertise, lots of resources, and a relatively long lead time (Tatum 2012). This chapter focuses on the implementation of the proposed methodology for both bulk (bored pile concreting) and engineered materials (steel girder fabrication) in a typical repetitive project environment; and the following chapter encapsulates the scheduling for engineered materials in a non-typical repetitive environment. The Bored pile case is selected for the case study because it resembles the fabrication problem being studied, with the heavy, bulky casing sections moved, handled, and connected, which plays the lead part in the operations.

4.1 Bored Pile Concreting

At the beginning of the concreting operation, a record laborer records the arrival of the truck mixer carrying concrete from a concrete supplier to the foundation construction site. If the Ready-mixed Concrete (RMC) of the truck mixer can pass the Quality Assurance (QA) tests, the truck mixer comes to the unloading bay and climbs up the inclined platform where a hopper is located and prepares for the unloading. When the hopper and crane are ready, the truck mixer starts unloading in hopper until the truck mixer is empty. For this project, each hopper can be filled by one truck mixer concrete. When empty, the truck mixer leaves the unloading bay immediately after unloading; goes to the washing bay for cleaning and then leaves the site. A record labor at the site-exit marks the leave time on the concrete slip and returns the receipt to the driver.

When a hopper is filled with RMC, the hopper is hooked up to the bored pile position by a crane where a journeyman is waiting to pour concrete from the hopper into the pile. The platform that acts as a stand for the concreting on the top of casing is then removed by the crane. When empty, the hopper is hooked back to the unloading bay for the next concreting cycle.


a) Park to Unload b) Load Concrete to Pile


c) Lift Casing d) Reinstall Platform

Figure 15. Site photos of the work packages for Bored Pile Concreting
(Photos taken by Ming Lu)

A temporary casing will be lifted up and truncated upon pouring ten hoppers of concrete. So, the hopper-concreting cycle needs to be repeated ten times until ten hoppers of concrete are cast. The truncation prevents the casing from being buried in the ground before the concrete hardening. To cut the temporary steel casing, the crane keeps hooking up the casing to hold it staying upright and when the unscrewed casing section is removed, the working platform will be re-installed to the top of bored pile for another concreting cycle. The resource requirement and capacity for the operation is as follows (Table 2):

Table 3. Resource requirement and maximum capacity for the case study

Resource	Available amount on site	Capacity
Laboratory	1	Test 1 truck mixer each time
Unloading Bay	1	Park 1 truck mixer each time
Washing Bay	1	Park 1 truck mixer each time
Crane	1	-
Working Crew	1	-
Hopper	1	7m3
Truck mixer	25 ordered	7m3
Casing	5 sections	-

4.1.1 AON+ Implementation

An AON+ process mapping will be created for the case study as follows. Firstly, each activity in the AON network of the operation is represented with one Flow Entity Diamond linked with one Activity Block in SDESA, confirming each activity is executed once only. Since the target of the operation is to dump concrete from a remote Ready-mixed Concrete (RMC) site to the hopper and then pouring the concrete from hopper into the pile, the Flow Entity needs to be defined as a substantial quantity of dump load. According to the project specifications:

1) One hopper is capable to receive one truck mixer of concrete that means the truck mixer will become empty after the unloading of RMC;
2) The hopper concreting cycle is repeated until there are ten hoppers of concrete accumulated in the pipe;

3) For a 50m long 2m diameter bored pile, 10 cut casing cycles are required after 10 hopper concreting cycles.

Based on the logic, the Flow Entity of the first workflow “10 Truck Load” (Figure 16) describes 10 truck mixers of concrete have to be dumped into the hopper to generate 10 hopper loads in order to fill up the whole bored pile. Secondly, the Disposable Resource Entities substitute for the arrows in the AON and act as an information unit to enforce the precedence relationship in AON. When all the preceding activities are finished, the required Disposable Resource Entities become available to trigger the start of the current activity. Once the AON+ process mapping is defined, the forward-pass calculations of CPM can be performed by executing the SDESA model, which accounts for both technological and resource constraints.

Table 3 is the resource workflow summary of the AON+ model using Truck load, Hopper load and Pile Section as flow entities. Each activity in the AON network is represented and linked with one of these three Flow Entities. Table 4 lists the different work packages the work units undergo, and what their resource constrained relationships are. The first disposable resource, “UNLD_R” is generated at the end of the activity “Park to Unload Bay” in the first crew workflow to represent one truck load has been dumped at the end of that activity. This disposable resource triggers the start of next crew workflow, where the Hopper load undergoes different work packages (i.e., receiving concrete, loading concrete to pile). The next disposable resource, “SIG_CUT” is generated at the end of “Load Concrete to Pile” activity. Since 10 “SIG_CUT” is in the resource required list of the activity “Remove Platform” in next crew workflow, it is assumed that the next crew workflow will be carried out when 10 Hopper loads of aggregates will be accumulated. These 10 cycles of aggregates accumulation will further lead to the Platform Removal, Cutting and Lifting Casing, and Reinstalling Platform again to complete the one Pile section cycle. SDESA can track the movement of the resources (labor, equipment, materials) from one location to another and identify the areas for productivity loss.

Table 4. Resource Constraints for Activities in Bored Pile Case Study

Flow Entity (Number of Cycles)			
I) Truckload (10)			
Activities		Resources	
No.	Name	Required	Released
1	Enter Site	1 JM	-
2	QA	2 JM, 1 QA	1 JM, 1 QA
3	Park to Unload Bay	1 JM, 1 UN_BAY	1 UN_BAY, 1 UNLD_R
4	Go to wash	1 JM, EMP_TRK	-
5	Wash Truck	1 JM, 1 WB	1 WB
6	Leave Site	1 JM	-
7	Reposition	1 JM	1 JM
II) Hopper Load (10)			
8	Receive Concrete	1 JM, 1 CR, 1 UN_BAY, 1 UNLD_R	1 UN_BAY, 1 EMP_TRK
9	Load Concrete to pile	2 JM	1 JM, 1 CR, 1 SIG_CUT
10	Reposition	1 JM	1 JM
III) Pile Section (1)			
11	Remove Platform	1 CR, 1 JM, 10 SIG_CUT	-
12	Cut Casing	1 OS, 1 JM	-
13	Lift Casing	2 JM	1 OS
14	Reinstall Platform	1 JM	1 CR
15	Reposition	1 JM	2 JM

Resource Pool
Non- Disposable: JM (Journeyman), QA (Quality Test), UN_BAY (Unloading Bay), CR (Crane), WB (Washing Bay) Disposable: UNLD_R (Ready to Unload), SIG_CUT (Cut Section Signal), SEC_CP (Section Complete), EMP_TRK (Empty Truck)

4.1.2 Results and Analysis

AON+ prioritizes the processing sequence of production jobs by the first-in-first-out rule. The start time of an activity is delayed until the demanded resources are available on site. Figure 16 shows the SDESA layout based on AON+ which tracks the movement of resources between different activities in the system.

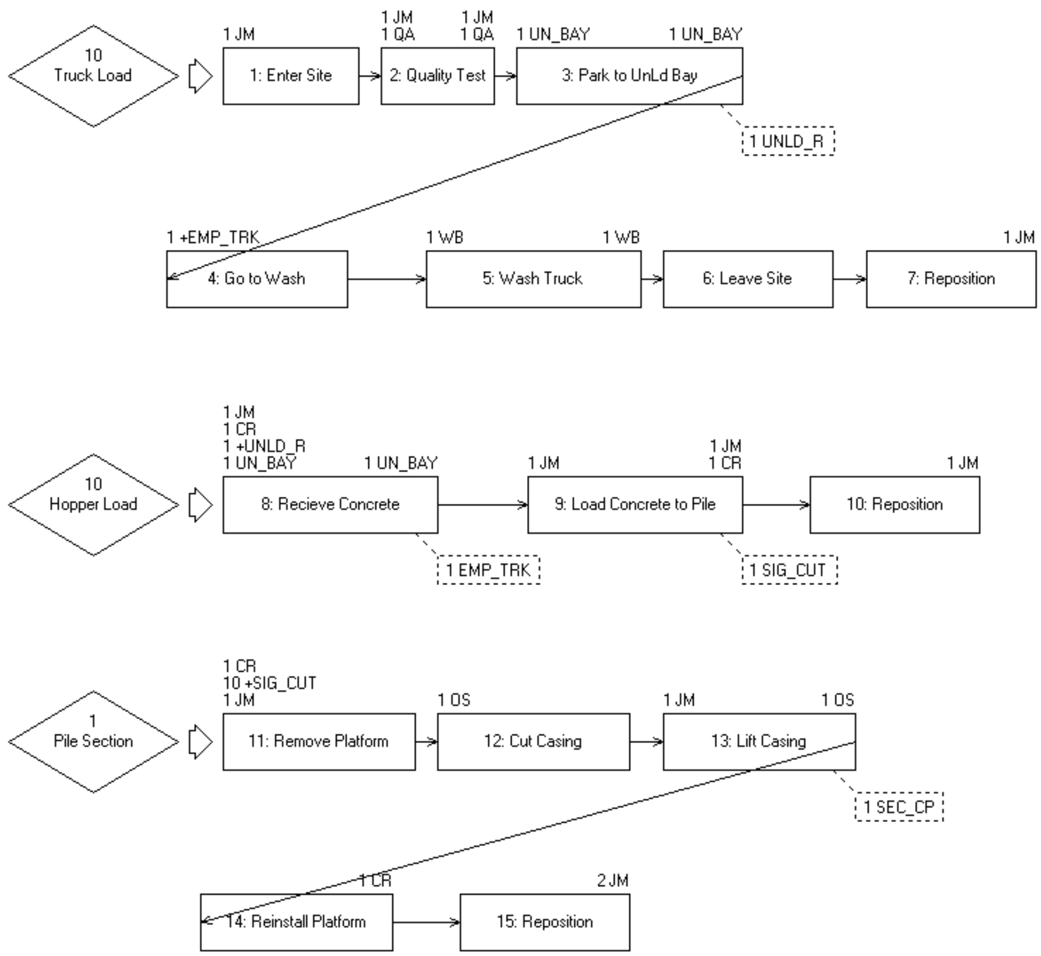


Figure 16. AON+ model formulated in SDESA for Bored Pile Case Study.

Since the activity duration in the parallel crew workflows varies based on the material properties, resource availability, and the position on the jobsite, the uncertainty in duration is characterized by defining the distributions for each resource workflow. For example, for this case study, the activity 'Park to Unload Bay' follows a Uniform Distribution (low= 0.5, high= 1) from 'Site Lab' to 'Site-Unload Bay', whereas the activity 'Load Concrete to Pile' follows a triangular distribution (low=3, mode=5, high= 6) from 'Site-Unload Spot' to 'Site-BP Spot'. In the SDESA platform, resource's location state is initialized by user and automatically tracked by computer algorithm. For this case study, this automated process enables the user to apply these distributions without the need to update each activity individually after each crew workflow.

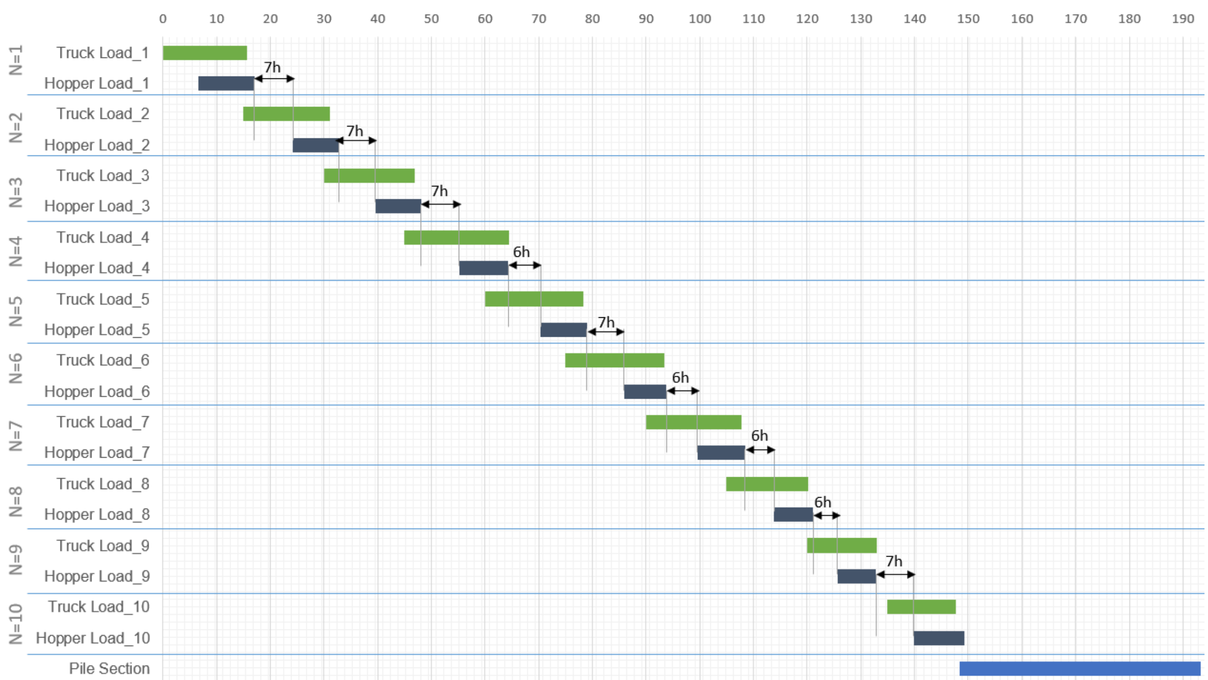


Figure 17. Bar Chart for Bored Pile Case Study.

After running the proposed simulation model for the case study based upon the non-uniform work units and repetitive workflows, the Hopper Load Crew's interruptions in their workflow (non-value-added time) is highlighted in Figure 17. The colored bar chart visualizes the non-uniform work units and repetitive workflows based upon resource and technological constrained relationships. The results from the "Crew Workflow" perspective in line with AON+ represents which crew executes what workflow, the interruptions in the middle due to what reason (in connection with another crew workflow).

The make span of a particular activity can be measured as the time difference between the end and start times of that process workflow. According to the simulation results, different units undergo different duration based on the variations in activity duration and crew availability. The truckload unit consists of seven activities and these activities have different quantities of work needed for each repetitive unit and utilize resources operating with different productivity.

The duration for each unit of Truckload varies in the range between 13 hours and 19 hours (most likely: 16 hours), whereas each unit of Hopper load undergoes the duration variation in the range between 7 hours and 11 hours (most likely: 9 hours). Also, the idle time (non-value-added time) between different activities in different crew workflows can be computed following the Bar Chart. For example, the idle time for the flow entity "Hopper Load" in Unit 3 and Unit 4 is 7 Hours, whereas between Unit 8 and Unit 9 the idle time is 6 Hours. After running the simulation model, the total project duration was calculated as 192 Hours.

4.2 Bridge Girder Fabrication

In bridge girder fabrication, the unique product is the steel plate girder. A steel plate girder is generally a prefabricated I-beam. When multiple I-beams are arranged in parallel girder lines while achieving the as-designed length of the bridge span, it provides longitudinal support for the bridge deck. All girders consist of a main middle plate (Web) which is connected perpendicularly to two other plates (Flanges) at the top (Top Flange) and the bottom (Bottom Flange). There is also a rectangular plate (Stiffener) fitted perpendicularly into the web and the flanges. Once shop drawings are ready, a set of repetitive production processes is performed for fabricating the steel products in a steel fabrication shop. The operation involves a set of manufacturing processes for assembling raw materials into final products. Based on the availability of all the required materials, girder fabrication begins with detailing raw flat plates, including pre-blast, cut, and drilling. Later, webs and flanges are prepared from these cut plates by straightening and splicing. Tack welds are generally applied as temporary connections for all the connections (e.g., splicing/assembling flanges and web) in order to hold components in position before the final welding is performed. The web and two flanges are assembled into a girder by tack welds, which requires specific machinery (e.g., cranes, squeezer) for lifting and handling the web or flanges. After the web and flanges are assembled, final welding connects web and flanges permanently with no gap. Finally, stiffeners and studs are also attached to the assembled girder based on engineering specifications. Upon finishing these steps, the fabricated plate girders are inspected before being shipped to the site for installation.

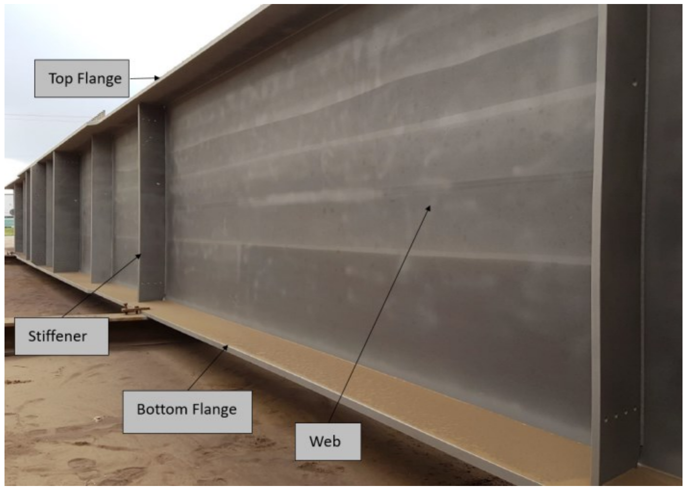


Figure 18. Attributes of girder.

In this case study, fabrication of 3 identical plate girders to make up one girder line on a bridge (i.e., Girder G1A, Girder G1B, Girder G1C) is planned and scheduled. The layout for the three girders is shown in Figure 19.

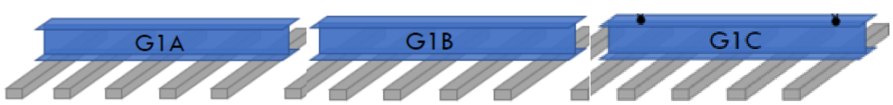


Figure 19. Diagram of Girder G1A, G1B, G1C.

Each girder needs to go through the identical fabrication process articulated by workstation-based activities, as shown in Figure 20. The fabrication processes are executed by both stationary machines (workstations) and mobile skilled workers. The repetitive production workflow involves the special activities such as cutting, fitting, welding, and painting processes to be performed on individual jobs and assemble the steel pieces to steel products based on the engineering design. Material handling systems like conveyor belts, forklifts, and overhead gantries are used to move the products throughout the production line.

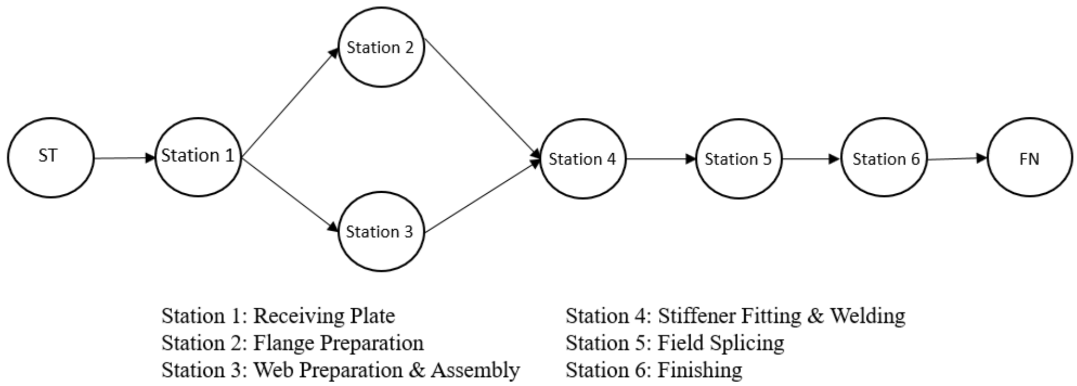


Figure 20. Working process for fabricating one plate girder.

The work content of each process (or job) in this operation is estimated based upon job complexities, historical data, and schedulers' expertise. The scheduler is responsible for allocating available resources (i.e., workers and machines) to deliver a detailed production schedule for guiding the production sequence of individual resources at the workface level on shop floor. AON+ process mapping can be created in the SDESA platform to cope with the exploding detail and dynamic complexities inherent in this practical problem. The production schedule has been proved more reliable by factoring in (i) multiple repetitive workflows of performing the process-jobs for multiple girders, (ii) the resource requirement for executing the process-jobs, and (iii) the availability limit of resources for delivering the jobs on the shop floor.

4.2.1 Challenges for planning and scheduling

In a study of 2006, Ruwanpura et al. (2006) found out that effective planning can decrease project cost by 40%, while inadequate planning can result in cost overrun as high as 400%. On top of the varied product designs, planning operations for made-to-order structural components is also subject to limited skilled laborers, finite space resources and client-imposed deadlines (Hasan et al. 2019). Keeping all these in mind, generating a practically feasible work plan requires each individual worker's job schedule to be linked with project resource allocation schedule (Ahuja et al. 1984). Additionally, the work plan needs to be role-specific, avoid any redundant information, and be straightforward for the workers to act on. Therefore, at the same time of being technology and process focus (i.e., what is to be done, how to do it in what sequence), being a resource use focus is equally important (Haplin et al. 1992).

In the current practice, industry practitioners largely rely on the past experience in production planning and control, however, manual project planning and scheduling is a time-consuming and error-prone process, especially for large-scale construction projects. The mainstream planning software tools (Primavera P6 or Microsoft Project) only apply Critical Path Method (CPM) to represent activity breakdown and predecessor relationships in the form of Activity on Node (AON) diagram and are heavily dependent on the manual formulation of project plans and schedules. Nonetheless, planning multiple one-of-a-kind fabrication projects subject to limited labor and space resources and client-imposed deadlines is overwhelmingly complex and dynamic, rendering current network-based approaches such as critical path method (CPM) or project evaluation review technique (PERT)- based project scheduling to be inadequate and impractical. This cumbersome and ineffective method of planning potentially result in an overwhelmingly complex AON network model in representation of repetitive workflows performed on non-uniform work units (Hyari et al. 2006). Besides, updating obtained schedules in a short turn-around time, probing "what-if" alternative scenarios, and generating an updated set of jobs (to do list for the trades) would be practically infeasible when a need to change operation logic or resource constraints arises. As a result, the efficiency and effectiveness of project plans and schedules (from human formulation) become severely insufficient and impractical in the real world.

Simulation keeps track of the changes of the state of a system occurring at discrete points of time, builds a logical model of the system and provides users with insight into the system's resource allocations, interactions, and constraints (Pidd 1998). Over the last few decades operations simulation has been widely applied in modeling multiple nonlinear complex manufacturing and construction systems. Discrete event simulation (DES) is being widely used to model and study real-world systems (Wang et al. 2004), especially for processes that are complex and repetitive in nature. DES reproduces the process of how products and resources interact with each other by simulating the behavior of a production system over time. It also provides a cost-effective framework, where various alternatives can be tested or compared and the best one can be selected without any interruption in the real system (Hu 2013).

Despite these advantages, DES has limitations in modeling the industrial fabrication shops, since industrial shop products, though undergoing the identical operations, differ considerably in the sequence of operations necessary to fabricate them. Most DES applications treat products in a production system as identical entities that follow rather straightforward processing logic (Hasan et al. 2019), whereas, in a made-to-order construction fabrication facility, each shop product must be uniquely modeled in a simulation model, since it has different routing in a shop and consumes different amount of processing time (Rose et al. 1999). Moreover, product sequencing in connection with a laborer or a workstation is dictated by fabrication technology (splicing) and site demand (delivery timing), therefore, activity duration of these manual operations needs to be explicitly calculated based on job sequencing and product features, instead of being randomly sampled from the possible ranges based on probability rules (Hasan et al. 2019).

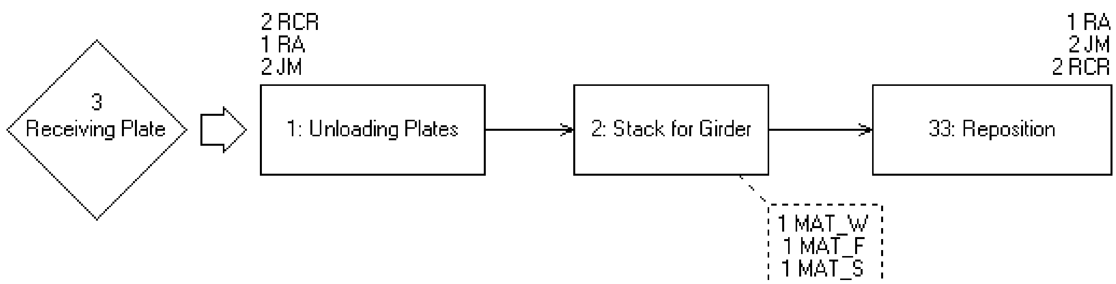
4.2.2 AON+ Implementation

SDESA simulation platform can be utilized to facilitate the AON+ framework in repetitive workflows subject to limited resources and activity interruptions. AON+ process mapping starts with identification of flow entities (workstations) and resource entities (Table 5) first, followed by the identification of activities and sequence of workflows.

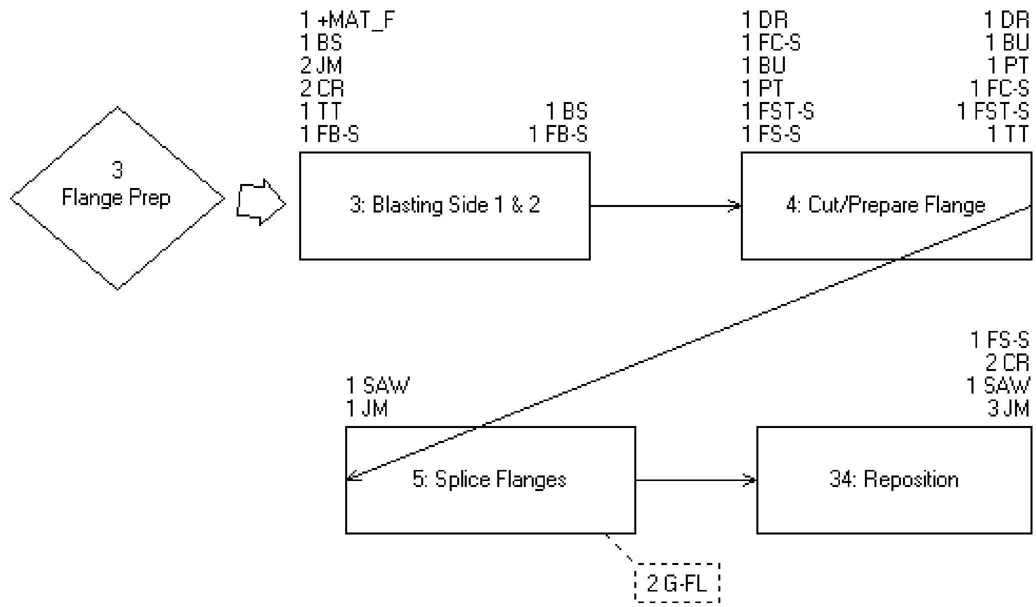
Table 5. Resource Constraints for Activities in Girder Fabrication Case Study

Resource ID	Resource Name	Amount	Resource Type
JM	Journeyman	5	Non- Disposable
RA	Receiving Area	1	Non- Disposable
TT	Transfer Table	1	Non- Disposable
CR	Crane	6	Non- Disposable
FC-S	Flange Culling Station	1	Non- Disposable
BS	Blaster	3	Non- Disposable
PT	Preheat Torch	2	Non- Disposable
BU	Burner	3	Non- Disposable
FST_S	Flange Straightening Station	1	Non- Disposable
DR	Drill	4	Non- Disposable
FS-S	Flange Splicing Station	1	Non- Disposable
GW-S	Girder Welding Station	2	Non- Disposable
SAW	Sub arc Weld	5	Non- Disposable
WP-S	Web Preparation Station	1	Non- Disposable
WC&A-S	Web Culling & Assembly Station	1	Non- Disposable
S-S	Stiffener Station	2	Non- Disposable
FSB-S	Final Sand Blasting Station	4	Non- Disposable
SD	Stud Welder	2	Non- Disposable
FB-S	Flange Blasting Station	2	Non- Disposable
GS-S	Girder Splicing Station	1	Non- Disposable
G-SP	+Spliced Girder	-	Disposable
G-STF	+Girder with Stiffener	-	Disposable
MAT_S	+Material for Stiffener	-	Disposable
MAT_F	+Material for Flange	-	Disposable
MAT_W	+Material for Web	-	Disposable
S-N-F	+Start New Flange	-	Disposable
N-F	+Next Flange	-	Disposable
S-N-W	+Start New Web	-	Disposable
N-W	+Next Web	-	Disposable
RG	+Release Girder	-	Disposable
G-FL	+Girder Flange	-	Disposable
T-G-S	+Track Girder Start	-	Disposable
F-G	+Finished Girder	-	Disposable
FCC_A	+Final Camber Check	-	Disposable
SD_A	+Splice Drill	-	Disposable
G-WLD	+Welded Girder without Stiffener	-	Disposable
SET	+Setup	-	Disposable
PSA	+Pull Splice out	-	Disposable

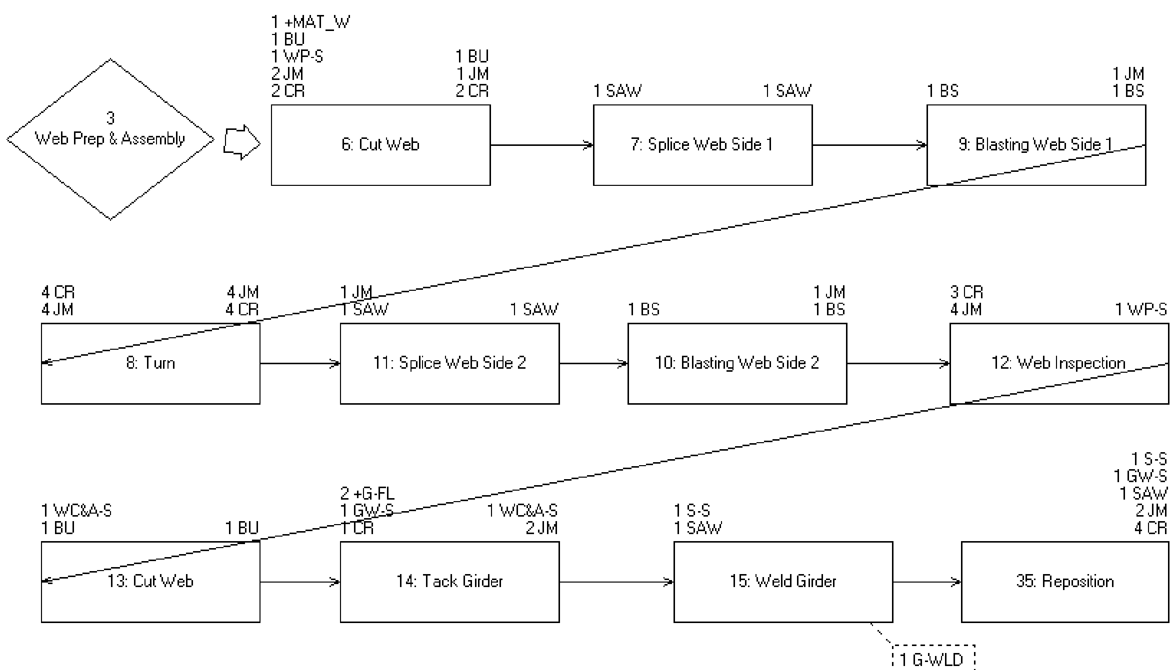
In order to define and generate macro-activities, WBS (Work Breakdown Structure) based on engineering design drawing and historical production database are investigated (Appendix A). To determine the resource requirements and duration of workstation-based fabrication activities, engineering design drawings of two bridges and historical productivity data from the industry partner company were investigated. The design features of girders have also been considered later in chapter 5 and 6, including the web thickness, girder length, depth, shape (e.g., kinked or not, skewed or not), and the number or type of stiffeners attached to the girder. The next step is to generate the time-dependent resource requirements for individual macro-activities by utilizing the engineering design drawing and historical production database. Once they are identified, the resource-constrained scheduling optimization problem can be solved formulating the job-shop production simulation model in SDESA. In order to develop the simulation model for scheduling the process-jobs for this fabrication problem, the workflow is abstracted first for each workstation (Figure 21).



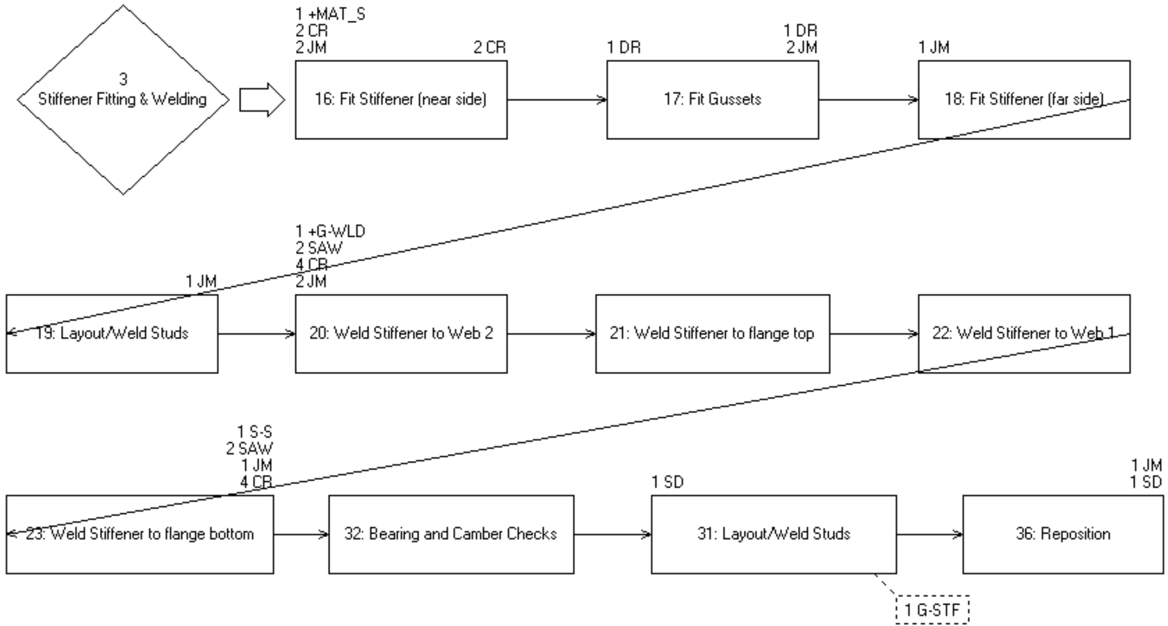
a) Station 1-Receiving Plate



b) Station 2-Flange Preparation

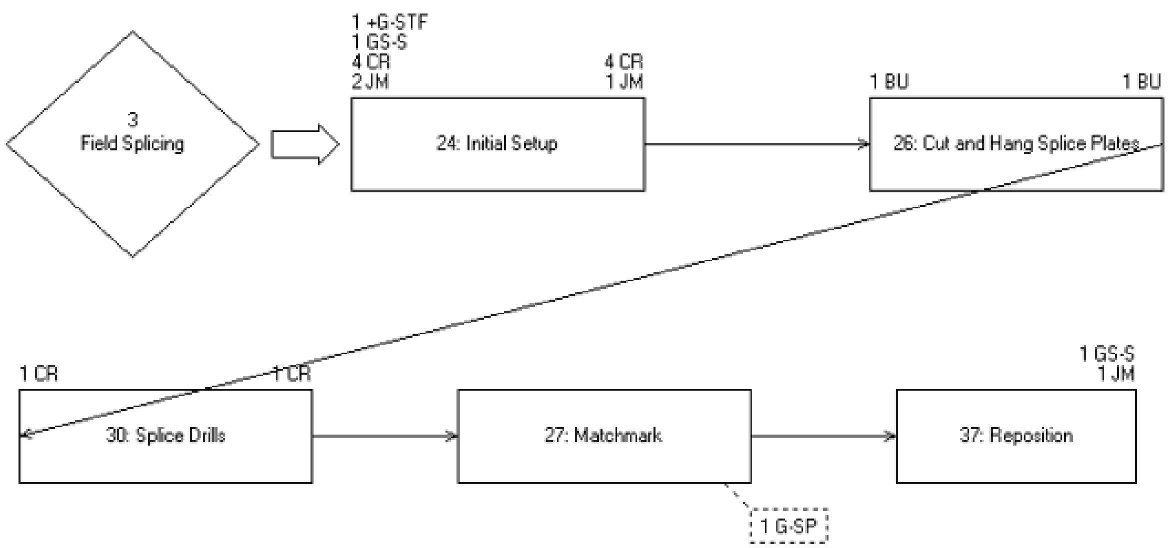


c) Station 3-Web Preparation and Assembly

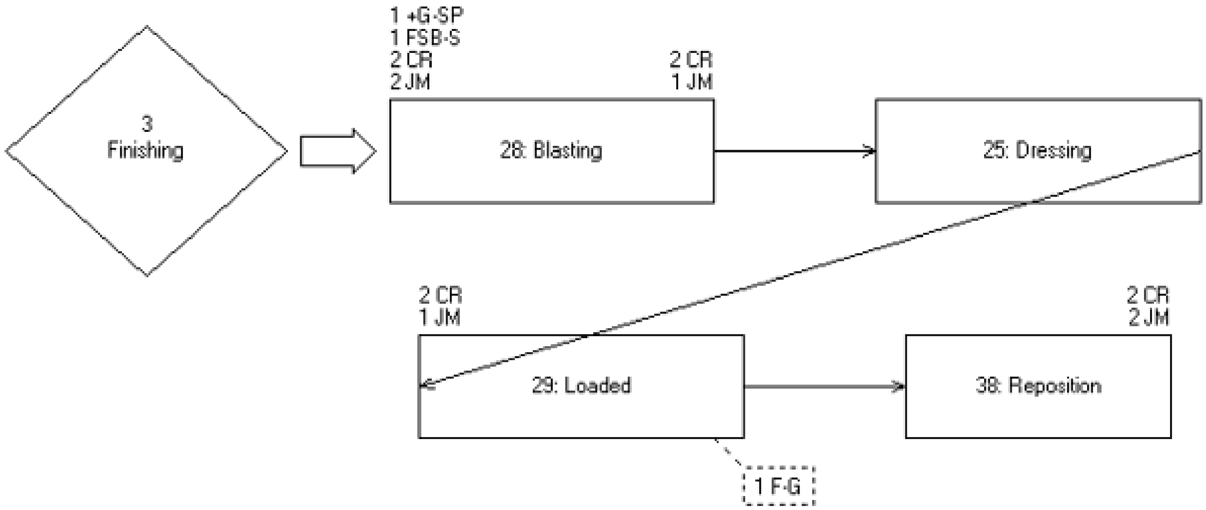


d) Station 4-Stiffener fitting and Welding

e)



e) Station 5-Field Splicing



f) Station 6-Finishing

Figure 21. AON+ model formulated in SDESA for Girder Case Study.

Figure 21 shows the proposed modeling structure for Workstation 1 to Workstation 6. The horizontal arrows define the technological constraints (i.e., cutting process precedes fitting process; fitting process precedes welding process; welding process precedes painting process), where the steel materials are assembled throughout the production line. SDESA represents the 6 workstations with six flow entities, where each activity or workflow can be executed no matter how many times the project demands. Here, each workflow has been repeated for 707 times complying with both limited resources and activity interruptions. The activity block in AON+ substitutes for the arrows in the AON, acting as an information unit to enforce the precedence relationship in AON. Each process-job is constrained by the demand of particular resources (Disposable and Non-disposable). The quantity of Non disposable resources (i.e., workers, machines) as required for performing a process is dependent on the work content. These resources are released after completing all the production processes on a particular workflow. A Disposable resource are generated at the end of an activity in a crew workflow, which triggers the start of next crew workflow. For example, the disposable resource, G-STF is generated at the end of Workstation 4 (Stiffener fitting and welding), which initiates the start of its successor crew workflow "Field Splicing", where the girder undergoes different work packages (i.e., cutting, splicing, matchmarking). Once the SDESA model is defined, the job-shop production schedule with resource constraints can be simulated by sequencing all process-jobs complying with the first-in-first-out rule at each workstation. Based upon the AON+ framework, the forward-pass calculation of CPM is performed by executing this simulation model, which derives the total project duration accounting for both technological and resource constraints. It is to be noted there is no backward-pass calculation in AON+ in the current scope, as the focus is set on resource utilization and lean planning; the plan is subject to frequent adjustment and updating; total float is not considered relevant in terms of keeping the original project duration.

4.2.3 Results and Analysis

In this application scenario, the resulting duration of each crew workflow in each workstation was specified in the SDESA simulation model (Figure 22). The colored bar chart generated by SDESA visualizes the duration variation of three identical girders based upon resource and technological constrained relationships. All the precedence relationships, daily labor resource limit, and material availability limits (daily) have been satisfied in the schedule and the feasibility of the optimized schedule were cross validated in the project control scenario. According to the simulation results, the three girders undergo different duration based on the variations in resource availability. The crew workflows consist of numerous activities and these activities have different quantities of work needed for each repetitive unit and utilize resources operating with different productivity. Figure 22 presents the schedule for the six workstations (i.e., receiving plate station, flange preparation station, web preparation and assembly station, stiffener fitting and welding station, field splicing station, and finishing station). The duration for each workflow in Station 1 varies in the range between 10 hours and 30.40 hours (most likely: 20 hours); whereas each workflow in Station 2 undergoes the duration variation in the range between 193.70 hours and 377.70 hours (most likely: 286 hours); Station 3 undergoes variation in the range between 240.4 hours and 426.20 hours (most likely: 333 hours); Station 4 varies in the range between and 570.30 hours and 656.5 hours (most likely: 613 hours); Station 5’s variation is in the range between 25.50 hours and 43.50 hours (most likely: 25.50 hours); and Station 6 undergoes variation in the range between 23 hours and 53.5 hours (most likely: 23 hours).

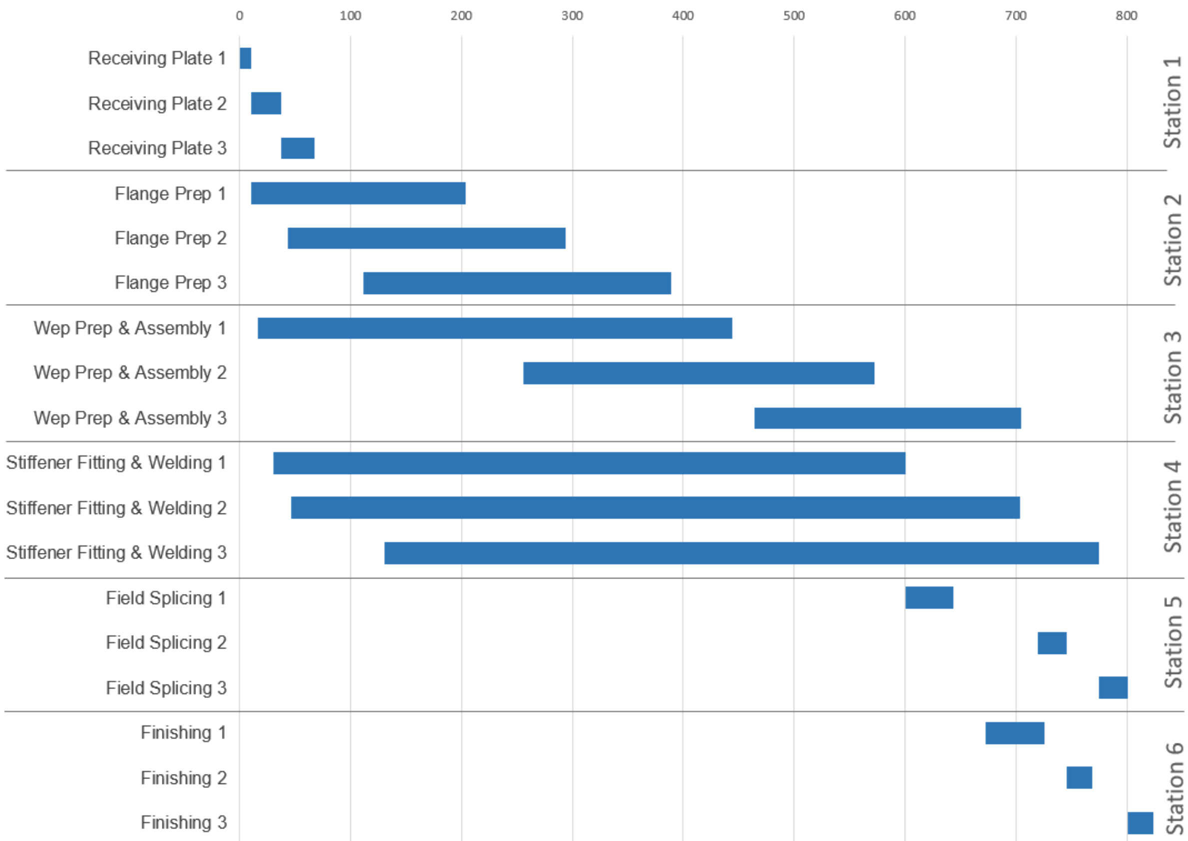


Figure 22. Bar Chart for different workstations in the Girder Case Study.

Also, the idle time (non-value-added time) and duration of all macro-activities in different crew workflows were computed following the Bar Chart (Table 6). After running the simulation model, the total project duration was calculated as 820 Hours.

Table 6. Activity duration and idle time for the Girder Fabrication case study.

Activity	Duration (hrs)	Busy (hrs)	Idle (hrs)
Unloading Plates	60	36	24
Stack for Girder	67.4	24	43.4
Blasting Side 1 & 2	217.2	120	97.2
Cut Web	112	102	10
Fit Stiffener (near side)	120.2	100.2	20
Cut/Prepare Flange	402	288	114
Splice Web Side 1	2.4	2.4	0
Fit Gussets	72.7	48	24.7
Blasting Web Side 1	6	6	0
Turn	258.5	48	210.5
Splice Flanges	398.7	324	74.7
Fit Stiffener (far side)	47.1	47.1	0
Splice Web Side 2	2.4	2.4	0
Blasting Web Side 2	6	6	0
Web Inspection	256.1	48	208.1
Layout/Weld Studs	3	3	0
Cut Web	342.9	132	210.9
Tack Girder	457.5	354	103.5
Weld Girder	165.7	132	33.7
Weld Stiffener to Web 2	233.4	93.6	139.8
Weld Stiffener to flange top	93.2	59.4	33.8
Weld Stiffener to Web 1	119.4	93.6	25.8
Weld Stiffener to flange bottom	69.4	59.4	10
Bearing and Camber Checks	9.9	6	3.9
Layout/Weld Studs	37.7	35.7	2
Initial Setup	108.7	36	72.7
Cut and Hang Splice Plates	36.8	24	12.8
Splice Drills	60.3	31.5	28.8
Matchmark	36.1	3	33.1
Blasting	150.1	72	78.1
Dressing	44.5	15	29.5
Loaded	92.7	36	56.7

In reality, the fragmented nature of current scheduling practice coupled with lack of effective communication makes it difficult for project managers to make effective and efficient production schedules at the workface facility in line with project goals and constraints (Han et al. 2007; Shokri et al. 2015). AON+ fills the gap by facilitating communication and finding solution to workface planning problems by DES (Discrete Event Simulation) or Optimization. AON+ is platform neutral; it represents the planning problem in a structured format that is much more streamlined than AON. SDESA is the DES simulation platform selected for these two case studies; however, any other DES platform can be applied to establish this proposed scheduling framework. The start time, finish time, and flow of girders going through each workstation depicted in this schedule can assist the shop superintendent in identifying critical constraints and removing production bottlenecks in advance. Given any variations or changes in the actual operation process, the operation schedule derived from the proposed framework has the potential to evaluate their impact on the overall project objectives.

Chapter 5: Modeling Labor Productivity in Industrial Steel Fabrication

This chapter showcases the application of AON+, providing structured inputs for computing simulation in performing time scheduling and dynamic resource use planning over time. The productivity and lean analyses based on AON+ process mapping is performed by extracting the simulation results from the virtual plant model validated by Mohsenijam et al. (2017) and Hasan et al. (2019) in collaboration with an industrial partner company in Edmonton. The original SDESA model for the virtual plant is presented in Appendix B.

5.1 Bridge Girder Fabrication Complexity

In the particular domain of Steel Bridge Girder Fabrication, the structural steel pieces are usually unique, need to be custom built, and can vary in material, configuration, and many other properties. Song and AbouRizk (2003) characterized the steel fabrication process by the high product mix and low production volume, and concluded that that most fabricated steel pieces are unique and vary in geometry and processing requirements. The unique design of the steel pieces is mainly determined by unique functions and sometimes unique loads. Each girder piece has a similar appearance but is indeed one-of-a-kind structural element with special features such as stiffeners, studs, number of drill holes, shop splice, field splice, weld thickness etc. These features play a crucial role in dictating the specification of different work packages and processing sequences for each girder to go through the workstations on a shop floor. This uniqueness differentiates the industrial fabrication shops from traditional mass production manufacturing shops, where identical or standard projects are produced and only a few typical routings are followed (Hu 2013). Therefore, production planning in fabrication is challenging and constantly needs to be changed or updated for each steel piece.

Due to the uniqueness of these industrial components, fabrication shops cannot entirely fabricate these components in advance and use on-hand inventory to buffer against the disruptions. Herein, the site demand poses a hard constraint: JIT (Just in time) delivery is required, since there is no buffer space on site (early delivery penalty would be imposed due to laydown yard cost and extra material handling cost; late delivery penalty would incur due to the idling field crews or project completion delay) (Hasan et al. 2019). The major consequence of the disrupted shop fabrication is the out-of-sequence or late delivery of fabricated industry components that, as a result, disrupts both the module assembly and site installation stages. Moreover, the cost in connection with inventory and extra material handling is prohibitively high due to the bulky size of the product and the finite shop space limit.

Between two extremes on the spectrum- one of a kind project and repetitive project, most of the construction projects are characterized by more or less degree of customization and repetitiveness. Industrial fabrication shops (e.g. steel fabrication shops or pipe spool fabrication shops) are an example, where the same set of operations is repetitively performed on different products (structural steel pieces and pipe spools), but the sequence of these operations varies considerably from one product to another, due to the variations in their design and configuration (Hu 2013). Moreover, change orders and order cancellations result in the occurrence of rework, stoppage in fabrication activities and change in steel fabrication sequence, which hamper shop operations and disrupt shop productivity.

5.2 Steel Bridge Girder Fabrication Process

The fabrication of structural steel elements involves multiple specialized trades carrying out a series of operations such as cutting, drilling, welding, sandblasting, fitting, painting, and other surface finishing work. Raw material pieces (steel plates) are heavy, bulky, which are handled in the confined space resembling a manufacturing setting, however steel fabrication is significantly different from other types of manufacturing where large quantities of identical products are produced in an automated or semi-automated environment with less uncertainty or fewer changes (Song and AbouRizk 2003). In a bridge girder fabrication shop, each girder piece has almost similar appearance, but is indeed one-of-a-kind structural element with distinguishable features (such as number of drill holes, stiffeners, studs, shop splice, field splice, weld thickness etc.) These features dictate the specification of work packages and processing sequences for each girder to go through in the constrained space of the fabrication shop. The fabrication operation in this case study mainly consists of the following main steps or work packages (Figure 23):

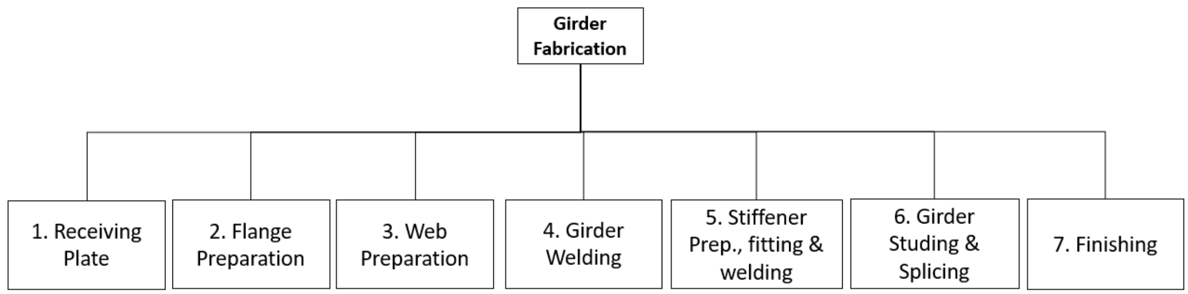


Figure 23. Work Packages of Bridge Girder Fabrication.

A plate girder generally consists of one web, two flanges (Top and Bottom flange), stiffeners, and shear studs (Krause 2015). The web and flanges mainly provide shear strength and bending strength, whereas stiffeners ensure shear bearing force, buckling and flexure resistance depending on the stiffener types (e.g., longitudinal stiffeners, bearing stiffeners, intermediate transverse stiffeners etc.) They are made from the cut plates through straightening and splicing processes. Once the web and flanges are attached, stiffeners and studs are assembled to the girder based on the engineering specifications. Shear studs act as shear connections between steel and concrete to prevent relative motions in both directions (horizontal and vertical). After all the required materials are ready, plate girders are usually arranged in parallel girder lines according to the bridge engineering design. Along each girder line, multiple girders are normally bolted together to form a continuous girder line with the as-designed length of the bridge span. The detailed WBS (Work Breakdown Structure) for this Bridge Girder Fabrication case study is explained below.

5.2.1 Receiving Plates

After shop drawings and all the required materials are ready, it starts with shop detailing on raw flat plates as defined by the fabrication drawings. The engineering design drawing provides all the details about the dimensions of the component to be fabricated. The raw materials may be domestically produced or sourced from different locations, which undergo a rigorous testing and approval process prior to purchase by the manufacturer. In order to check whether the chemical and physical properties of those plates meet the minimum requirements set forth by the applicable standards, testing or checking is done prior to moving to fabrication. After the evaluation of strength, hardness and quality of the material, plates of different sizes and shapes are stacked together following proper precautions.

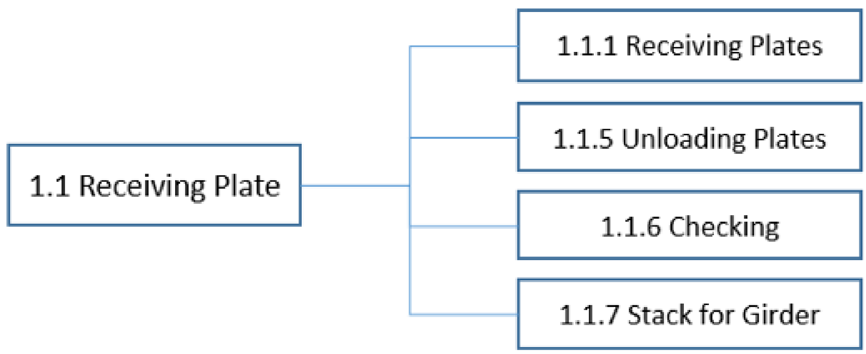


Figure 24. WBS for Receiving plate.

5.2.2 Flange Preparation

Flanges are horizontal elements of plate girder which are provided at the top and bottom and are separated by the web. They are made from the received cut plates through straightening and splicing processes. Since these flange plates (FPL) resist the bending moment acting on the girder, they need to be provided with a required width and thickness as per the design requirements to offer good resistance against bending moment. The basic flange production for a girder includes processing raw materials, and then forming them to meet the appropriate specifications. The major workflows for flange preparation are:

- FPL Pre blasting,
- FPL Cutting,
- FPL Straightening,
- Flange Splicing.

After the steel plates arrive in the shop, they are examined carefully first for damage like cracks, dings, burrs etc. and then brought to the flange blasting shop for surface cleaning and roughening. After the fitness test, the cut flange (or plate flange) manufacturing process begins in the cutting station by flattening steel metal stock using rollers to thin the material until it reaches the intended plate thickness. The flanges are preheated and cut following the appropriate design specifications using a torch, laser, or water jet. The deformation that occurs during welding in the flanges are removed in the flange straightening station. The flange splices enable to design and check the load-bearing capacity of erection joints between flanges and web with high strength bolts or ordinary bolts using plates or endplates. Bolt holes and necessary serrations are cut, and the flange is further machined to exact specifications. For all connections (e.g., splicing flanges, or assembling flanges and web), tack welds are applied as temporary connections to hold components in position before the final welding is performed.

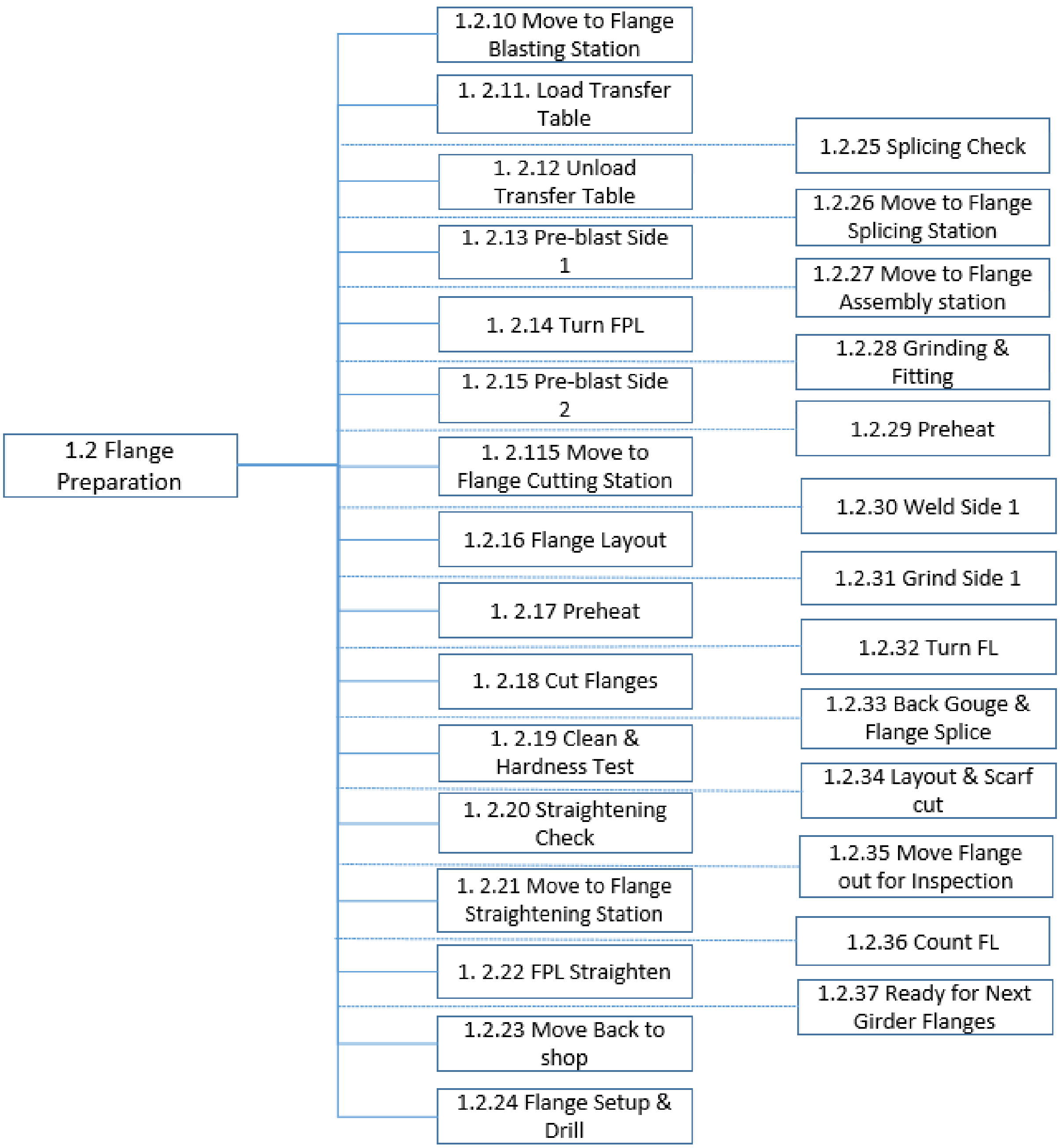


Figure 25. WBS for Flange Preparation.

5.2.3 Web Preparation

Splice plates are lapped across the joint and bolted to the flanges and the webs of the girder in order to transfer the load. This type of splice is usually referred to as a web-flange splice. When determining the web splicing plate's width, it is necessary to leave enough space to open the welding rod when welding the longitudinal weld. Web preparation can be divided into four workflows: web splicing, web cutting, girder assembly, and stiffener fitting.

- Web splicing: Web plates are moved to the splicing station and pre-set for camber; then welding and grinding are done on both web side 1 and 2.
- Web cutting: Plates are taken to the cutting station and shaped according to the shop drawings.
- Girder assembly: After preparing the webs and flanges, one web and two flanges are assembled into a girder by implementing tack welds. Specific machinery like overhead cranes is utilized to lift, handle, and fix the web and flanges and they are fit tightly leaving no gap.
- Stiffener fitting: Next, stiffeners and studs are attached to the assembled girder (web and flanges) based on the engineering drawings. Upon finishing this stage, one girder is formed to shape.

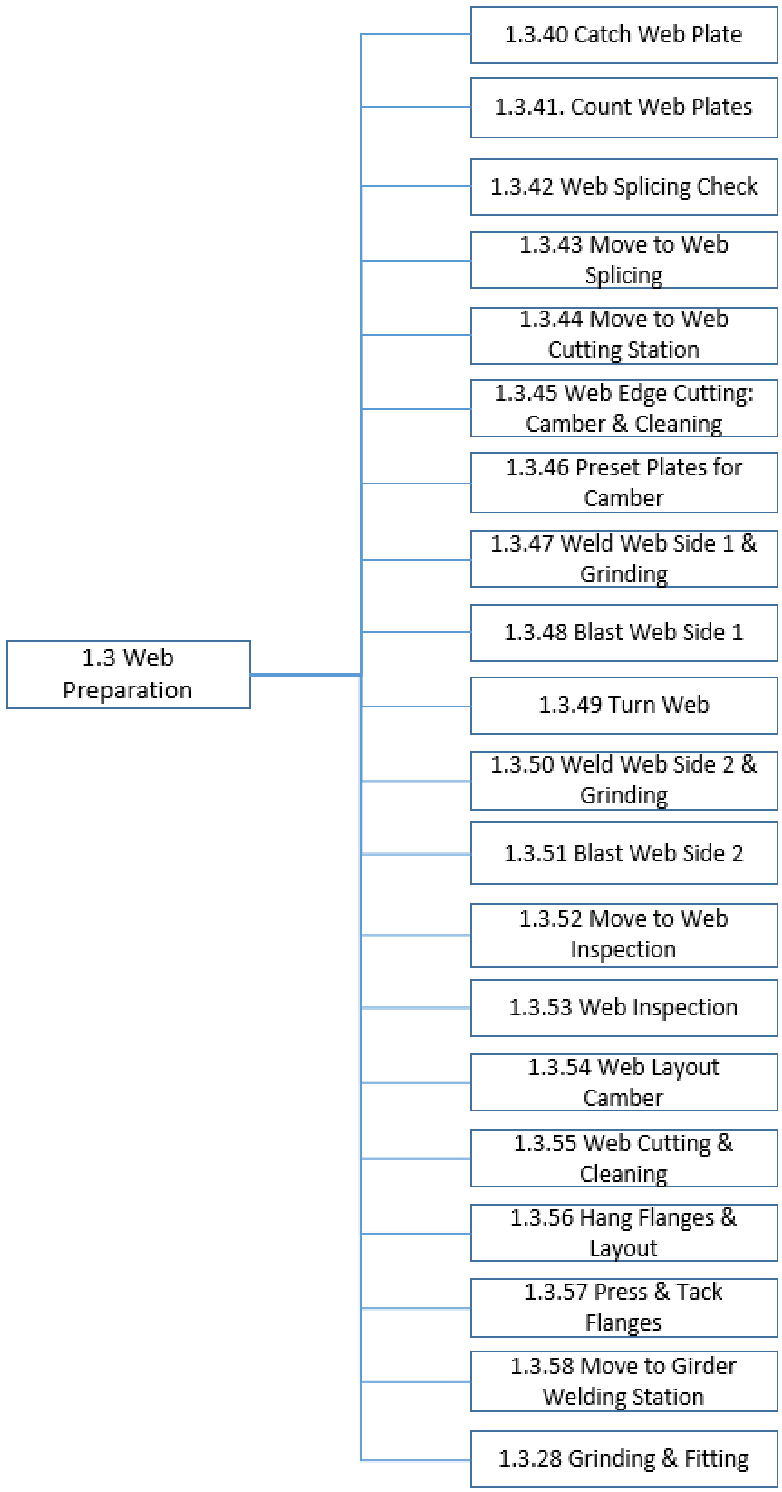


Figure 26. WBS for Web Preparation.

5.2.4 Girder Welding

Stiffeners are attached to beam webs or flanges as secondary plates or sections which stiffens the girder against out of plane deformations. Once the web, flanges, and stiffeners are assembled, final welding is performed to permanently connect web with flanges and stiffeners.

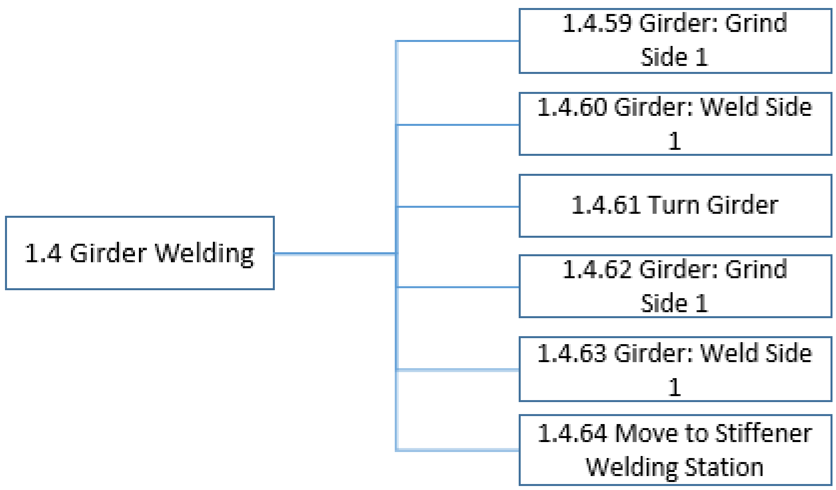


Figure 27. WBS for Girder Welding.

5.2.5 Stiffener Preparation

Intermediate transverse web stiffeners are also commonly situated at intervals along the length of the girder where there is a possibility of web-buckling due to rotational moments at the connection. The likelihood of web-buckling increases as the girder depth increases. These stiffeners are commonly welded to only one side of the web (normally the outside face) but may be welded to both the sides depending on the requirements. After the stiffener is welded to the flange, the fabricator grinds the stiffener end in order to make a good fit with the flange over a substantial proportion of the stiffener area.

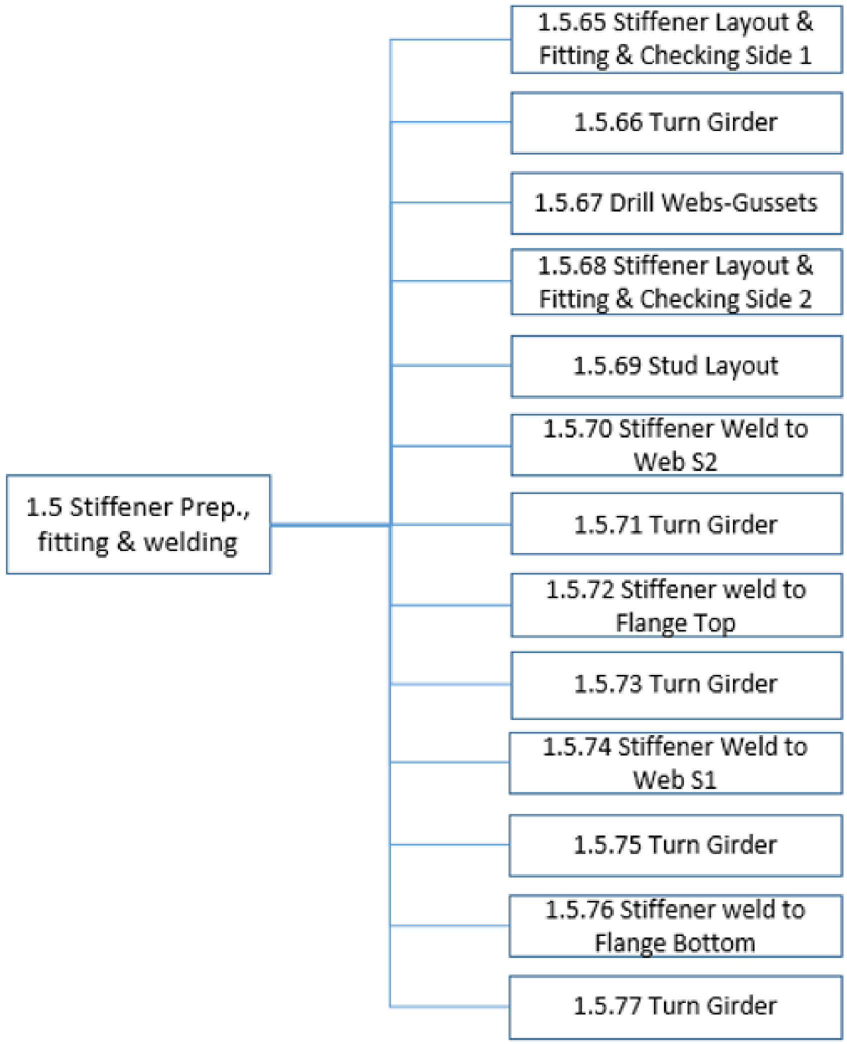


Figure 28. WBS for Stiffener preparation, fitting and welding.

5.2.6 Girder Studding and Field Splicing

In the following stage, multiple holes are drilled on the girder for field splicing so that two adjacent girders located in the same girder line can be connected by bolting in on-site

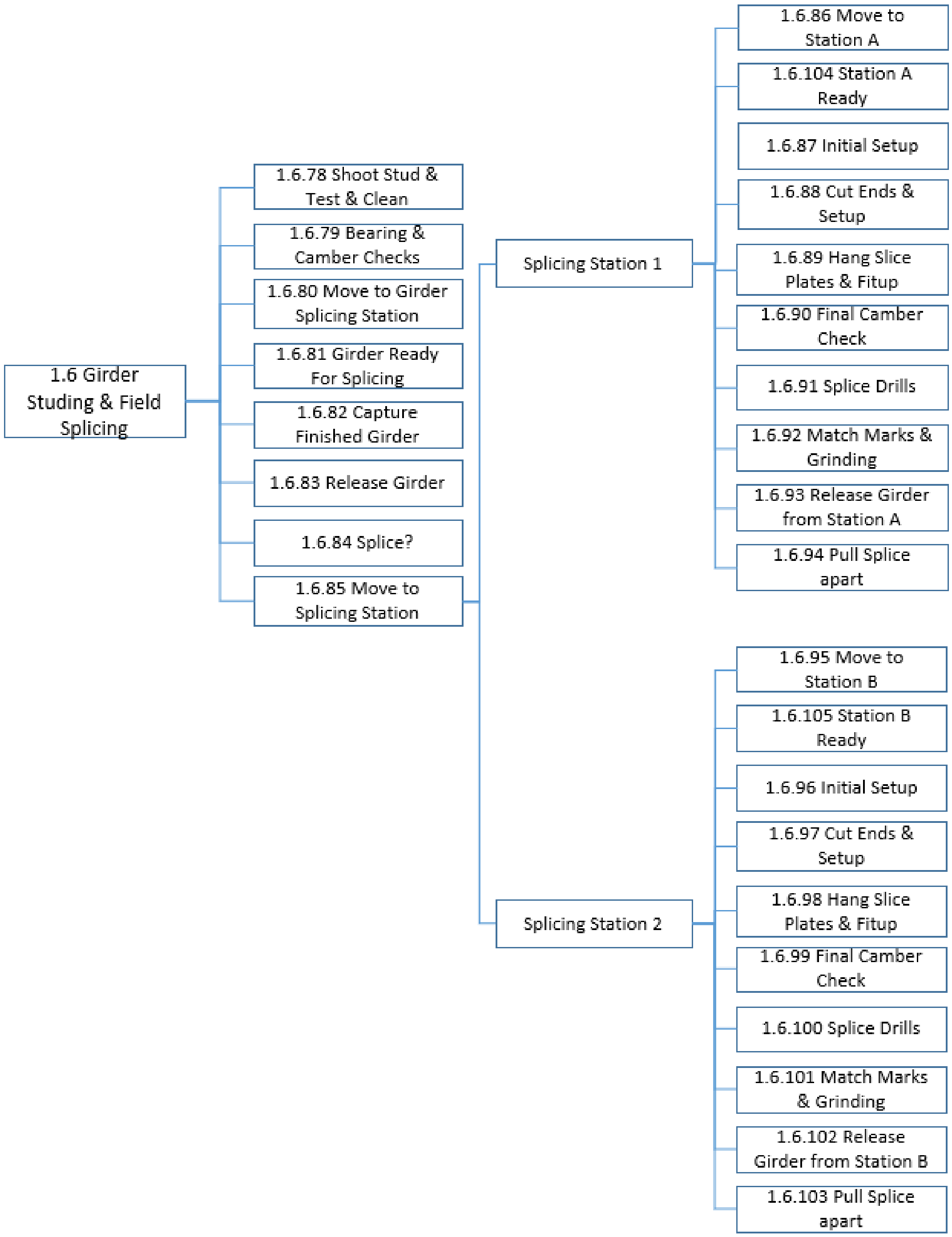


Figure 29. WBS for Girder studding and field splicing.

installation. During this period, the two adjacent girders are first aligned in the fabrication shop; and drilling is then performed on the girder splice end, web splice plates, and flange splice plates followed by surface finishing works like sandblasting and painting before being shipped to site for installation. The steel structure splicing (welding and bolting) is always implemented based on ensuring the strength of the components.

5.2.7 Finishing

As for drilling for field splicing, one fabricated girder sometimes has to wait until the next girder is ready. However, if the next girder cannot be completed soon, the finished girder has to be moved out of the shop in order to create space for fabricating subsequent girders. That girder can only be moved back to the shop for drilling at a later time when the other girders are ready. To solve this problem, girders on one girder line are fabricated continuously to avoid extra handling. This logical constraint inherent in girder fabrication provides the basis for defining the scope of macro-activities in the girder fabrication projects.

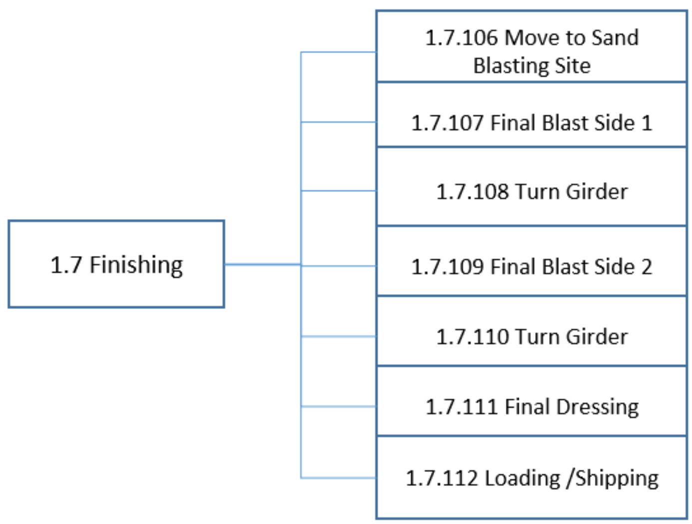


Figure 30. WBS for Finishing girder.

All the work packages identified above during girder fabrication denote processes, the occurrence or repetition of which are dictated by girder's specific features. If these workflows are elaborated based on their individual features, each girder type will be associated with a unique AON network model exploding in size and giving rise to thousands of complex technological or resource relationships. The ability of the scheduler to simulate these complexities in a simplified automated framework can greatly reduce these planning uncertainties and improve the quality of the finished product. Thus, within these conditions of simplification, Discrete Event Simulation has been implemented in this research as a tool to simulate the current conditions of a fabrication shop while analyzing different options for optimization without need for real-life experimentation.

5.3 Practical Case Study

Specific to bridge girder fabrication, this case study is to implement the proposed simulation framework on a real project, measure the project performance and determine whether steel fabricators should further adopt this planning methodology. The case study was conducted based on a steel bridge fabrication shop and the scope of production planning consists of 21 girders that make up three girder lines for a bridge project. The girders have been classified into six categories (Type 1- 6) based on their design attributes, out of which 6 girders have a length of 46 meters; 12 girders have a length of 36 meters and 3 girders have a length of 20 meters. The total weight of all girders amounts to 600 metric ton.

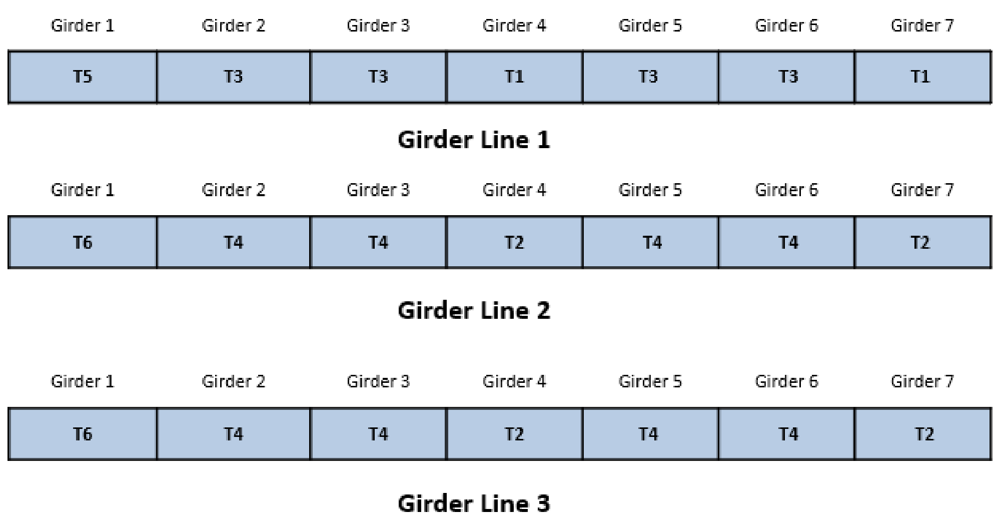


Figure 31. Schematic diagram of the Girder lines.

Table 7. Number of girders in different girder types.

Girder Type	Number of Girders
T1	2
T2	4
T3	4
T4	8
T5	1
T6	2

According to the design specifications, plates of different dimensions are fitted together to produce 21 unique steel plate girders. Table 8, 9 and 10 summarizes the attributes of web, flange and stiffeners of the girders that define a unique type of girder as defined by industry practitioners (Hasan et al. 2019).

5.3.1 Flange Attributes

- Length, width, and thickness of the flanges (Top and Bottom) vary based on dimension as per structural design.
- Number of flange splices can be determined using Eq.1:

$$N_1 = \frac{length\ of\ the\ girder}{Individual\ flange\ plate\ length} - 1 \quad (1)$$

Here, N1 is upper rounded whole number.

- Number of drills in one end is defined in the dimensions as per structural design.

Table 8. Flange attributes of different types of girders.

ID		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
FPL.Attr1	Length of the flanges (Top and Bottom)	46 m	23 m	36 m	18 m	20 m	10 m
FPL.Attr2	Width of the flanges (Top and Bottom)	0.6 m	0.6 m	0.6 m	0.6 m	0.6 m	0.6 m
FPL.Attr3	Thickness of the flanges	0.06 m	0.06 m	0.06 m	0.06 m	0.06 m	0.06 m
FPL.Attr4	Number of holes in one end of the flange	30	30	30	30	30	30
FPL.Attr5	Number of flange splices	0	1	0	1	0	1

5.3.2 Web Attributes

- Length, width, and thickness of the web vary based on dimension as per structural design.
- Number of the web plates can be determined using Eq. 2:

$$N_2 = \frac{length\ of\ the\ girder}{Individual\ web\ plate\ length} \qquad (2)$$

Here, N2 is upper rounded whole number.

Table 9. Web attributes of different types of girders.

ID		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
WPL.Attr1	Length of the web plate	46 m	23 m	36 m	18 m	20 m	10 m
WPL.Attr2	Thickness of the web plates	0.02 m	0.02 m	0.02 m	0.02 m	0.02 m	0.02 m
WPL.Attr3	Width of the web plates	2.7 m	2.7 m	2.7 m	2.7 m	2.7 m	2.7 m
WPL.Attr4	Number of the web plates	1	2	1	2	1	2

5.3.3 Girder Attributes

- Length of the girder vary based on dimension as per structural design.
- Number of the field splices is equal to

  a) 0, when there is only one girder in the girder line;

  b) 1, when there are multiple girders in the girder line and girder is the abutment side girder;

  c) 2, when there are multiple girders in the girder line and subject girder is the middle one with two other girders at each end of it.
- Stiffener Complexity Factor (compared against a standard condition) can be any positive number and can be determined using Eq. 3:

$$\mathrm{CF} = \frac{LH\ required\ to\ work\ on\ specific\ feature\ of\ new\ girder\ type}{LH\ required\ to\ work\ on\ specific\ feature\ of\ standard\ girder} \quad (3)$$

- Stiffener welding complexity (compared against standard condition) equals to

  a) 1, if the angle between the web and stiffeners is 90 degree;

  b) 1.5, if the angle between the web and stiffeners is 45 degree;

  c) for all other cases.
- Girder shape complexity (compared against the standard girder) can also be determined using Eq. 3.

Table 10. Other girder attributes of different types of girders.

ID		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
FG.Attr1	Length of the girder	46 m	46 m	36 m	36 m	20 m	20 m
FG.Attr2	Number of the field splice	1	2	1	2	1	2
FG.Attr3	Stiffener complexity (compared against a standard condition)	1	1.5	1	1.5	1	1.5
FG.Attr4	Stiffener welding complexity (compared against standard condition)	1	1.5	1	1.5	1	1.5
FG.Attr5	Girder shape complexity (compared against the standard girder)	1	1	1	1	1	1

Now depending on the girder type, a particular girder undergoes certain processes on the shop floor. How to sufficiently define these different girder attributes and specify girder types is conducive to planning for the fabrication operations in the shop. Besides, these shop floor operations generally consist of repetitive workflows to be performed on different nonuniform work units. For example, in the fabrication shop, the operation schedule for one particular girder normally consists of seven to ten work packages, which can be elaborated into more than hundred fabrication activities. Each activity then can be associated with multiple (four to five) technology precedence relationships in addition to many implicit resource constrained precedence relationships. In general, one project consists of multiple girder lines, where each girder line is made up of multiple unique girders. Moreover, the scheduler needs to handle multiple bridge projects simultaneously in the limited timeframe. Even if we consider only one single span bridge project consisting of three girder lines each having only two girders, the total number of activities can be more than six hundred with over two thousand technological and resource constraints. Simplified Discrete-Event Simulation Approach (SDESA) presents itself as a tool in this case to extend the activity on node (AON) and critical path method (CPM) into an operations simulation model by adding labour, material, equipment, and workstation constraints.

5.4 AON+ Implementation

To adapt and cater to these construction simulation needs and simplify construction operations modeling, Lu (2003) formalized and developed the simplified discrete-event simulation approach (SDESA). This activity-based simulation framework mimics the common practice of using CPM in construction planning, but requires less modeling efforts or knowledge to adequately represent repetitive work flows and resource transit in construction operations. SDESA essentially provides a generic process mapping for integrating the site layout and operations planning in construction (Hasan et al. 2019). In processing any sequence of activities or jobs, specified logical conditions are satisfied and the start time of an activity is delayed until demanded resources are available. Unlike AON, SDESA enriches the definition of project network models or resource workflow models by defining resource pools, flow entities, and resource transit information relevant to a construction operations system (Lu 2003). Since its introduction, SDESA, along with the in-house developed computing platform has been transforming available data and information into an optimized design of project network model utilizing automated planning methods and has been successfully implemented in different practical implementation cases. Chan et al. (2006) applied the framework to model the process of erecting the prefabricated structural elements using cranes in the construction of the steel structure of a stadium. Later, they utilized the framework to model the operations of installing the precast deck segments considering the site constraints of limited site space and logistics on a precast viaduct construction project in real world.

The workflow simulation model developed for this case study in SDESA is a three-tiered modeling framework, where the complex workflows are presented in straightforward and adaptive models to sufficiently represent essential operational details on the shop floor from the perspective of a shop superintendent. The top tier interface of this three-layer architecture allows the planner to change job processing order and resource availability on the shop without requiring any expertise in computer programming or simulation. The interface designed as a dashboard, allows users to enter unique structural features for each individual girder and specify the fabrication sequence based on drawings and specifications directed by editable arrows. The middle tier is the core of the model where three sources of information are fed into the simulation model: (1) Shop operation logic, (2) Duration of each activity and process, and (3) Resource use constraints of the fabrication shop. When the shop operation logic changes, the modeler can easily adjust the parameters and update the simulation model in this tier accordingly. The bottom tier acts as the robust simulation engine, responsible for automatically manipulating every simulation event and constraint specified in the top and middle tiers.

In order to observe and document the fabrication activities, sequences and the resources required, extended visits were conducted to a Bridge Girder Fabrication shop located in Edmonton, AB. All the process activities required for fabricating the complete girders from raw plates were identified and mapped in SDESA to simulate a more realistic image of the fabrication shop in association with an experienced production manager of the shop. In order to explain how SDESA facilitates different properties of different girder types for the case study problem, this section takes Type 1 girder as an example.

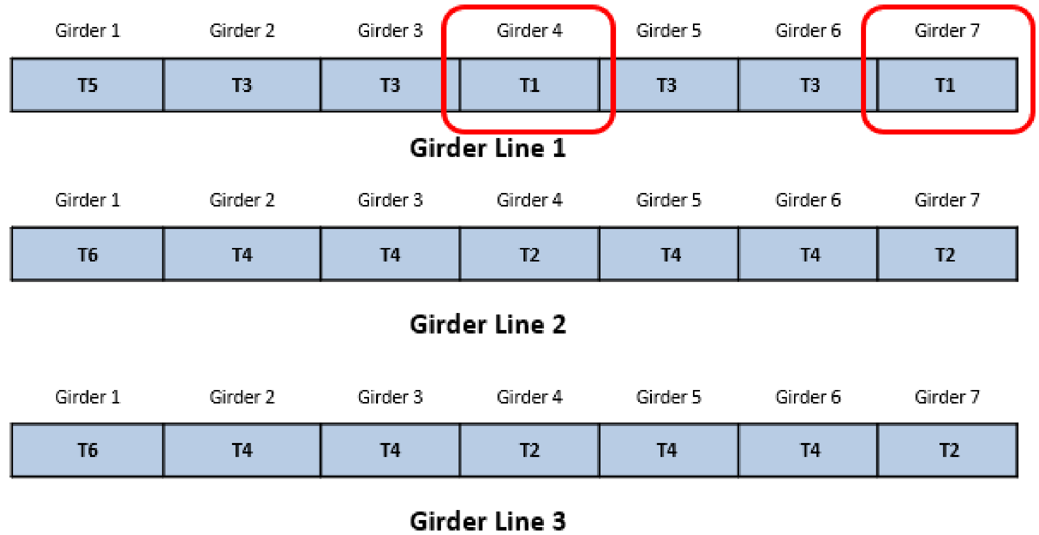


Figure 32. Girder Type 1 in Girder Line 1.

The developed model (explained in Appendix B) provides simulated "what-if" alternative scenarios based on the change operation logic and resource constraints and provided proactive measures to assist in the decision-making process. In contrast to the current scheduling and estimating methods, the framework presented in this research became successful to predict the outcomes before performing the activities by providing accurate and reliable feedback to the planner regarding the overall system performance, activity durations and labor performance of the actual fabrication shop.

Chapter 6: Results and Analysis

6.1 Productivity Matrix

SDESA presents itself as a tool to extend the Activity on Node (AON) and Critical Path Method (CPM) into an operations simulation model by adding labor, material, equipment, and workstation constraints. The proposed bridge shop simulation model encapsulates the detailed shop-floor activities, the logic of workflows, and classification of bridge girder products from the perspective of a shop operations manager. Activity times in simulation denote the most likely times (in minutes) it would take to process a certain amount of work by the tradespersons. The definition of activities is associated with certain attributes of the processed girder (e.g., length, width, depth, weight, design specs). Based on the activity analysis, the simulation model classifies all the activities in a matrix of five groups, which accounts for:

- Productive Activities: Considered those which harness a company's resources to facilitate the objectives of a project in place (e.g., crews using tools, equipment processing products etc.)
- Semi-productive Activities: Defined as support work that do not directly add value but support the implementation of Productive activities (e.g., material handling, instruction and decision making, equipment maintenance, preparing tools, workspace, and auxiliary materials etc.)
- Value-Added Activities (VA): Operational efforts that realize project requirements defined in the contract data (Fidelis and John 2011) and help in converting materials and/or information towards what is required by the costumer in the least possible time at minimum costs (e.g., assembling a product, painting, grinding, cutting, splicing etc.)
- Business Value-Added Activities (BVA): Can also be called "Non-negotiable waste", which support value added activities and are essential for running the workflows, but not directly valued by the client (e.g., initial setup, movement between locations, equipment inspection, safety etc.)
- Non-value-Added Activities (NVA): Considered to be pure waste in the construction process that consume time, cost and resources but do not add value to the construction

process (e.g., over-production, waiting, rework, interruption etc.) Alarcon et al. (1994), Koskela et al. (1992) and Love et al. (1997) defined NVA as activities that produce costs (direct or indirect) and consume time and resources but do not add value or progress to the product. According to Saito et al. (2012), NVAs are the main cause of cost overruns and delays, and the identification of their causes of occurrence and a measurement of their level of importance would provide useful information that would allow management to actively reduce their negative effects in advance.

Based on simulation results, Table 11, Table 12, Table 13 and Table 14 provide a visual representation of the activity duration matrix by identifying and segregating all the activities into these five groups.

Table 11. Productivity Matrix

<table>
<tr><td></td><td>VA</td><td>BVA</td></tr>
<tr><td>Productive</td><td>3315.75</td><td>814.49</td></tr>
<tr><td></td><td>34.49%</td><td>8.47%</td></tr>
<tr><td>Semi-productive</td><td>1798.37</td><td>706.38</td></tr>
<tr><td></td><td>18.70%</td><td>7.35%</td></tr>
<tr><td rowspan="2">Unproductive/NVA (Waste)</td><td colspan="2">2979.60</td></tr>
<tr><td colspan="2">31%</td></tr>
</table>

Table 12. Value Added Productive and Semi-Productive Matrix

	Value-Added (VA)				
	No.	Activities	Busy (hour)	Idle (hour)	Total (hour)
Productive	*15*	Pre-blast side two	124.53	0.00	124.53
	16	Flange Layout	35.58	18.66	54.24
	18	Cut Flanges	35.58	36.25	71.83
	22	FPL Straighten	337.40	0.00	337.40
	24	Flange Setup & Drill	144.00	42.54	186.54
	28	Grinding and Fitting	64.80	1.15	65.95
	30	Weld Side 1	43.20	6.31	49.50
	31	Grind Side1	64.80	0.00	64.80
	33	Back gouge & Flange splice	64.80	1.91	66.72
	34	Layout & Scarf Cut	32.40	0.00	32.40
	47	Weld Web Side1 & Grinding	14.58	3.67	18.25
	48	Blast Web Side1	48.60	0.00	48.60
	50	Weld Web Side2 & Grinding	14.58	2.02	16.60
	51	Blast Web Side2	48.60	0.00	48.60
	54	Web Layout Camber	135.00	4.50	139.50
	55	Web Cutting & Cleaning	180.00	9.50	189.51
	57	Press & Tack Flanges	216.00	18.65	234.65
	59	Girder: Grind Side1	90.00	16.24	106.23
	60	Girder: Weld Side1	72.00	3.00	75.00
	62	Girder: Grind Side2	90.00	15.67	105.67
	63	Girder Weld Side2	72.00	2.91	74.91
	67	Drill Webs-Gussets	216.00	36.04	252.04
	70	Stiffener Weld to Web S2	0.00	47.75	47.75
	72	Stiffener Weld to Flange Top	0.00	29.81	29.81
	74	Stiffener Weld to Web S1	0.00	13.56	13.56
	76	Stiffener Weld to Flange Bottom	0.00	20.23	20.23
	78	Shoot Stud & Test & Clean	180.00	1.87	181.87
	88	Cut Ends & Setup	73.80	7.29	81.09
	91	Splice Drills	304.00	14.99	318.99
	92	Match Marks & Grinding	38.00	102.56	140.55
	97	Cut Ends & Setup	76.00	15.69	91.69
	100	Splice Drills	147.60	285.00	432.60
	101	Match Marks & Grinding	36.90	82.06	118.96
	107	Final Blast Side1	126.00	27.44	153.44
	109	Final Blast Side2	126.00	26.44	152.44
	111	Final Dressing	63.00	30.05	93.05

Table 13. Value Added Productive and Semi-Productive Matrix

	Value-Added (VA)				
	No.	Activities	Busy (hour)	Idle (hour)	Total (hour)
Semi-productive	*5*	Unloading Plates	84.00	17.62	101.62
	7	Stack for Girder	10.50	29.34	39.84
	11	Load Transfer Table	21.00	32.64	53.64
	12	Unload Transfer Table	21.00	51.79	72.79
	14	Turn FPL	84.00	92.05	176.05
	17	Preheat	17.79	37.31	55.10
	19	Cleanup and hardness test	42.00	41.32	83.32
	29	Preheat	10.80	20.56	31.36
	32	Turn FL	27.00	47.84	74.84
	35	Move flange out for inspection	27.00	68.05	95.05
	46	Preset Plates for Camber	132.48	48.12	180.60
	49	Turn Web	72.00	69.33	141.33
	56	Hang Flanges & Layout	432.00	95.03	527.03
	61	Turn Girder	42.00	30.45	72.45
	66	Turn Girder	42.00	57.14	99.14
	69	Stud Layout	45.00	12.09	57.09
	71	Turn Girder	42.00	12.86	54.86
	73	Turn Girder	42.00	13.69	55.69
	75	Turn Girder	42.00	29.05	71.05
	77	Turn Girder	42.00	40.10	82.10
	89	Hang Splice Plates and Fit up	73.80	19.20	93.00
	94	Pull Splice apart	17.00	63.81	80.81
	98	Hang Splice Plates and Fit up	76.00	21.50	97.50
	103	Pull Splice apart	17.00	89.92	106.92
	108	Turn Girder	42.00	73.02	115.02
	110	Turn Girder	42.00	77.26	119.26
	112	Loading/Shipping	252.00	64.01	316.01

Table 14. Value Added Productive and Semi-Productive Matrix

	Business Value-Added (BVA)				
	No.	Activities	Busy (hour)	Idle (hour)	Total (hour)
Productive	*65*	Stiffener Layout & Fitting & Checking Side1	303.12	6.90	310.02
	68	Stiffener Layout & Fitting & Checking Side2	303.12	3.36	306.48
	79	Bearing & Camber Checks	21.00	19.25	40.25
	87	Initial Setup	73.80	72.00	145.80
	90	Final Camber Check	19.00	20.25	39.25
	96	Initial Setup	76.00	99.77	175.77
	99	Final Camber Check	18.45	28.01	46.46
Semi-productive	*10*	Move: Flange Blasting Station	21.00	0.00	21.00
	21	Move to Flange Straightening Station	20.00	23.25	43.25
	23	Move back to shop	20.00	22.40	42.40
	26	Move to Flange Splicing Station	18.00	17.75	35.75
	43	Move: Web Splicing	108.00	14.69	122.69
	44	Move: Web Cutting Staton	30.38	80.40	110.77
	52	Move: Web Inspection	27.00	68.05	95.05
	58	Move: Girder Welding Station	63.00	28.72	91.72
	64	Move: Stiffener Welding Station	126.00	31.70	157.70
	86	Move to Station A	66.00	34.70	100.70
	95	Move to Station B	60.00	28.53	88.53
	106	Move: Sand Blasting Site	126.00	142.70	268.70
	115	Move to Flange Cutting Station	21.00	58.31	79.31

From the simulation results, all fabrication activities are defined and considered within each category of the classification system. As shown in the Productivity Matrix in Table 15, the total Value Added-Productive duration after considering all the activities in this category is 3315.75 h (34.49%) and the Value Added-Semi Productive time is 1798.37 h (18.70%). 814.49 h (8.47%) has been spent on BVA-Productive activities, whereas 706.38 h (7.35%) has been consumed by BVA-Semi Productive activities. Also, the total time spent on non-value added (unproductive) activities is 2979.60 h (31%). Based on the results, the action activities that that should be targeted to ensure a Lean transformation are Table 16.

Table 15. Action activities for Lean transformation.

No.	Activity Type	Action During Lean
1	VA-Productive	Optimize and standardize
2	VA-Semi productive	Optimize and standardize
3	BVA-Productive	Question and reduce
4	BVA-Semi productive	Question and reduce
5	Unproductive/NVA (Waste)	Eliminate

Some of the reasons that lead to non-value-added activities or waste in this case study can be caused by constraints such as the unavailability of material required, administration work, poorly organized project site, limited equipment, and skilled workers. As evident from the observations, this understanding and classification of value and waste in this research can be used to benchmark the labor productivity, identify holistic reasons for productivity loss and reduce 'Muda' (Waste or Non-value-added activities) in construction.

6.2 Determining Maximum Shop Capacity from Concurrent Girders Processing

In addition to job processing plans and resource allocation plans, shop managers can also customize different useful plans in connection with various management functions by extracting relevant data from simulation results. It is noteworthy at a given moment, multiple girders can be processed concurrently in the fabrication shop, making it essential to determine the maximum concurrent processed girders in a shop based on the shop capacity. The variations in the specifications of product design and fabrication process requirements, plus the interruption time (waiting for limited resources, trades or constrained space) generate different start and finish dates for each individual girder. When multiple girders are assembled to make the girder lines, the girder sequences can be rearranged based on their design and process requirements to maximize the number of concurrent girders processing in the shop. For this case study, a total of 20 girder sequences have been investigated for the 21 girders in three girder lines when 9 journeymen are available in order to identify the best sequence for processing maximum girders at a given time (Table 16).

Table 16. Concurrent girders processing (%) comparison for different girder sequences.

Sequences	Concurrency %	
	8 Girders	9 Girders
1	4.59%	
2	5.30%	
3	13.17%	1.23%
4	11.49%	0.85%
5	11.01%	1.27%
6	12.40%	0.83%
7	11.11%	1.23%
8	10.79%	
9	7.38%	
10	10.00%	1.25%
11	11.16%	
12	9.17%	0.83%
13	8.60%	
14	24.35%	1.30%
15	13.04%	
16	10.33%	
17	8.68%	2.48%
18	10.74%	
19	6.78%	
20	9.50%	3.31%

In Table 16, the concurrent multiple girders processing time is derived from the most likely value for processing each girder based on virtual shop simulation utilized in this case study. Since multiple girders will be processed concurrently in the fabrication shop; at one time, a maximum of 9 girders can be processed simultaneously in 10 out of these 20 sequences and for the other 10 sequences, 8 girders can be processed at maximum. The maximum 8 girders concurrent processing time (24.35%) can be found in sequence 14, whereas the maximum 9 girders concurrent processing time (3.31%) can be found in sequence 20. A snapshot of the roll-up bar chart schedule with each girder's start and finish dates for these two sequences are presented in Figure 33 and Figure 34.

The bar charts show the processing time for each girder and when maximum girders are being processed at a given time along with their duration of occurrence. Taking the fabrication work for girder sequence 14 for example, the total duration is 1158 hours when there are 9 journeymen. The blue dotted lines show the duration when 8 girders are being processed concurrently in the shop. After summing all these durations, it is found 24.35% of the time throughout the make span of girder sequence 14, 8 girders are processed. In the same way, 9 girders are processed 1.30% of the time throughout the make span of the processing 21 girders in this specific sequence. Now if the shop has a capacity of processing maximum 8 girders at a given time, sequence 14 is the best choice to minimize waste; and if the shop has a capacity of 9 girders to be processed concurrently, sequence 20 should be their best choice to maximize the crew productivity.

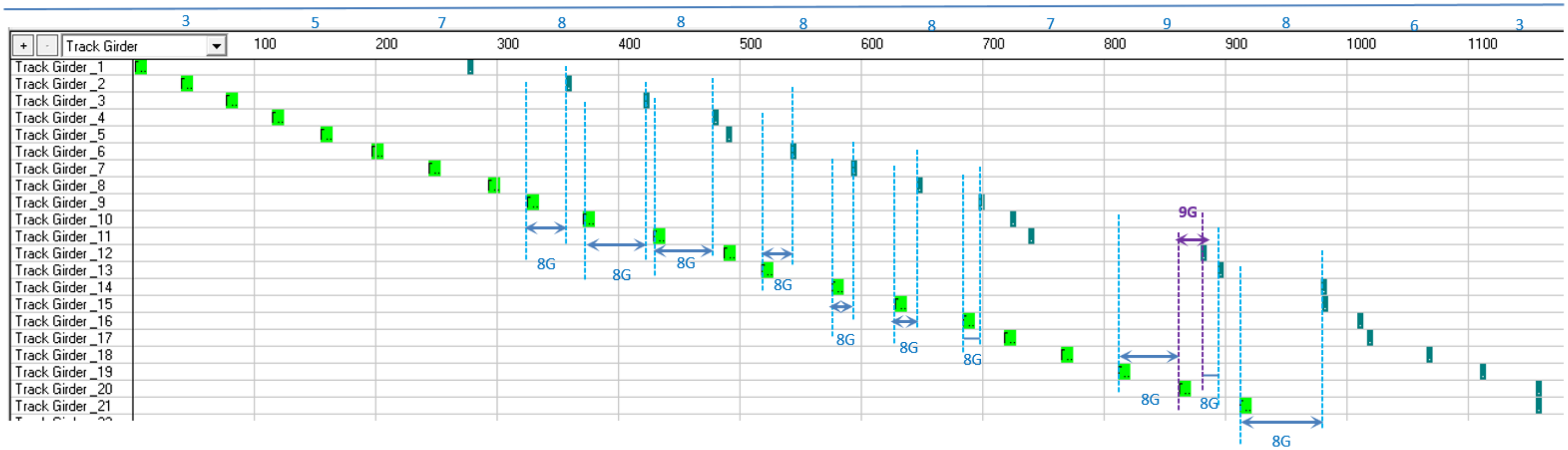


Figure 33. Maximum 8 Girders Concurrent Processing Duration (24.35%, Sequence 14).

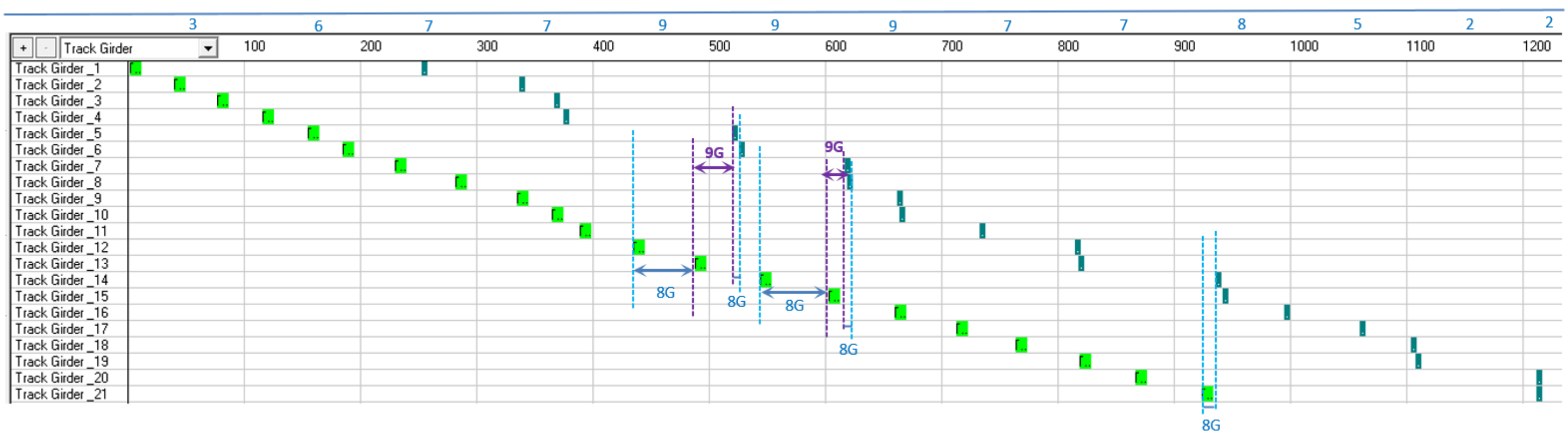


Figure 34. Maximum 9 Girders Concurrent Processing Duration (3.31%, Sequence 20)

For this case, if the production manager's objective is to further minimize the total labor-hours spent in this project, the results from the best girder sequence can be used in this regard to identify the optimum number of crews to reduce waste and maximize productivity. Taking the crew allocation for girder sequence 20 for example (Table 18), having 9 journeymen in the project is the best scenario if the manager aims for maximum resource utilization. Now if the client demands the project to be completed in the least possible duration, the production manager can change the number of journeymen and run the simulation to find out the best crew allocation for this sequence. In this case, the number of journeymen should be extended to 11 to complete this project in the least possible time (1075 hrs).

Table 17. Different crew allocation for Girder Sequence 14.

ID	Job Sequence	Journeyman No.	Labor hours		Project Duration (hrs)	Utilization Rate
			Busy	Idle		
1	14	7	7596	3803	1631	66.64%
2		8	7606	2817	1306	72.97%
3		9	7577	2793	1158	73.07%
4		10	7591	3230	1088	70.15%
5		11	7605	3776	1040	66.82%

Table 18. Different crew allocation for Girder Sequence 20.

ID	Job Sequence	Journeyman No.	Labor hours		Project Duration (hrs)	Utilization Rate
			Busy	Idle		
1	20	7	7641	3818	1638	66.68%
2		8	7604	3290	1364	69.80%
3		9	7605	3271	1212	69.92%
4		10	7632	3661	1133	67.58%
5		11	7591	4185	1075	64.46%

It is critical to formulate thorough workface plans prior to starting a project to effectively direct job allocation to particular trades and workstations while ensuring resources are utilized as fully as practically possible. Thus, if there is a particular deadline to meet, these alternative scenarios in Table 18 and Table 19 can aid the production manager to make decision regarding the number of crews after they choose the best girder sequence for their shop. The simulation results in this form of customized schedules can be very beneficial for the project managers to ensure maximum resource allocation based on shop capacity and crew size.

The results based on the virtual shop model were found closely aligned with actual shop performances and proved reliable in predicting labor hours on a typical bridge girder fabrication project. The model was developed in a DES platform based on the shop workflow logic and estimator's numbers. The definition of activities was associated with certain attributes of the processed girder (e.g., design specs, dimensions, weight). Activity times denoted the most likely times (in minutes) in order to process a certain amount of work (connecting pieces or handling pieces) by tradespersons. The main variations in production planning in this research were not in activity time, rather in production sequence and crew size. The virtual shop model was utilized to experiment with various scenarios in the end in terms of production sequence and crew size. The results from this shop production model was found closely aligned with actual shop performances and proved reliable for predicting labor hours on a typical bridge girder fabrication project. Therefore, the virtual shop model can be used to check the estimate and produce a practical production plan by fine-tuning production sequence and crew size resulting in increased performances in crew productive time%, cost control, and client satisfaction (Hasan et al. 2019).

Chapter 7: Lean Construction Planning Subject to Variations in Detailed Features of Fabricated Bridge Girders

7.1 'Mura' in Fabrication

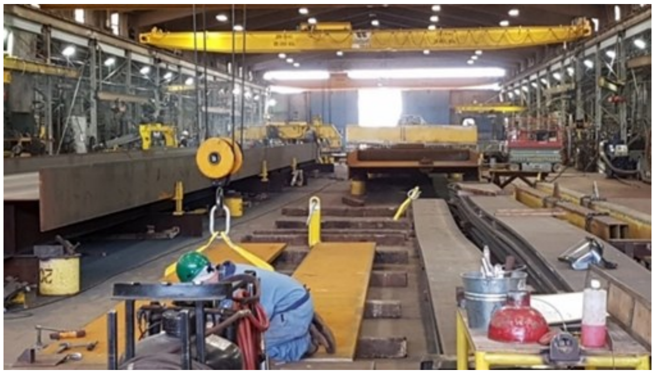
Offsite construction (such as prefabrication, pre-assembly, or modularization) has been practiced widely for decades in the construction industry in pursuit of realizing the lower cost, tighter schedules, higher resource use efficiency, and ultimately, productivity improvement. Nonetheless, to produce structural components of similar types in executing precast and prefabrication projects, variations in design features and fabrication processes result in one-of-a-kind jobs and add to the complexity in project planning. Without acknowledging these variations that could potentially multiply uncertainties in resource utilization and work processes in the process of production planning, it would result in significant errors in the project schedule and cost budget. This would also present a distinctive challenge in delivering predictable project performances and making it difficult to reduce cost overruns, delays, and disputes between different parties (Tzortzopoulos and Formoso 1999, Dosumu and Aigbavboa 2017).

The lean philosophy was developed aiming at the removal of 'muda' (the waste in material, time and space) (Womack and Jones 1997) through systematic planning; however, if the existence of 'mura' (variations in product design and production process) (Shingo and Dillon 1989) is not well understood and even ignored in planning and scheduling, muda would be impossible to be controlled, let alone to be reduced or eliminated. For this reason, this paper uses a real-world case of planning bridge girder fabrication at a steel fabrication shop to illuminate on the above-identified problem. It is worth mentioning that in a separate, recent endeavor, a computer simulation model had been developed to account for sufficient details from the perspective of the actual shop manager and thoroughly validated in conjunction with an industry partner (Hasan et al. 2019). The resulting simulation model provides a reliable and convenient vehicle for the present research to design "what-if" scenarios for simulation and collect simulation data as if they would have been the consequences from executing a postulated scenario in the fabrication shop being studied. An in-depth analysis of the simulation model reveals the mura inherent in girder design and fabrication processes, which is especially instrumental in planning lean processes for girder shipment, storage, and installation in the field aimed at minimizing the muda waste (such as renting extra laydown yard in the field or idling installation crew in the field due to waiting for girder delivery.)

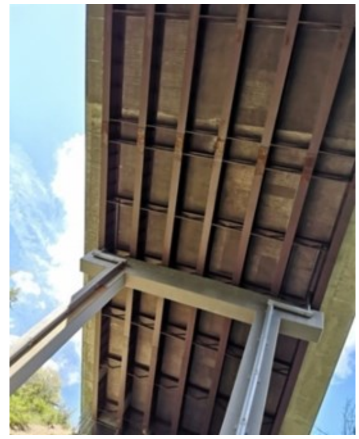
The current practice of project planning and scheduling generally uses MS Projects or P6 to generate a precedence diagram schedule without accounting for the impact of variations in girder design and fabrication process upon fabrication time and logic, ultimately causing significant 'muda' waste in girder storage, shipment and field installation. In this research, we take advantage of a validated simulation model for a structural component fabrication shop in the service of construction projects. The simulation model was developed and validated in Hasan et al. (2019), which serves as the virtual plant for a bridge girder fabrication shop in the real world. In the case study, insights gained from the virtual plant in regards to girder fabrication time and start-to-start lag time between consecutive girders are extracted and further generalized as planning guidelines for project schedulers.

7.2 Case Study

Planning and scheduling operations at the steel fabrication shop pose distinctive challenges due to one-of-a-kind girder design, multi-project simultaneous execution, and limited limits of the available skilled trades (Song and Abourizk 2003). Each girder piece is alike in appearance but is indeed a unique structural component with special features (such as shop splice, field splice, stiffeners, studs, number of drill holes, weld thickness, etc.). These features play a vital role in determining the specification of work package layout and processing sequences for each girder to go through the shop floor workstations. Figure 35 shows (a) the setting of a typical bridge girder fabrication shop and (b) structural steel girders underneath a built bridge.



(a)



(b)

Figure 35. (a) setting of a typical bridge girder fabrication shop; (b) structural steel girders underneath a built bridge.

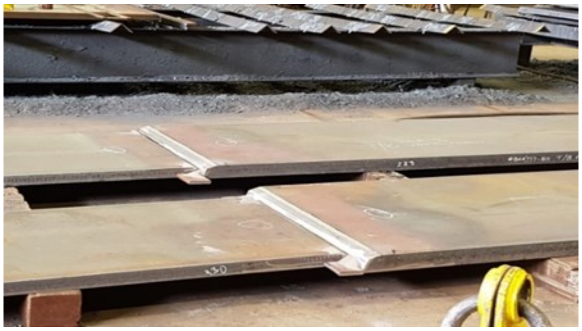
The case study was conducted based on a steel bridge fabrication shop located at Alberta; the scope of production planning consists of 15 girders that make up five girder lines for a bridge project. The girders have been classified into four categories (Type 1- 4) based on their design attributes (length, depth, shop splices, field splices, stiffener quantity and locations). Table 19 summarizes the girders' attributes defining a unique type of girder, and their structural design variations, which is defined in the simulation model developed for the bridge girder fabrication shop being studied (Hasan et al. 2019).

Table 19. Properties of different girder types of the case study

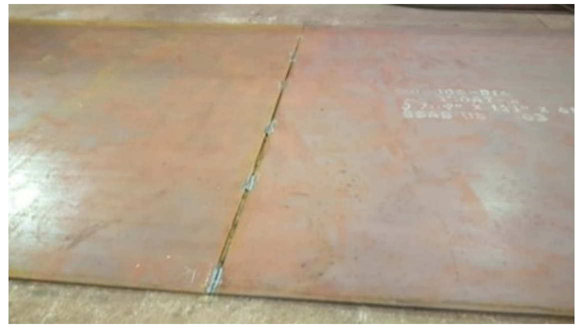
Type	Length of the girder/ flanges/ web-plate	Number of the field splices	Number of flange splices	Number of web plates	Stiffener complexity	Stiffener welding complexity
1	24 m	1	0	1	1	1
2	32 m	2	1	2	1	1
3	24 m	1	0	1	1.5	1.5
4	32 m	2	1	2	1.5	1.5

The four types of girders share some identical features among them (e.g. width of the flanges and web plates, thickness of the flanges and web plates, number of holes in one end of the flange, girder shape complexity etc.). Aside from these similarities, numerous variations among them are notable. Type 1 and Type 3 have the same length of the girder (24 m), flanges and web-plates, have one field splices on one end of the girder, zero flange splices and one web-plate, whereas Type 2 and Type 4 share similar attributes between them. The length of the girder, flanges and web-plates vary based on the geometrical dimension as per structural design. The number of field splices (NF) is dependent on the number of girders in the girder line. If there is one girder in the girder line, NF is 0; if there are multiple girders and the subject girder is the abutment side girder, NF becomes 1, and if the subject girder is the middle one with two girders at each end, NF equals 2.

Besides, the number of flange splices is dependent on the ratio of the girder length to the flange plate length; whereas the number of web-plates varies based on the ratio of the girder length to the web plate length. Irrespective of these attributes, Type 1 is distinguished from Type 3 in terms of stiffener complexity and welding complexity but shares the same properties with Type 2; whereas Type 3 shares these attributes with Type 4. The stiffener complexity varies based on the relative features of a particular girder type against the standard girder configuration; whereas the welding complexity depends on the angle between the web and stiffeners (a factor of 1 stands for 90 degree, 1.5 for 45 degree, and 2 for other cases). These variations are due to their structural design and their relative features against the specific features of the standard girder. Figure 36 illustrates some detailed features relevant to girder type definition in bridge girder fabrication.



(a) Flange Splice



(b) Web Splice

(c) End Holes for Field Splice

(d) Stiffener

Figure 36. Detailed features relevant to girder type definition in bridge girder fabrication.

The scope of the simulation study is to model detailed workflows in fabrication of girders for a highway bridge at a bridge girder fabrication shop. The project entails the fabrication of a total of 15 girders, making up five girder lines (GL1, GL2, GL3, GL4, and GL5) for a bridge project (Figure 37). Three girders are connected along each girder line to form the bridge span. Raw materials required for the fabrication of girder are structural steel plates. Steel fabrication produces steel components and converts steel plates into girders in the constrained space of the fabrication shop and as per shop drawings and engineering design. The fabrication operation consists primarily of the following major steps: (1) receiving plates, (2) preparation of flanges, (3) preparation of web and (4) preparation stiffener, (5) girder assembling by fitting and welding flanges to web, (6) stiffener fitting and welding, (7) studding, (8) field splicing, (9) sandblasting and finishing. Description of detailed processes and work flows for different girder types can be found in Hasan et al. (2019).

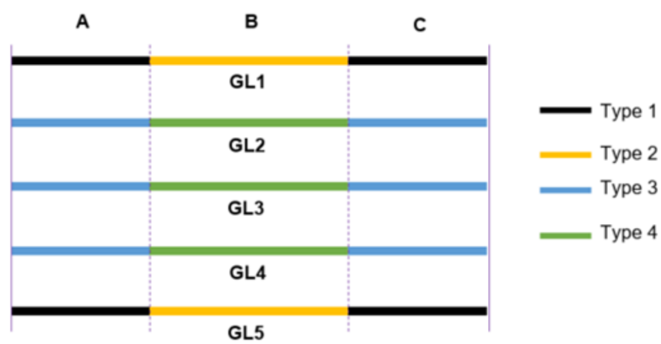


Figure 37. Schematic diagram of the girder lines.

Table 20. Classification of girders into four types

Type of Girder	Type 1	Type 2	Type 3	Type 4
Girders	GL1A, GL1C, GL5A, GL5C	GL1B, GL5B	GL2A, GL2C, GL3A, GL3C, GL4A, GL4C	GL2B, GL3B, GL4B
Symbol	○	□	△	▽

Different symbols have been assigned to each girder type, and specific girders under each type are shown in Table 20. In short, given two girders, the structural design parameters such as web or flange dimensions, load capacity can be the same, but fabrication features would make each girder one of a kind. Detailed features of the products differentiate the steel fabrication process and ensuing field installation method from typical manufacturing where identical products are produced in a predominantly linear process in mass quantities. To a certain degree, it is difficult for a project scheduler to sufficiently account for the impact of subtle variations in product design and fabrications processes at the time of planning or scheduling and thus pulls off lean application in construction. As a matter of fact, a valid simulation model of the fabrication shop that has considered all the relevant variations in girder fabrication potentially provides a virtual plant for planning and scheduling girder fabrication, shipment, field installation for the bridge project. In short, this study explores a new lean approach to project planning and scheduling assisted with production operations planning by simulation.

7.3 Girder-by-girder production plan with SS and FF lags

In the simulation case study, shop floor operations follow the sequence of fabricating all the girder lines subject to resource availability constraints (such as finite quantities of laborers and workstations) and in line with the proposed field construction plan (i.e., GL1, GL2, GL3, GL4, GL5) as shown in Figure 38.

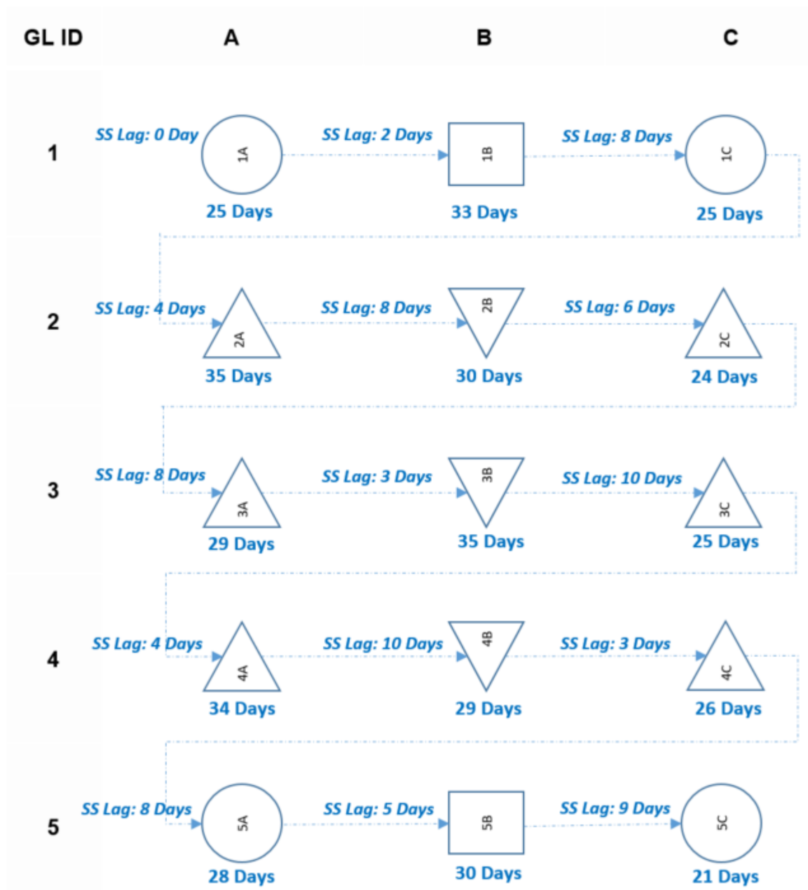


Figure 38. Start and finish schedule for the case study project (Girder by girder).

Hasan et al. (2019) formalized the methodology for implementing the Simplified Discrete-Event Simulation Approach (SDESA) in this application domain; the resulting SDESA model mimics the common practice of using CPM in construction planning but requires much less effort in modeling construction operations to adequately represent girder type-dependent workflows and resource transfer (Liu et al. 2018). An SDESA model normally contains (1) a process model for describing jobs (flow entities), activities, precedence relationships, resource requirements, and any logical constraints, (2) a resource pool for holding all resource entities provided, and (3) a resource transit information system for modeling the additional state changes (if any) of the system due to resource transit between activity locations (Lu and Wong 2007). Due to size limit, refer to Hasan et al. (2019) for the elaboration of SDESA fabrication shop model development and validation. Herein, the results from the SDESA model are extracted and further analyzed in support of a project planner to implementing lean construction in regard to predicting girder fabrication duration for just-in-time shipment to the field for erection.

In contrast with the current scheduling practice in platforms like MS Project, Primavera P6 (defining activity predecessor relationship one by one, and estimating activity duration or lag times), the girder production schedule is "automatically" generated by detailed aggregating data resulting from the shop production planning simulation model in SDESA. It is clarified in this simulation application; the SDESA sets most likely values on input variables in the simulation model to derive deterministic results representing the time duration of each girder of a particular type and the start-to-start lag time between girders of different types. According to the girder-fabrication schedule from simulation, multiple girders (maximum 5 girders) can be processed concurrently at any given moment in the shop –this had been validated by the experienced shop manager who has a good grasp of the shop production capacity. As shown in Figure 45, the shop fabrication duration for each girder (in workdays) and the start-to-start (SS) lag time between two consecutive girders in the present case study is derived from SDESA simulation.

7.4 Results and Analysis

In current project planning and scheduling practice, we assume (1) all girders of the same type have same time duration for shop fabrication and (2) the SS lag linking two girders of specific types is a constant. The results from the simulation model shows notable variations on fabrication duration (Table 21) and SS lags given two girders of the same type combination (Table 22).

Table 21. Start and finish fabrication time of each girder

Girder Type	Girder ID	Start (D-M)	Finish (D-M)	Duration (Days)
○	1A	01-Apr	26-Apr	25
	1C	11-Apr	06-May	25
	5A	14-Jun	12-Jul	28
	5C	28-Jun	19-Jul	21
□	1B	03-Apr	06-May	33
	5B	19-Jun	19-Jul	30
△	2A	15-Apr	20-May	35
	2C	29-Apr	23-May	24
	3A	07-May	05-Jun	29
	3C	20-May	14-Jun	25
	4A	24-May	27-Jun	34
	4C	06-Jun	02-Jul	26
▽	2B	23-Apr	23-May	30
	3B	10-May	14-Jun	35
	4B	03-Jun	02-Jul	29

Table 21 shows the start and finish fabrication time of each girder as well as the duration in days required to fabricate each girder resulting from simulation. In terms of girder lines, each girder line also needs different number of days to be completed. GL 1 takes 36 days, GL 2 and 3 each take 38 days, GL 4 takes 39 days, while GL 5 finishes in 35 Days. It is observed not only girders of different types have different duration, but the girders of same type also can take different duration. For example, the duration to complete the Type 2 girders (33 days, and 30 days) is in contrast with the number of days it takes for the completion of Type 3 girders (35 days, 24 days, 29 days, 25 days, 34 days, and 26 days). If we consider the same type of girders, for example, the different girders under Type 3 (GL2A, GL2C, GL3A, GL3C, GL4A, GL4C), there is also a notable variation in fabrication duration (35 days, 24 days, 29 days, 25 days, 34 days, and 26 days). In addition to the individual girder fabrication duration, the SS lag time between two different types is the other critical piece of input information to develop the project schedule for bridge fabrication and installation. In SDESA, the lag times were calculated from the delay between the start of two activities (Table 21) to establish a Start-to-Start (SS) dependency. Table 22 shows the variations in the SS lag times between two different types of girders, which can be attributed to variations in product design and fabrication processes.

Table 22. SS lag times (days) between two different types of girders

Girder Type Combination	Remarks	Instances	Lag Time (Days)
○→□	Type 1 girder precedes Type 2 girder with SS lag time	1A-1B	2
		5A-5B	5
□→○	Type 2 girder precedes Type 1 girder with SS lag time	2B-2C	8
		5B-5C	9
○→△	Type 1 girder precedes Type 3 girder with SS lag time	1C-2A	4
△→▽	Type 3 girder precedes Type 4 girder with SS lag time	2A-2B	8
		3A-3B	3
		4A-4B	10
△→△	Type 3 girder precedes another Type 3 girder with SS lag time	2C-3A	8
		3C-4A	4
▽→△	Type 4 girder precedes Type 3 girder with SS lag time	2B-2C	6
		3B-3C	10
		4B-4C	3
△→○	Type 3 girder precedes Type 1 girder with SS lag time	4C-5A	8

The SS lag refers to the amount of time whereby the fabrication of a successor girder type is required to be delayed with respect to the start event on the predecessor girder type, which varies dependent on the girder type combination in relation with the SS lag definition. It is seen from Table 22, under each particular girder type combination, different instances of the SS relationship between consecutive girders are associated with distinct lag time. For example, as for the girder type combination of Type 3 girder preceding Type 4 girder, SS lag time is 8 days, 3 days, and 10 days respectively, on the three particular instances identified in the case study (they are 2A-2B; 3A-3B; 4A-4B). Given girders of similar types, shop fabrication duration and start-to-start lags between consecutive girders show broad variations.

In short, the variations in time duration required to process the identical steel girders at a bridge girder shop are characterized and quantified based on a valid simulation model of the fabrication shop operations. It is noteworthy that given a particular sequence of construction in the field, the finish time of each girder fabrication needs to be predicted, which is critical input to plan (1) shipment and just-in-time (JIT) delivery of bridge girders on-site and (2) field crew installation. In the construction industry, waste exists in terms of resource idling or waiting, excessive storing inventory, or unnecessary materials moving and handling (Ballard and Howell 1997). Applying sufficient buffers in time and space between fabricators and contractors might shield the project manager from the immediate impact of early or late deliveries of fabricated components. However, this can be expensive and practically infeasible; more important, such solutions are against the lean principles. As demonstrated in the present case study, the proactive solution is to directly address the root causes of variations in order to materialize project objectives in regards to cost efficiency, productivity, and lean production. Therefore, more effective model-based variations assessment tools (such as SDESA utilized in the present research) are particularly instrumental in the revelation of these sources of variations, potentially leading to a highly predictable, more productive, and leaner system of bridge girder fabrication and installation.

Chapter 8: Conclusions

8.1 Summary

This research study proposes an enhanced Activity-on-Node network diagramming method (named AON+) for construction planning and scheduling applications to formulate production schedules for repetitive workflows in fabrication projects. In contrast to established project planning techniques, AON+ enables construction managers to represent details in workflows in a streamlined network diagram by sufficiently factoring in logical constraints imposed by both technology and resource. A production schedule of structural steel fabrication facility entails a repetitive job execution sequence to assemble raw materials into final products in limited workplace and storage areas. Projects of this type are considered high risk because they usually maintain a technologically driven sequence and are continuously subject to resource constraints imposed by internal technological, managerial, or external causes throughout the life span of the project. Although AON-CPM is still the most popular scheduling method in scheduling these types of repetitive activities, its inability to accurately model resource constrained relationships and reflect actual conditions leads to its inadequacy to schedule complex construction environments, posing a complex challenge to interpret information for the practitioners. The research inquires how to enhance AON so to keep its flexibility and ease of use while making it more efficient and scalable considering various resource constrained relationships and logics. Within this study, a novel simulation-based production planning approach AON+ has been proposed, developed, and validated that would benefit researchers and practitioners by tapping into knowledge that is captured through simulation, optimization, and data analysis, while simultaneously maintaining transparency and accuracy. Moreover, AON+ is platform neutral; any other DES platform can be applied to establish this proposed scheduling framework which can link simulation modeling with engineering design, material quantity takeoff, and dynamic resource allocation in an integrative, seamless approach.

This research has addressed three questions in connection with the multi-units repetitive scheduling problem: (1) how to effectively perform frequent resource transfers among multiple activities or units in order to enhance the schedule robustness; (2) how to link and synchronize construction schedules for repetitive units with complex process workflows so as to cope with projects of any practical size and complexity; and (3) how to analytically evaluate the impact of ‘mura’ (variations in material properties) on individual project schedules to facilitate applying lean concepts. To answer these questions, the research study consists of four stages: the first stage is the in-depth analysis stage, and its purpose is to investigate the tools and techniques tailored for optimized scheduling and the difficulty in their applicability for managing repetitive construction projects. The second stage is the development of a novel resource-constrained scheduling framework named AON+, capable of circumventing the aforementioned limitations and research gaps in the existing models. The third stage elaborates the feasibility and capabilities of the proposed virtual plant in real world applications to derive the crew performance KPIs at various levels of granularity. The fourth and final stage is the application of a discrete-event simulation approach in an attempt to shed light on the effect of variations due to product design and workflows, and how lean concepts can be applied for planning field construction operations in practice.

8.2 Research Contributions

The main research contributions of this research study to existing knowledge include the following:

- Advancement of the repetitive units scheduling approaches by enhancing the effectiveness AON-CPM so to keep its flexibility and ease of use while making it more efficient and scalable considering various resource constrained relationships and logics.
- Implementation of the proposed model to maximize crew work continuity in a complex resource-constrained construction environment with repetitive process workflow patterns.
- Exploitation of a validated discrete even simulation approach in an attempt to deriving crew performance KPIs while maintaining modelling simplicity and transparency to improve communication efficiency at different levels of project management, which is crucial to civil engineering applications.
- Maximizing resource utilization by allowing overlapping among different activities at various locations or workstations. This enables project managers to prepare corrective actions based on automated what-if scenarios while enhancing the flexibility of the scheduling and control.
- Analyzing the ‘mura’ (variations) inherent in product design and minimizing the ‘muda’ (waste) in typical or nontypical repetitive projects of any size or complexity, which is instrumental in planning a lean environment.

8.3 Recommendations for Future Research

While the conducted research was able to achieve its research objectives, a number of additional research thrusts have been recommended to expand and build upon the presented work in this study. These opportunities include:

- Expanding the developed resource driven scheduling framework to consider risk and uncertainty in estimating activity duration and costs by applying a stochastic programming formulation.
- Testing the proposed systematic simulation tests to investigate the scalability of the proposed optimization models in larger projects with more complex resource workflows and project networks, intractable by the existing algorithms.
- Enhancing the model to account for more scheduling constraints (e.g., resource availability, resource use conflicts, rework, change orders) while managing multiple projects that share the same resource pool.

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Appendix A

SDESA Model Setups

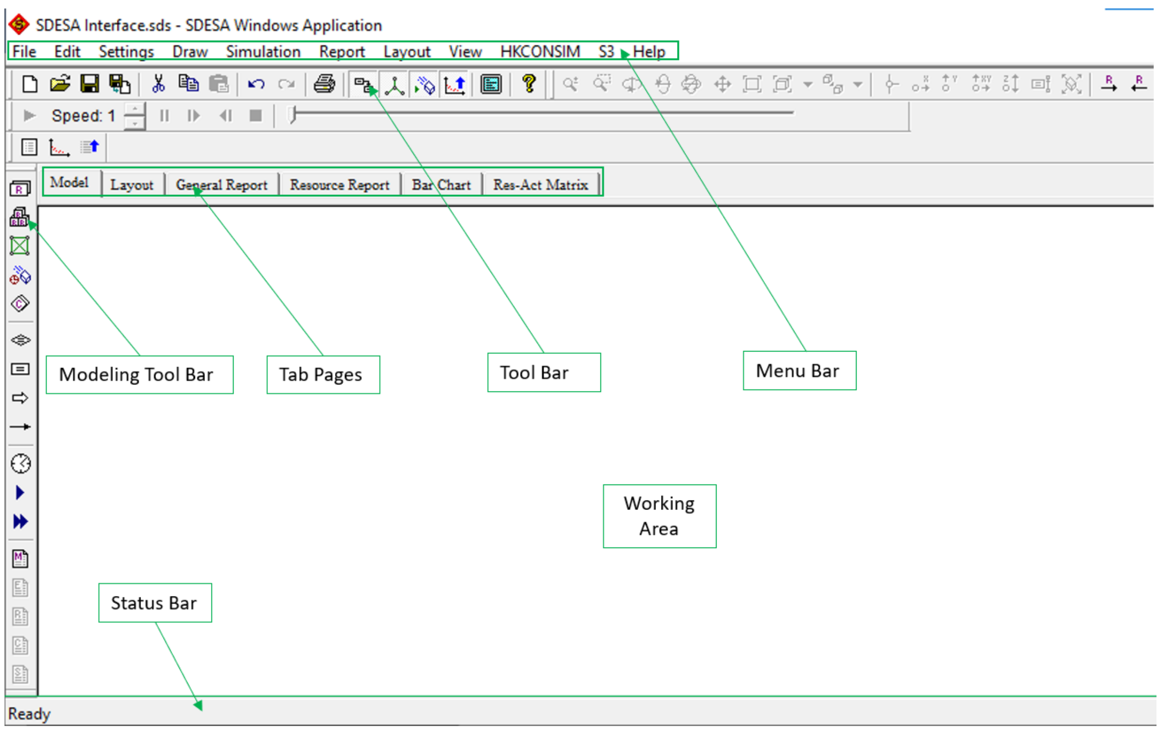
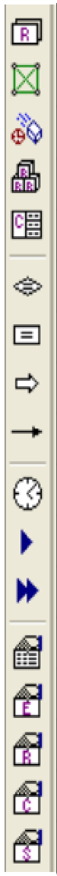


Figure A.1: The main SDESA interface



Resource Type	Resource & Location Definition
Define Locations	
Resource Travel Time	
Resource Entity	
Control Variable	
Flow Entity	SDESA model Elements
Activity	
Link Flow Entity	
Link Activity	
Time Setting	Simulation Time and Run
Start Single Run	
Start Multiple Run	
Model Statement	Output Report
Entity Processed	
Resource Utilization	
Control Variable	
Statistical Result	

Figure A.2: Model Tool Bar

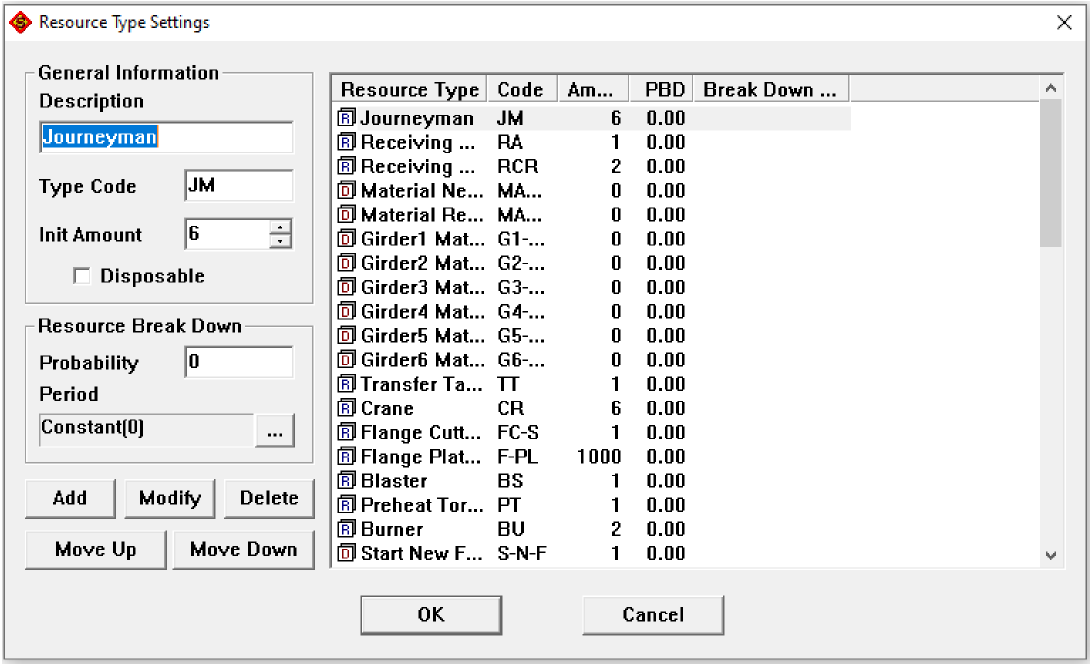


Figure A.3: Resource Type Settings

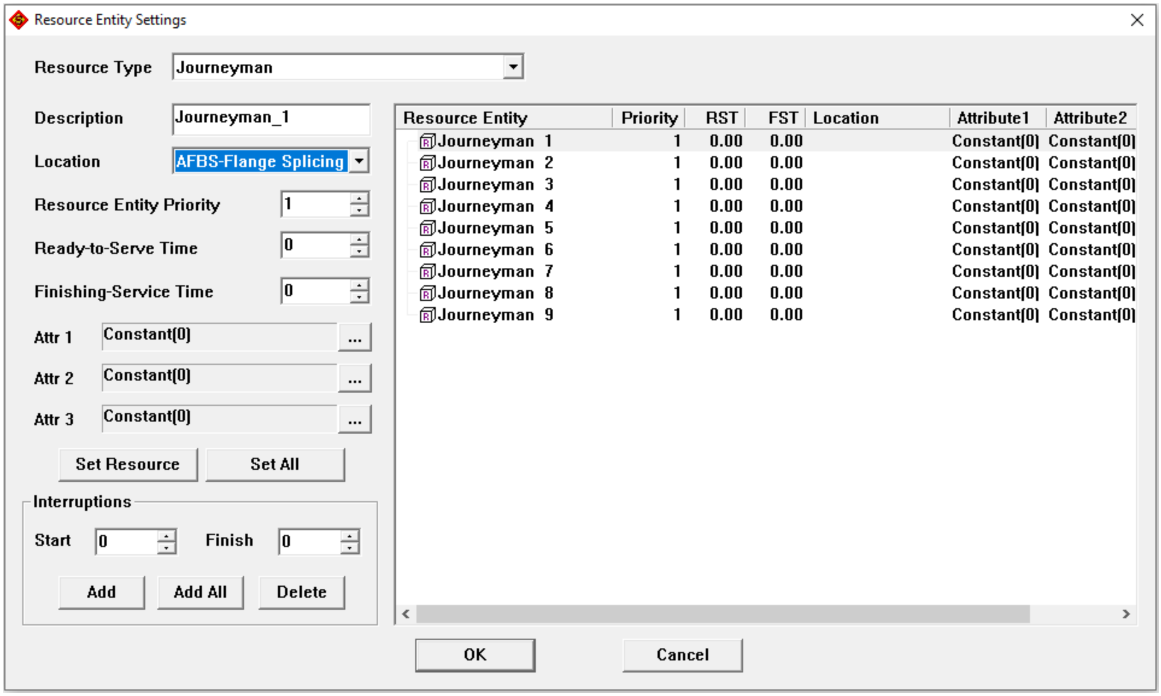


Figure A.4: Resource Entity Setting (primary location, break time, priority)

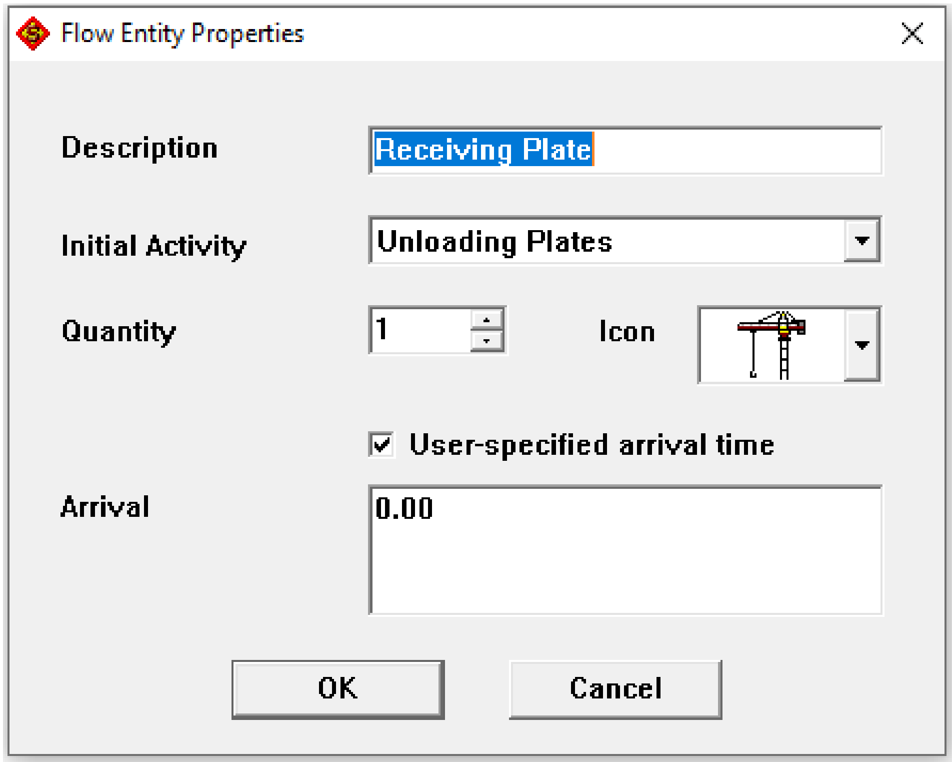


Figure A.5: Flow Entity Property

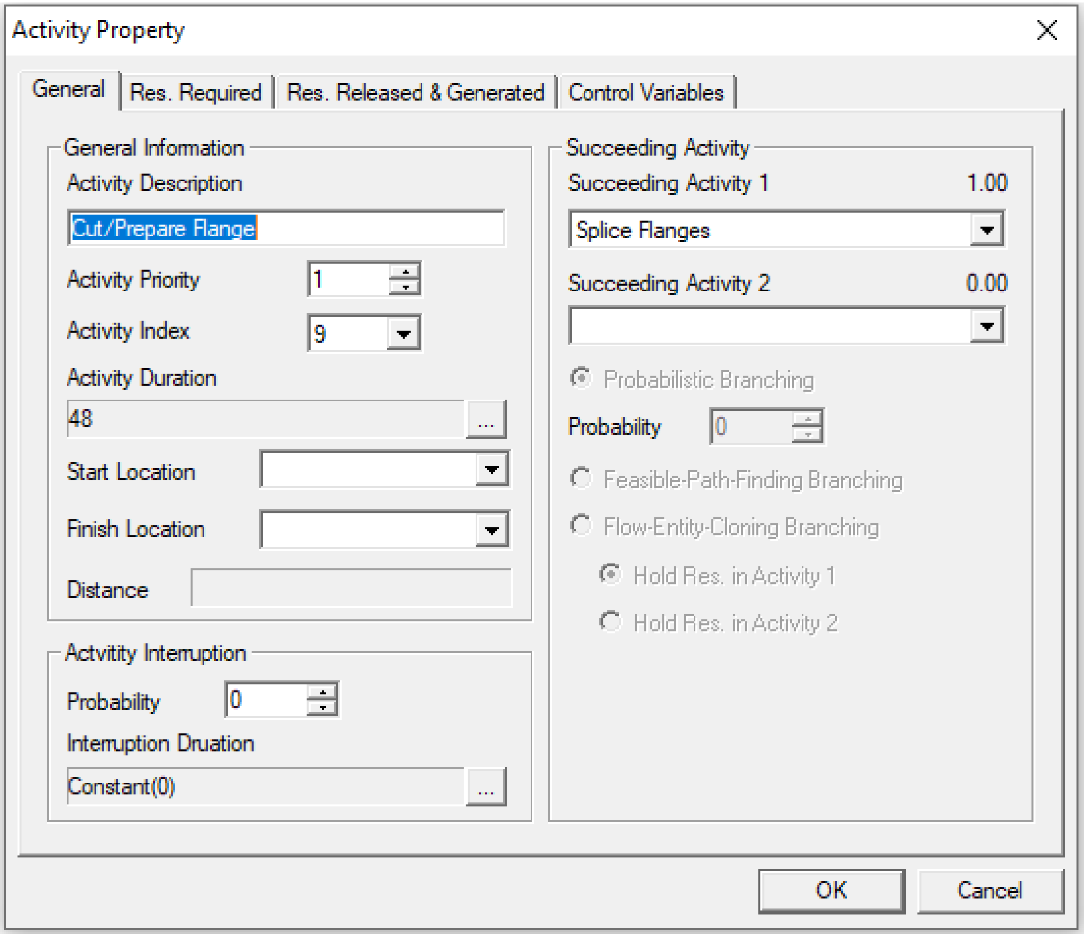


Figure A.6: Activity Property (General Information)

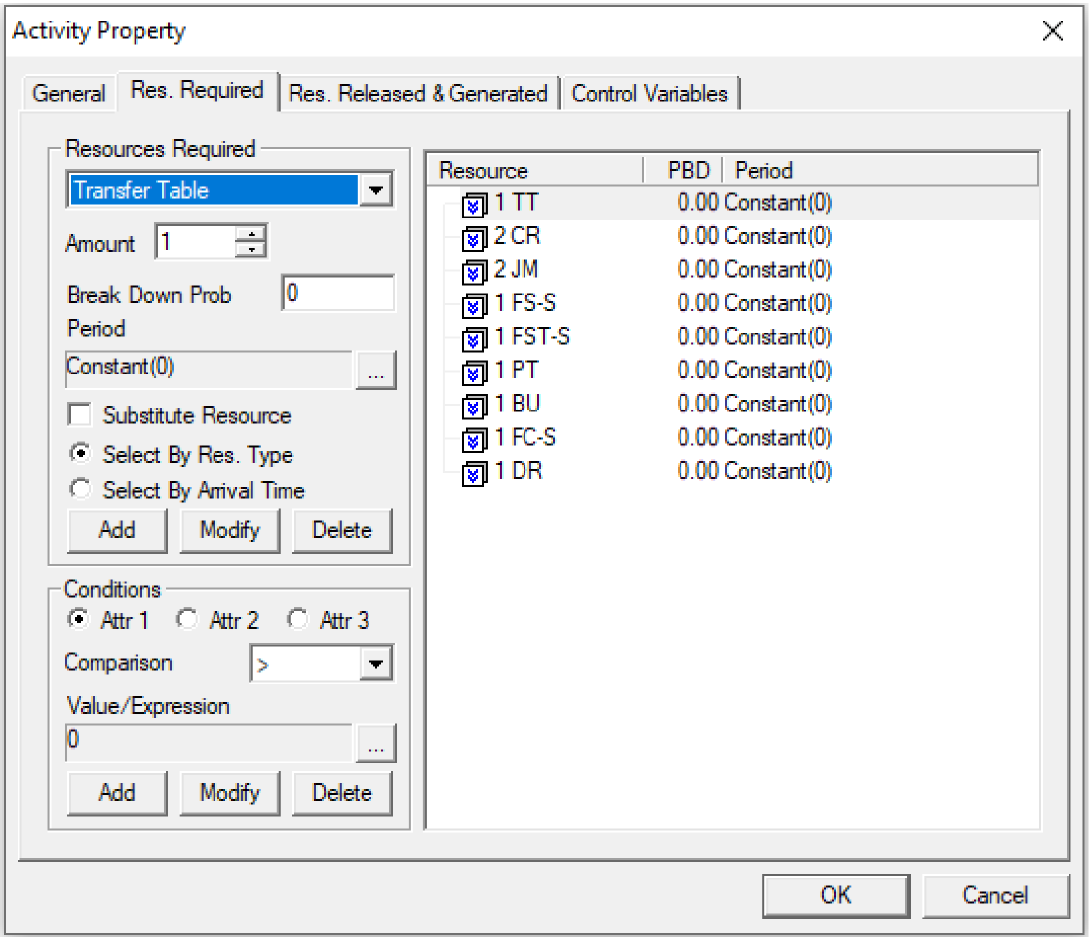


Figure A.7: Activity Property (Resource Required)

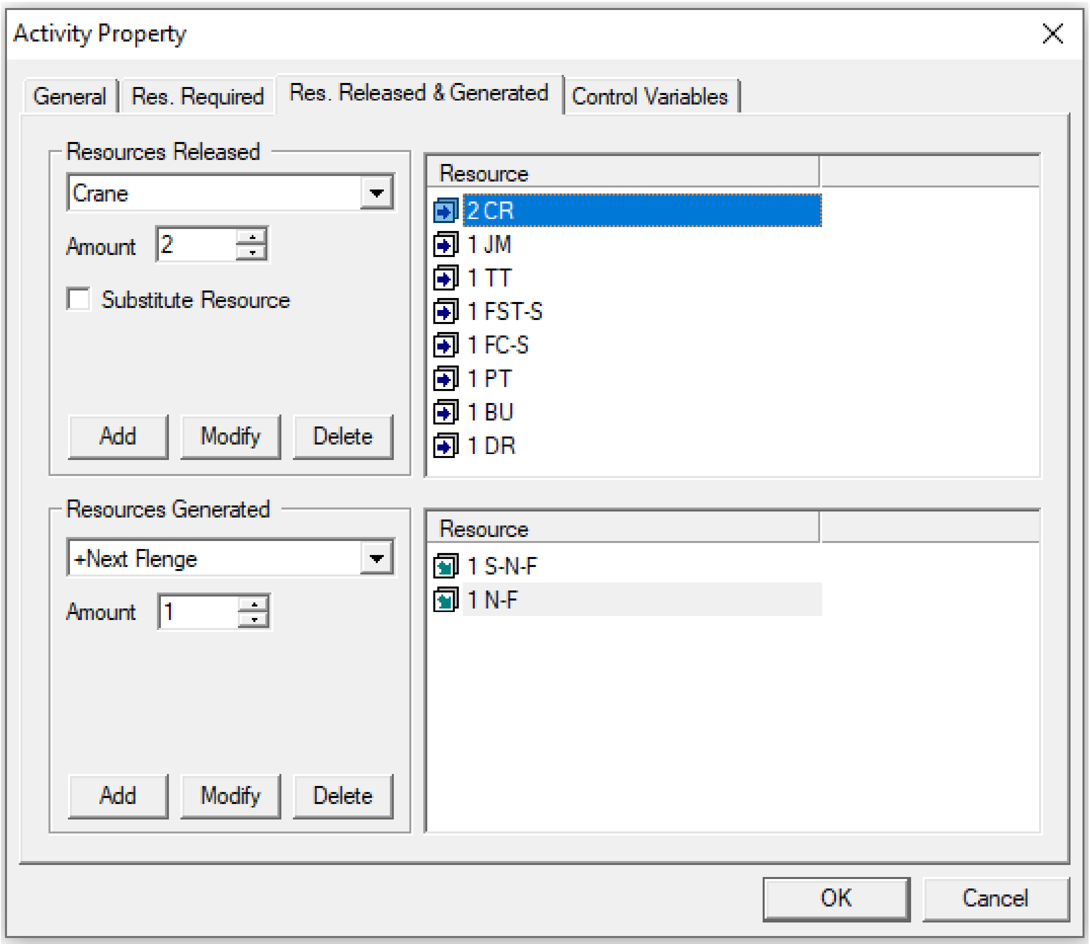


Figure A.8: Activity Property (Resource Released and Generated)

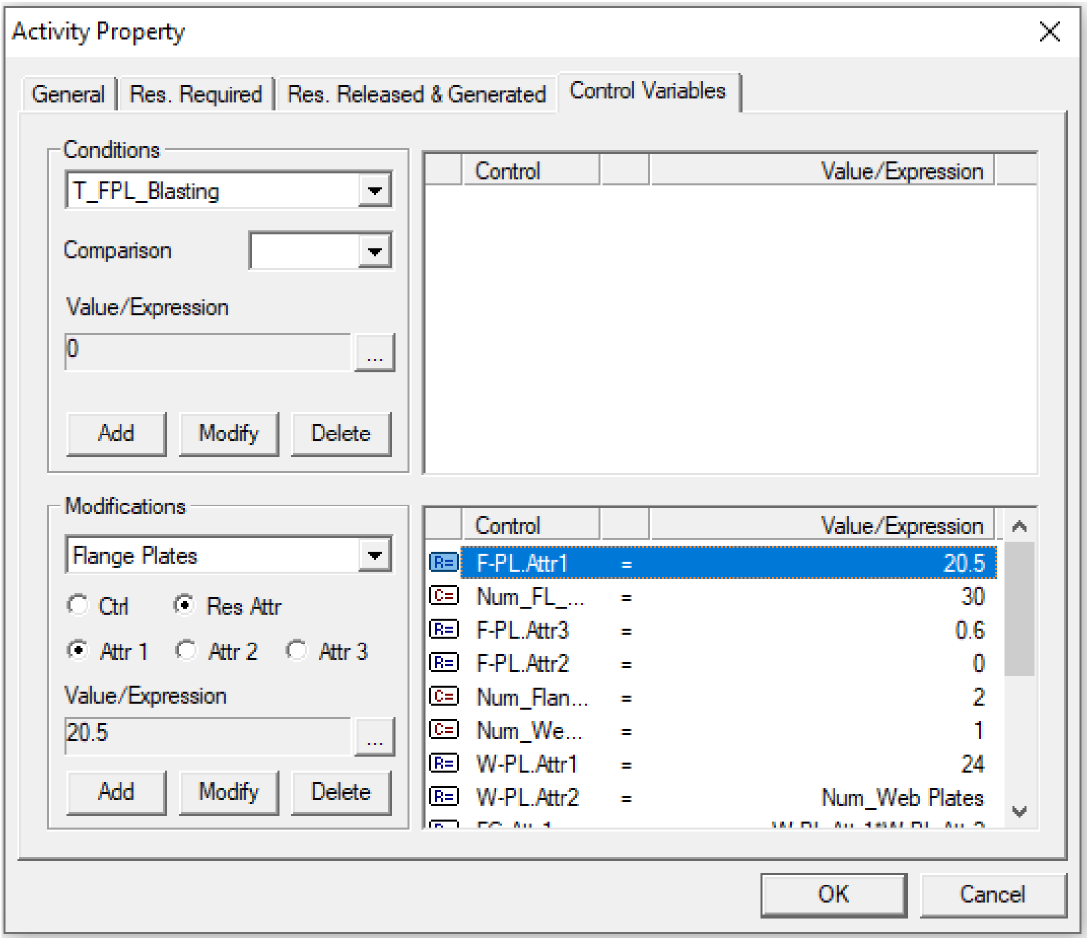


Figure A.9: Control Variable

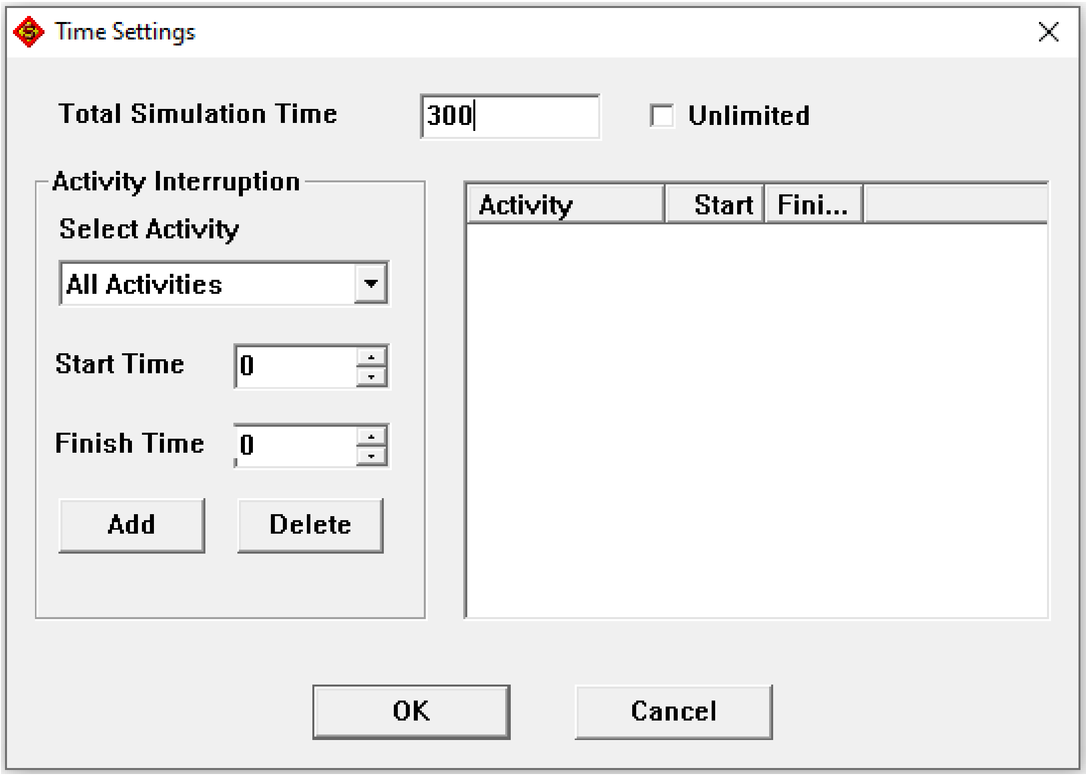


Figure A.10: Simulation Time Setting

Run	ResID	Resource	ActID	Activity	RST	Begin	End	Idle	Travel
1	2	QA_1	1	QA	0.00	1.00	7.44	1.00	0.00
1	8	Unloading Labor_1	2	Park to UnLd	0.00	7.44	8.23	7.44	0.00
1	3	Unloading Bay_1	2	Park to UnLd	0.00	7.44	8.23	7.44	0.00
1	3	Unloading Bay_1	5	Recieve Conc.	8.23	8.23	12.20	0.00	0.00
1	10	Ready to unload	5	Recieve Conc.	8.23	8.23	12.20	0.00	0.00
1	8	Unloading Labor_1	5	Recieve Conc.	8.23	8.23	12.20	0.00	0.00
1	4	Crane_1	5	Recieve Conc.	0.00	8.23	12.20	8.23	0.00
1	11	Empty Truck	12	GOTO Wash	12.20	12.20	13.00	0.00	0.00
1	4	Crane_1	6	Load Conc. to Pile	12.20	12.20	15.94	0.00	0.00
1	6	Labour Crew_1	6	Load Conc. to Pile	0.00	12.20	15.94	12.20	0.00
1	7	Washing Bay_1	3	Truck Washing	0.00	13.00	15.99	13.00	0.00
1	9	Record Labor_1	4	Leave	0.00	15.99	16.50	15.99	0.00
1	2	QA_1	1	QA	7.44	16.00	22.47	8.56	0.00
1	8	Unloading Labor_1	2	Park to UnLd	12.20	22.47	23.05	10.27	0.00
1	3	Unloading Bay_1	2	Park to UnLd	12.20	22.47	23.05	10.27	0.00
1	3	Unloading Bay_1	5	Recieve Conc.	23.05	23.05	25.47	0.00	0.00
1	13	Ready to unload	5	Recieve Conc.	23.05	23.05	25.47	0.00	0.00
1	8	Unloading Labor_1	5	Recieve Conc.	23.05	23.05	25.47	0.00	0.00
1	4	Crane_1	5	Recieve Conc.	15.94	23.05	25.47	6.61	0.50
1	14	Empty Truck	12	GOTO Wash	25.47	25.47	26.27	0.00	0.00
1	4	Crane_1	6	Load Conc. to Pile	25.47	25.47	31.10	0.00	0.00
1	6	Labour Crew_1	6	Load Conc. to Pile	15.94	25.47	31.10	9.02	0.50
1	7	Washing Bay_1	3	Truck Washing	15.99	26.27	28.73	10.28	0.00
1	9	Record Labor_1	4	Leave	16.50	28.73	29.33	12.23	0.00
1	2	QA_1	1	QA	22.47	31.00	39.93	8.53	0.00
1	8	Unloading Labor_1	2	Park to UnLd	25.47	39.93	40.57	14.47	0.00
1	3	Unloading Bay_1	2	Park to UnLd	25.47	39.93	40.57	14.47	0.00
1	3	Unloading Bay_1	5	Recieve Conc.	40.57	40.57	43.63	0.00	0.00
1	16	Ready to unload	5	Recieve Conc.	40.57	40.57	43.63	0.00	0.00
1	8	Unloading Labor_1	5	Recieve Conc.	40.57	40.57	43.63	0.00	0.00
1	4	Crane_1	5	Recieve Conc.	31.10	40.57	43.63	8.96	0.50
1	17	Empty Truck	12	GOTO Wash	43.63	43.63	44.43	0.00	0.00
1	4	Crane_1	6	Load Conc. to Pile	43.63	43.63	48.51	0.00	0.00
1	6	Labour Crew_1	6	Load Conc. to Pile	31.10	43.63	48.51	12.03	0.50
1	7	Washing Bay_1	3	Truck Washing	28.73	44.43	46.92	15.70	0.00
1	2	QA_1	1	QA	39.93	46.00	52.00	6.07	0.00
1	9	Record Labor_1	4	Leave	29.33	46.92	47.47	17.58	0.00
1	8	Unloading Labor_1	2	Park to UnLd	43.63	52.00	52.87	8.37	0.00
1	3	Unloading Bay_1	2	Park to UnLd	43.63	52.00	52.87	8.37	0.00
1	3	Unloading Bay_1	5	Recieve Conc.	52.87	52.87	55.55	0.00	0.00
1	19	Ready to unload	5	Recieve Conc.	52.87	52.87	55.55	0.00	0.00
1	8	Unloading Labor_1	5	Recieve Conc.	52.87	52.87	55.55	0.00	0.00
1	4	Crane_1	5	Recieve Conc.	48.51	52.87	55.55	3.86	0.50
1	20	Empty Truck	12	GOTO Wash	55.55	55.55	56.35	0.00	0.00
1	4	Crane_1	6	Load Conc. to Pile	55.55	55.55	59.55	0.00	0.00
1	6	Labour Crew_1	6	Load Conc. to Pile	48.51	55.55	59.55	6.53	0.50
1	7	Washing Bay_1	3	Truck Washing	46.92	56.35	59.05	9.43	0.00
1	9	Record Labor_1	4	Leave	47.47	59.05	60.02	11.57	0.00

Figure A.11: SDESA Resource Report

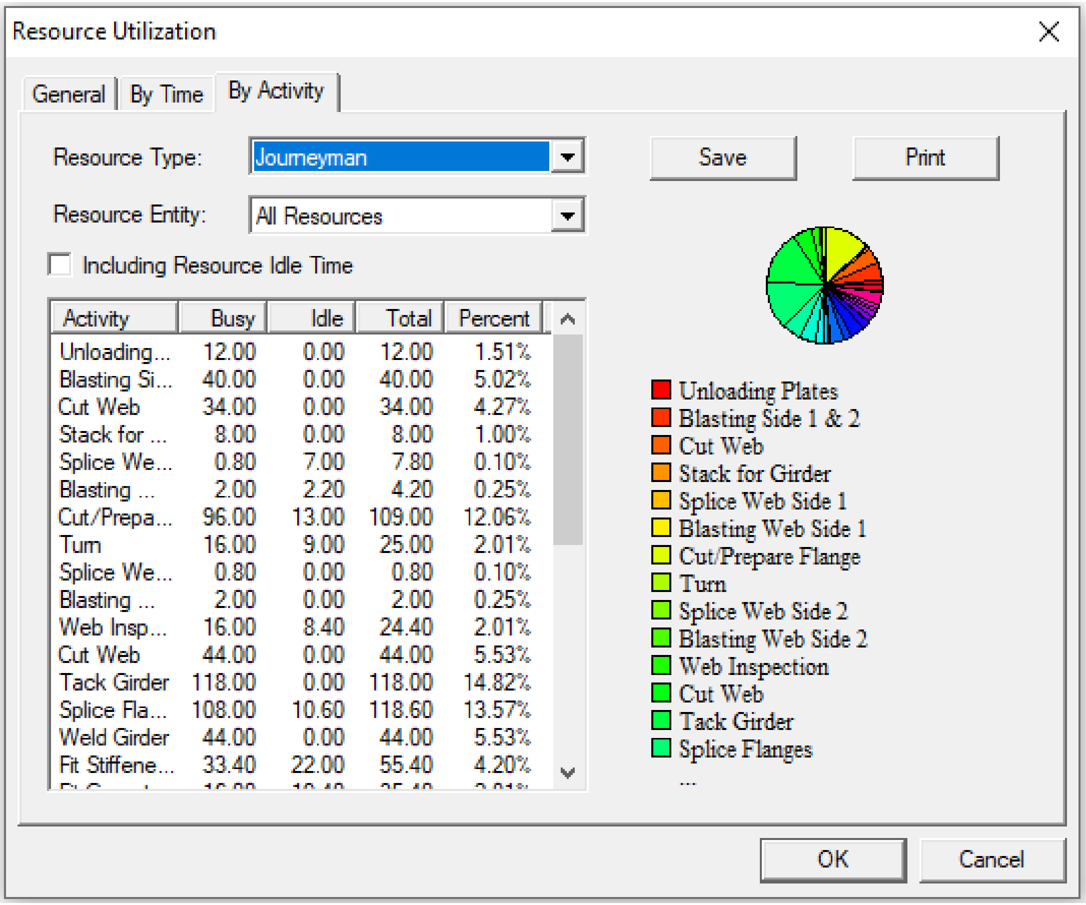


Figure A.12: Resource Utilization

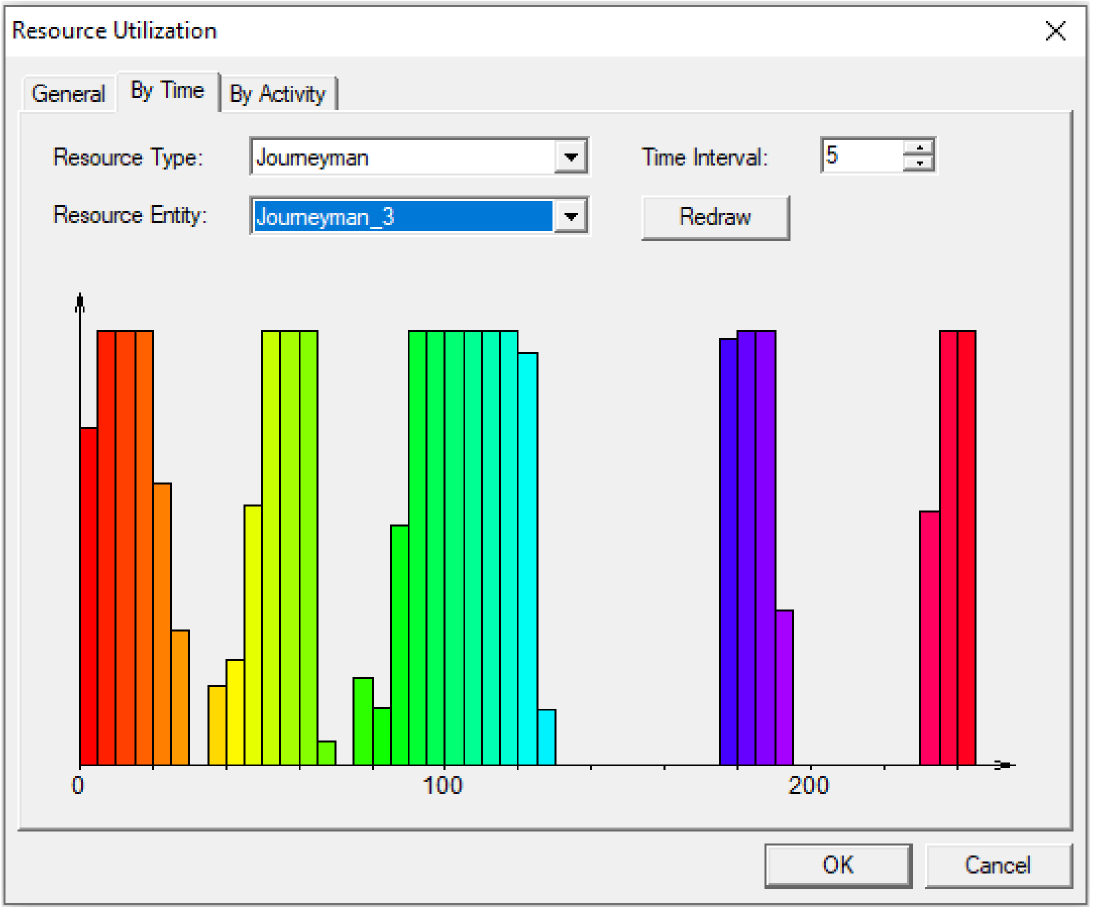


Figure A.13: Resource Utilization by Journeymen

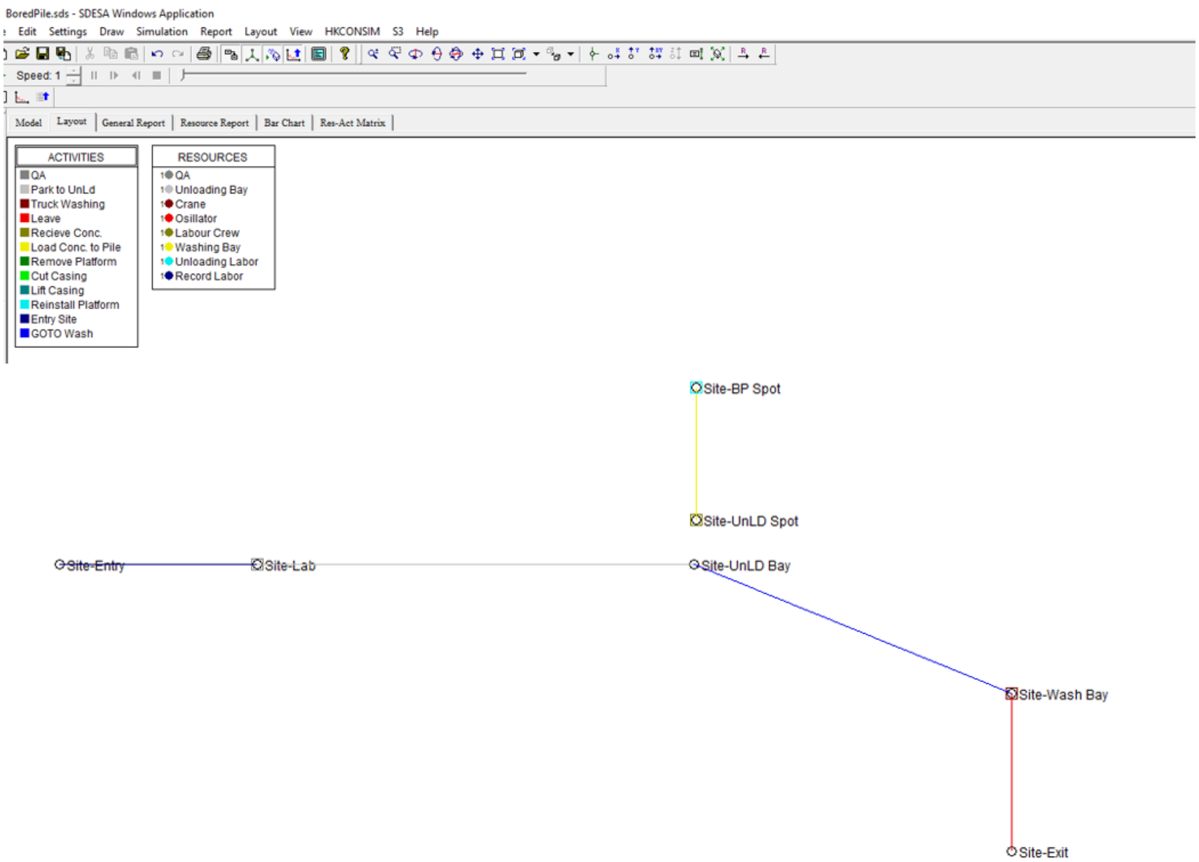


Figure A.14: SDESA Layout

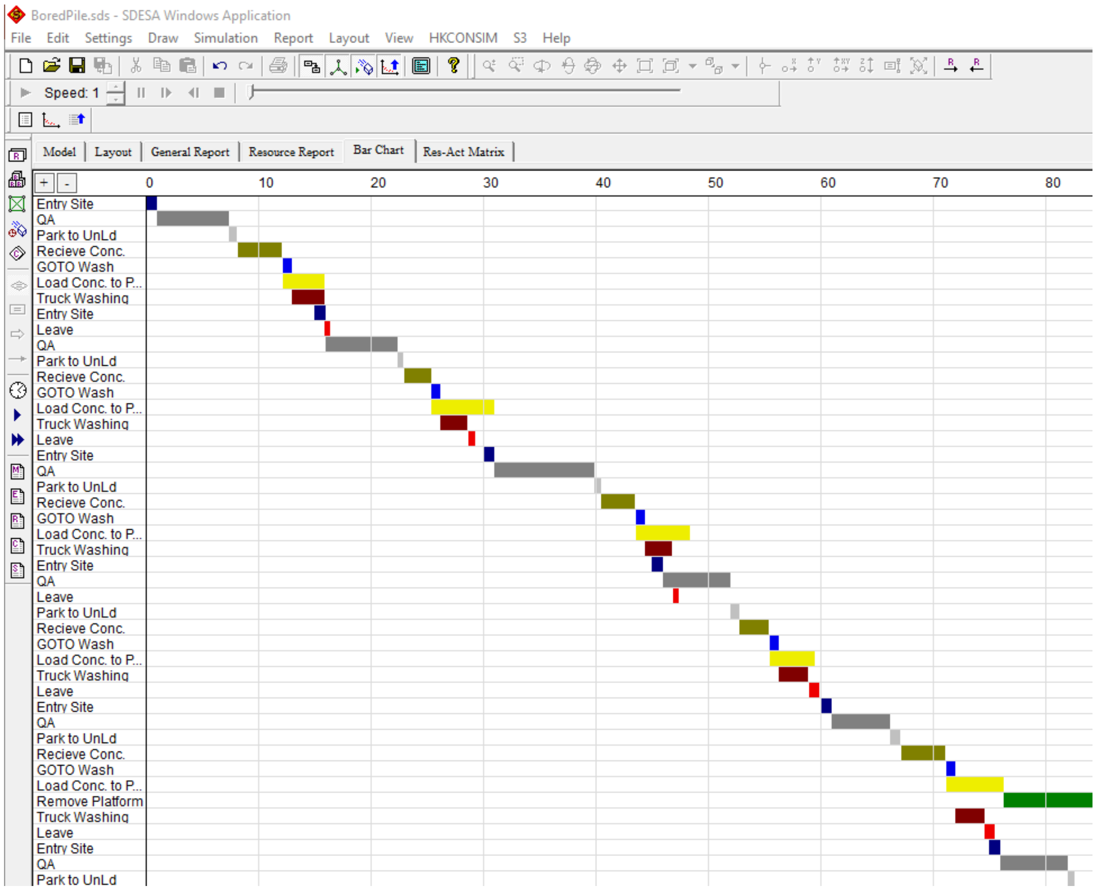


Figure A.15: Bar Chart (Bored Pile Case Study)

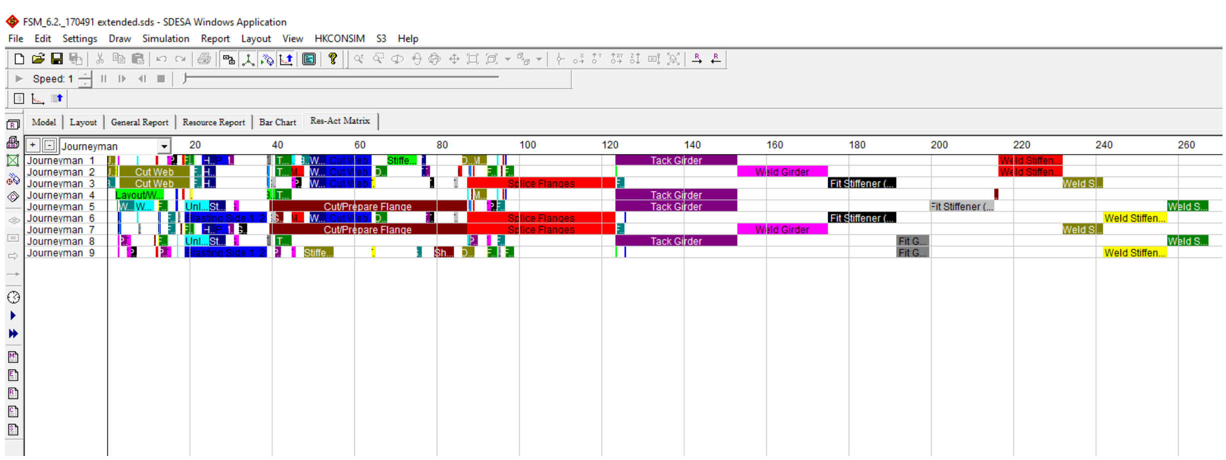


Figure A.16: Resource-Activity Matrix

Appendix B

SDESA Modeling for Bridge Girder Fabrication

B.1 Input Data

Table B.1. Attributes of Girder Type 1.

ID	Attribute Name	Value
FPL.Attr1	Length of the flanges (Top and Bottom)	46 m
FPL.Attr2	Width of the flanges (Top and Bottom)	0.6 m
FPL.Attr3	Thickness of the flanges	0.06 m
FPL.Attr4	Number of holes in one end of the flange	30
FPL.Attr5	Number of flange splices	0
WPL.Attr1	Length of the web plate	46 m
WPL.Attr2	Thickness of the web plates	0.02 m
WPL.Attr3	Width of the web plates	2.7 m
WPL.Attr4	Number of the web plates	1
FG.Attr1	Length of the girder	46 m
FG.Attr2	Number of the field splice	1
FG.Attr3	Stiffener complexity (compared against a standard condition)	1
FG.Attr4	Stiffener welding complexity (compared against standard condition)	1
FG.Attr5	Girder shape complexity (compared against the standard girder)	1

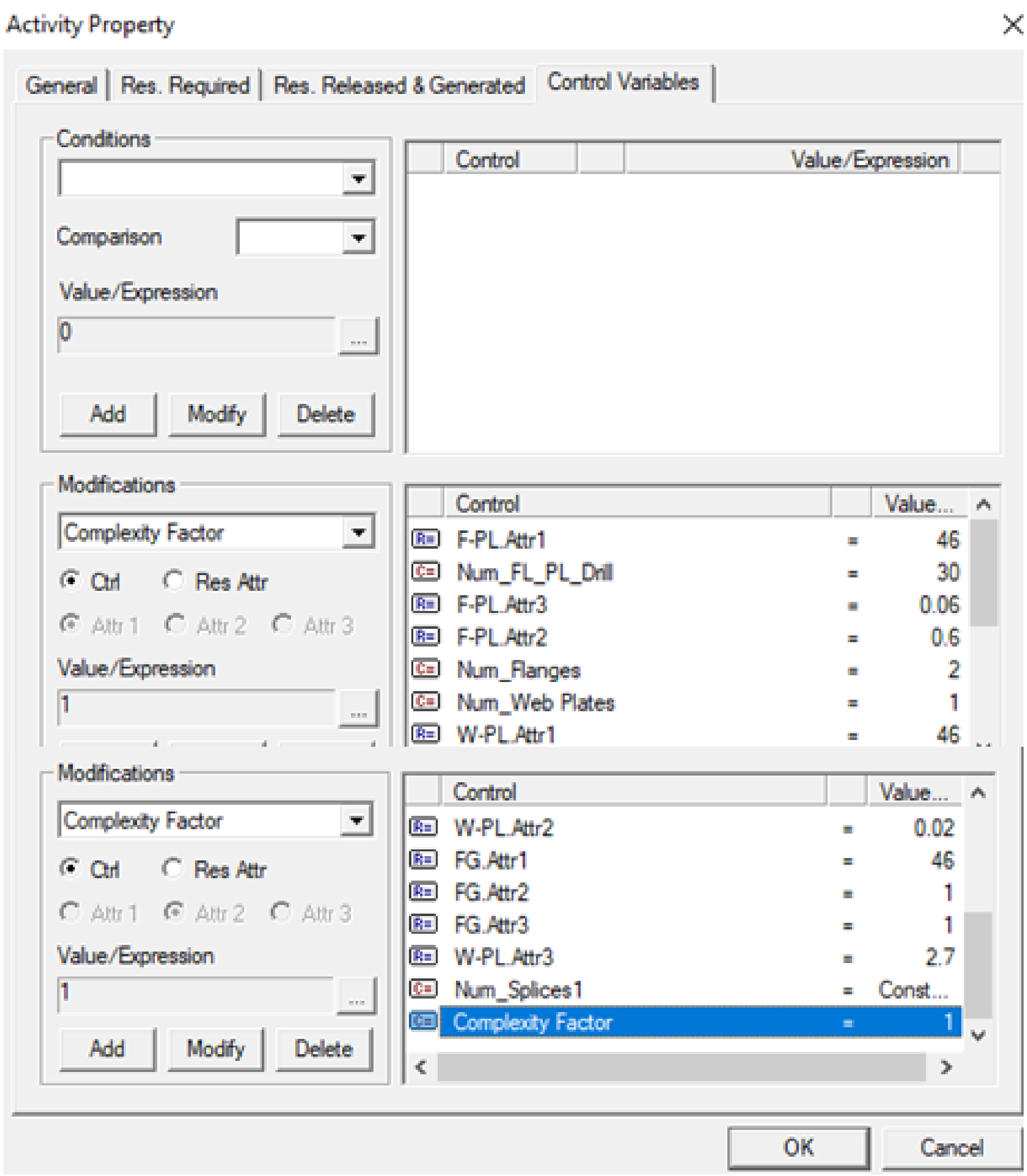


Figure B.1: Attributes input in SDESA.

B.2 Shop Floor Modeling Logic

In conventional scheduling methods, it is difficult for a project scheduler to sufficiently account for the impact of these subtle variations in product design and fabrications processes at the time of planning or scheduling. SDESA not only makes it easy to input and update the numerical attribute values (named as 'Control Variables' in SDESA) for each type of girder, but also makes it possible to elaborate on the effect of variations in attributes in the context of applying lean concepts for planning field construction operations in practice. After the attributes are defined and input for all the six girder types, the schematic model can be setup by identifying resources required for each of them. The graphical model in SDESA is a combination of 'Flows' and a 'Flow' is formed by one Flow Entity and a chain of activities following it. In order to introduce the attributes of the girders to the model, each girder type is assigned with a flow entity (Figure B.2), which identifies the resources required or released based on the properties.

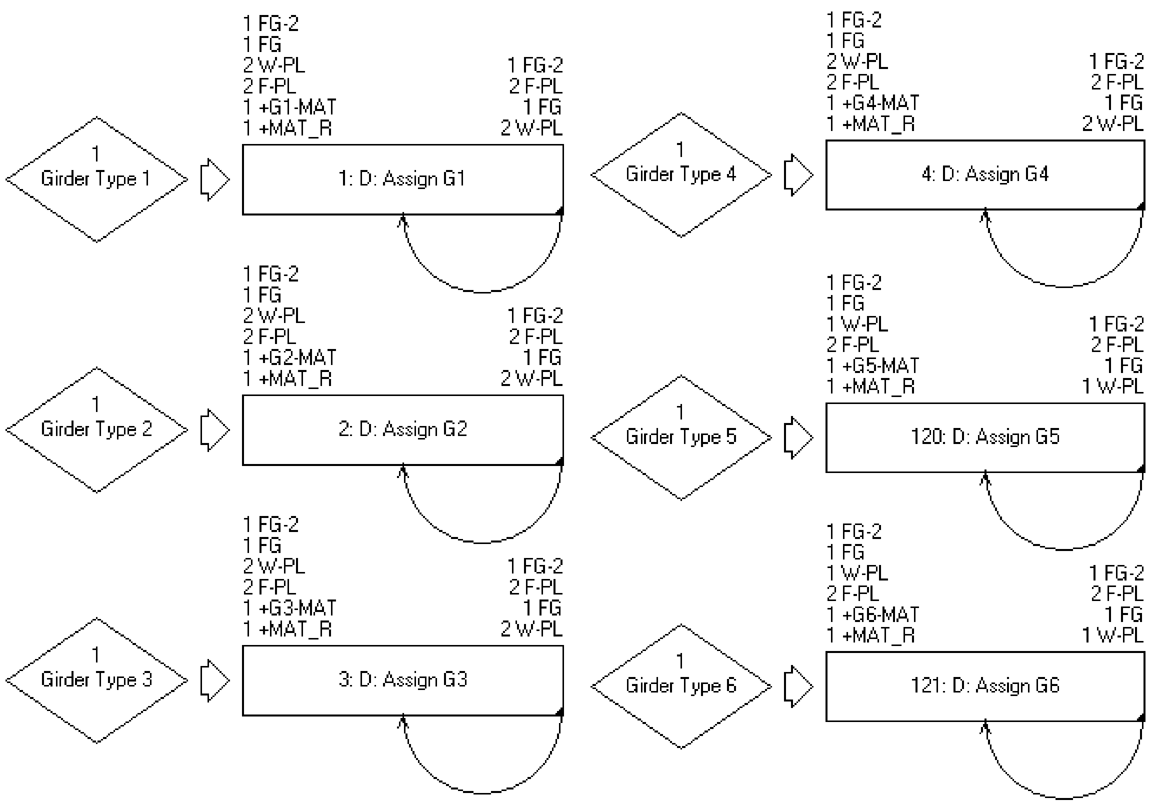


Figure B.2: Assigning different girder types in SDESA.

According to the requirements, seven girders form a girder line, and this case study consists of 21 girders in 3 girder lines. Based on the girder line configuration in Figure 32, seven girders are linked together in the model to form a work flow of girder line, which can be viewed as a sub-system of the construction operations or a kind of production lines (Figure B.3).

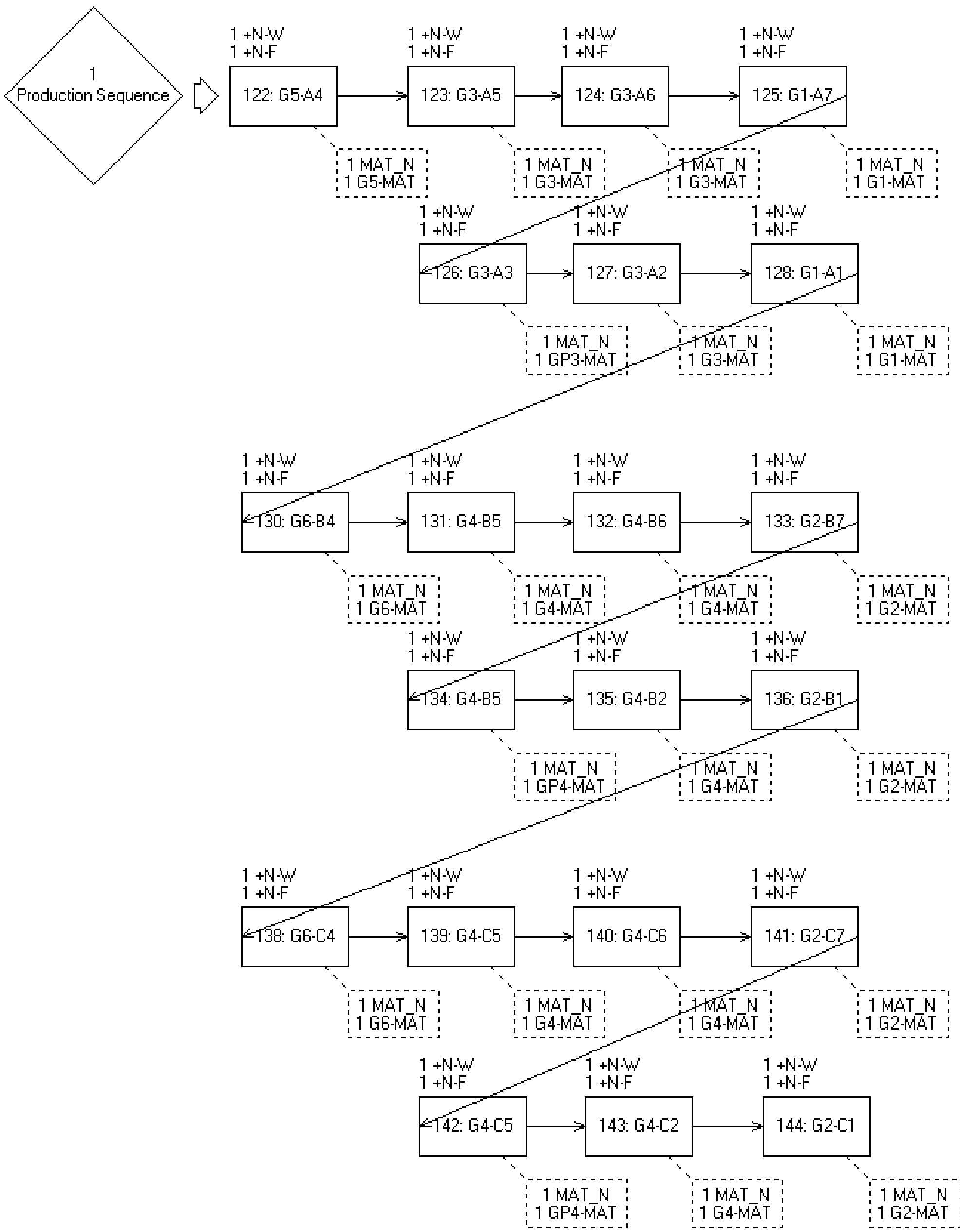


Figure B.3: Modeling of girder lines in SDESA.

G1, G2, G3, G4, G5, G6 represents the six girder types, whereas A (A1-A7), B (B1-B7), C (C1-C7) defines girder line 1, 2 and 3 with the seven girders. Without defining the required resource, an activity can not be initiated during the simulation run. The "Res. Required" tab (Figure B.4) helps the user to assign the required resource type and amount to an activity.

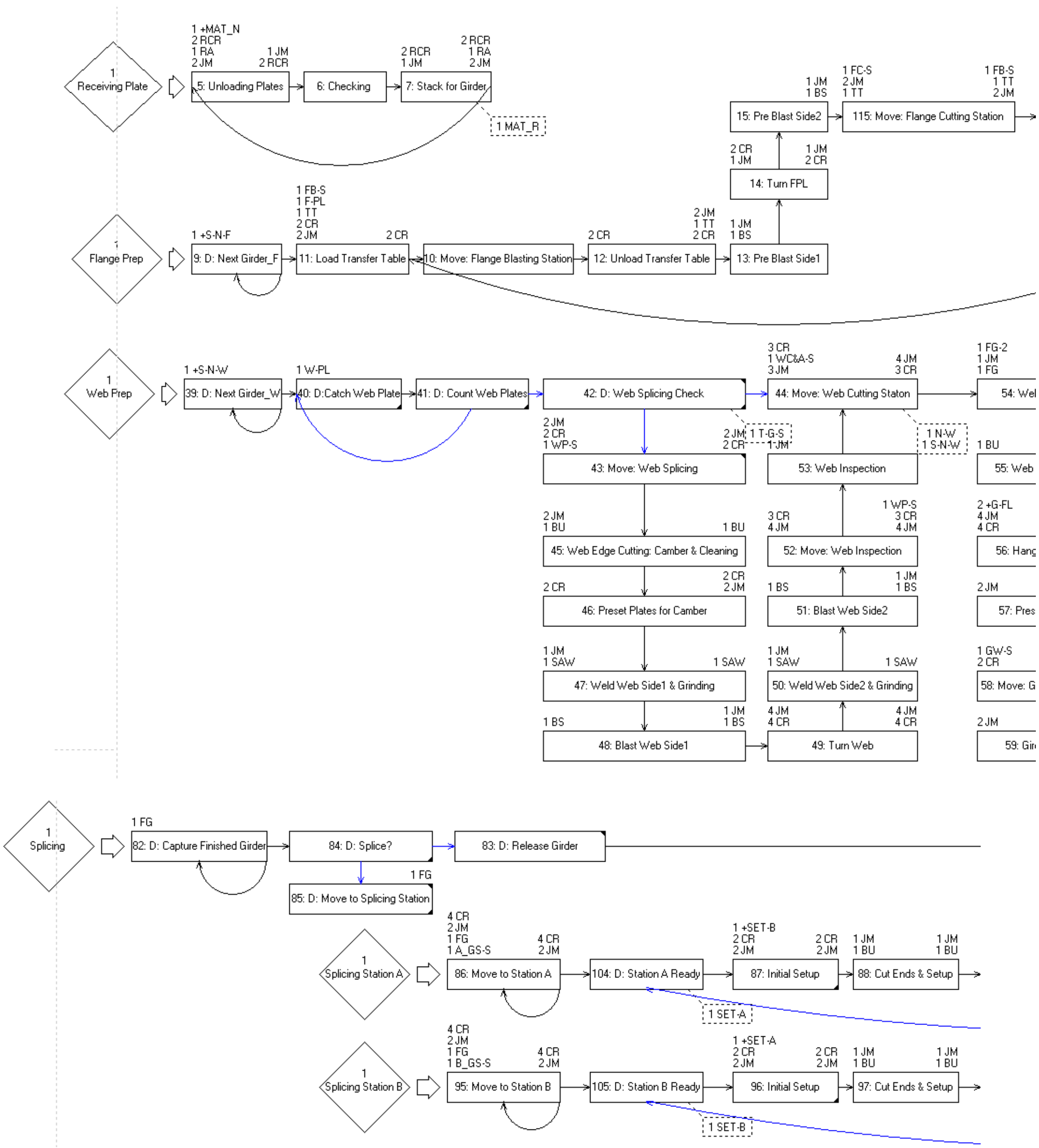


Figure B.4: Snapshot of the simulation model in SDESA.

Also, the user can even specify the breakdown chance of a resource, resource substitution rules, and screening conditions of resource (Disposable and Non-disposable) based on their existing resource attribute. Beside assigning the required resources, it is to be defined whether a resource is released and becomes available again in the resource pool at the end of the activity or the same resource should be kept to continue the succeeding activity. The “Res. Release & Generated” tab controls the release of resource and generation of Disposable Resource at the end of an activity. In the next step, the work packages are defined as flow entities in the model and the disposable and non-disposable resources logically connect different activities and multiple workflows acting as an information unit to enforce the precedence relationship in the construction system.

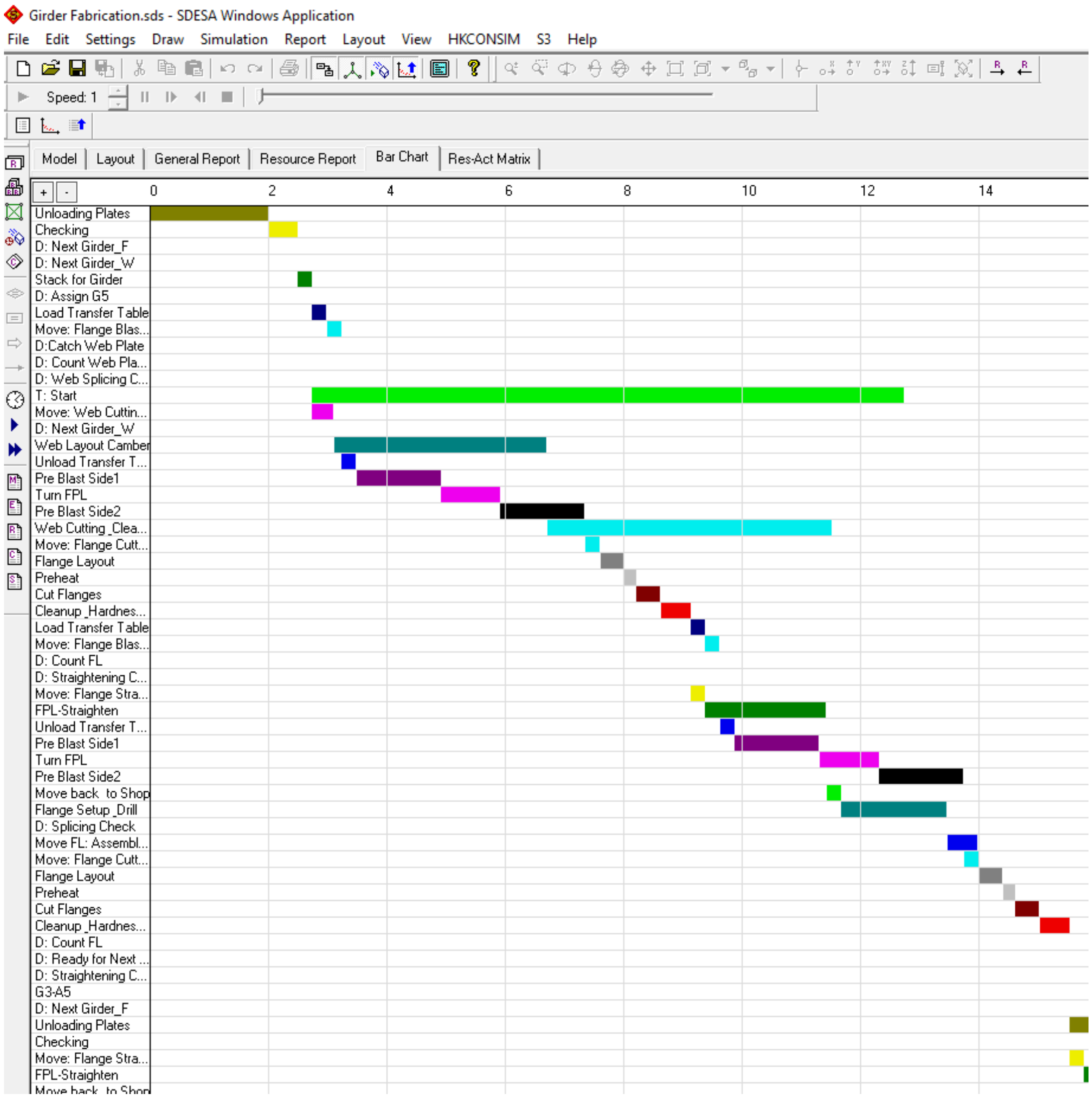
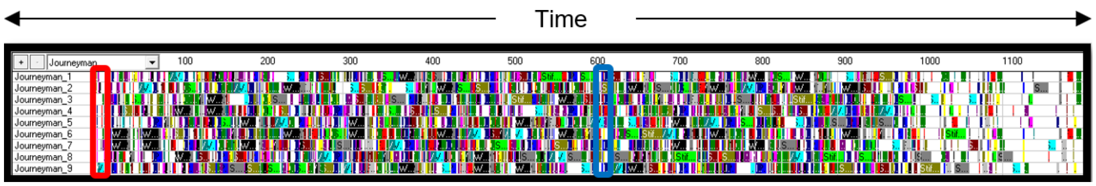
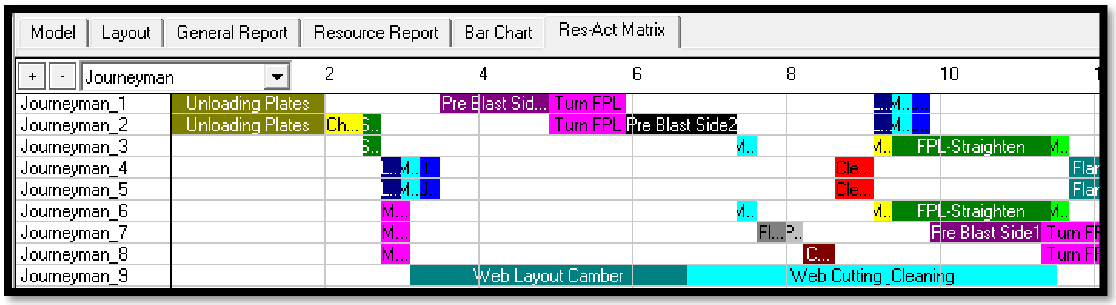


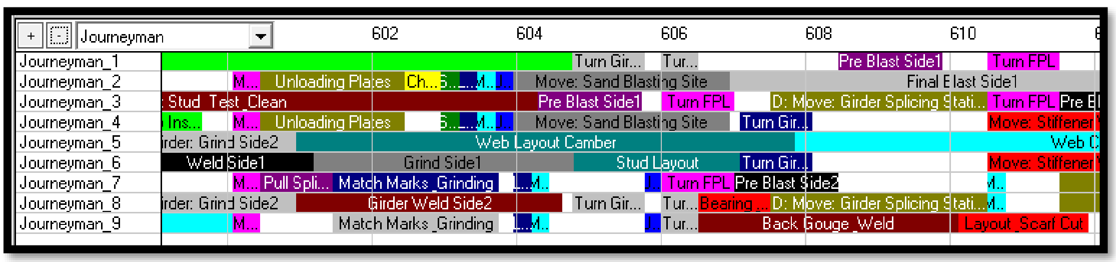
Figure B.5: Activity by activity plan for the Girder Fabrication case study in SDESA



a) Overall (Start to finish)



b) From 0 to 10 hrs (Red marked above)



c) From 600 to 610 hrs (Blue marked above)

Figure B.6: Resource Utilization Matrix (Journeyman) in SDESA for the Girder Fabrication case study.

Appendix C

Different Girder Sequences and their Overlap (%) in Bar Chart

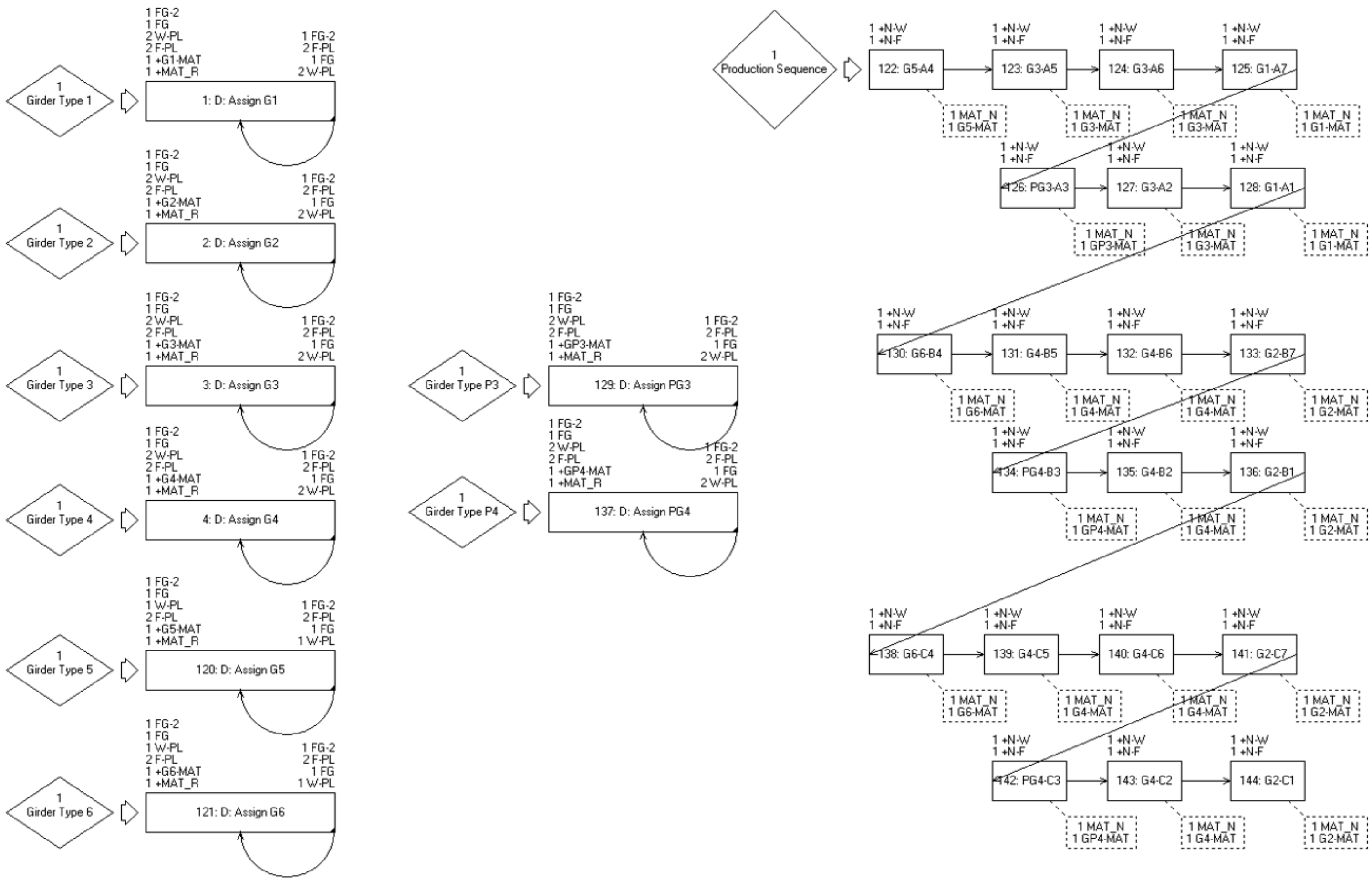


Figure C.1: SDESA model of Job Sequence 1.

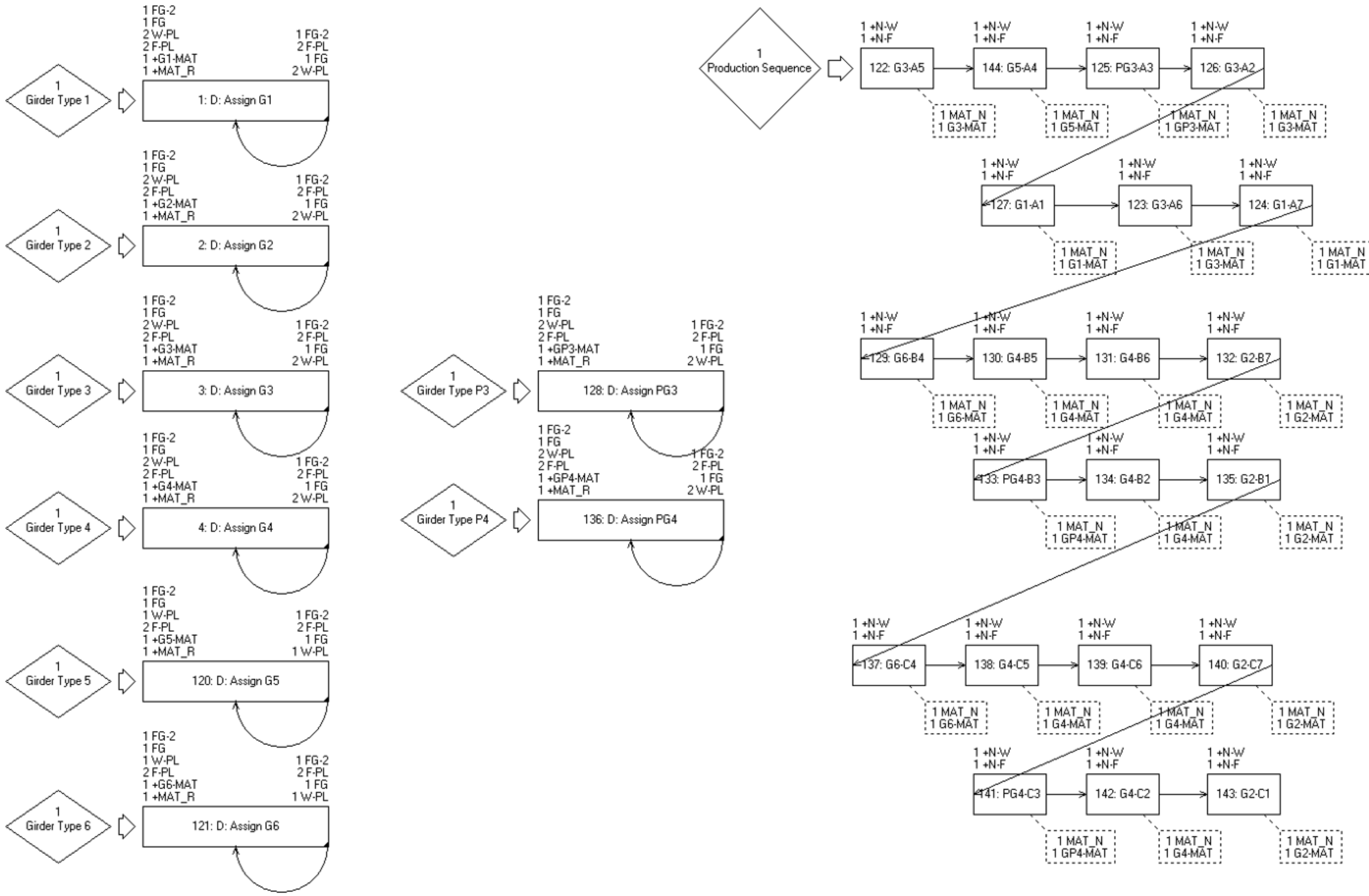


Figure C.2: SDESA model of Job Sequence 2.

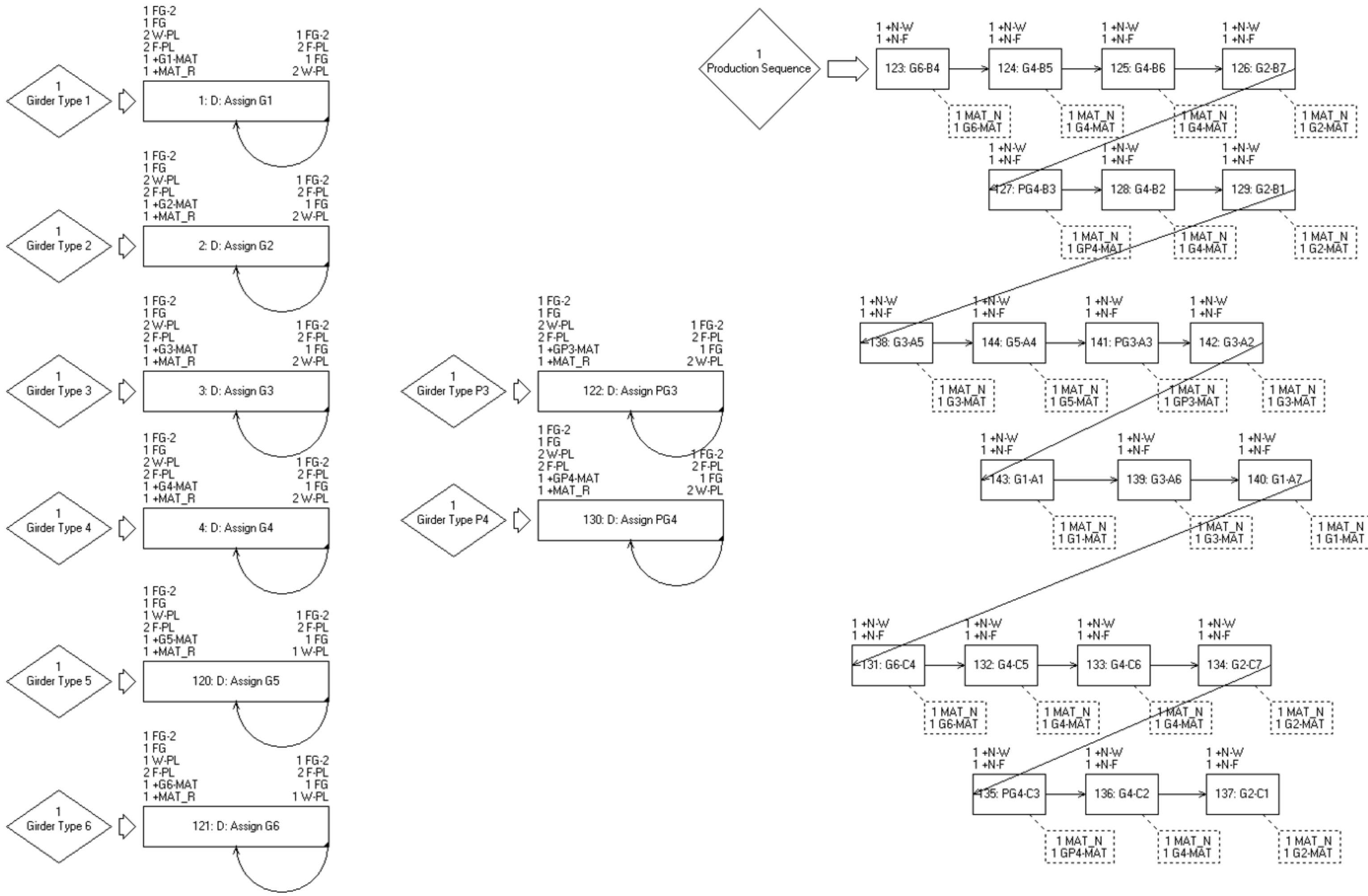


Figure C.3: SDESA model of Job Sequence 3.

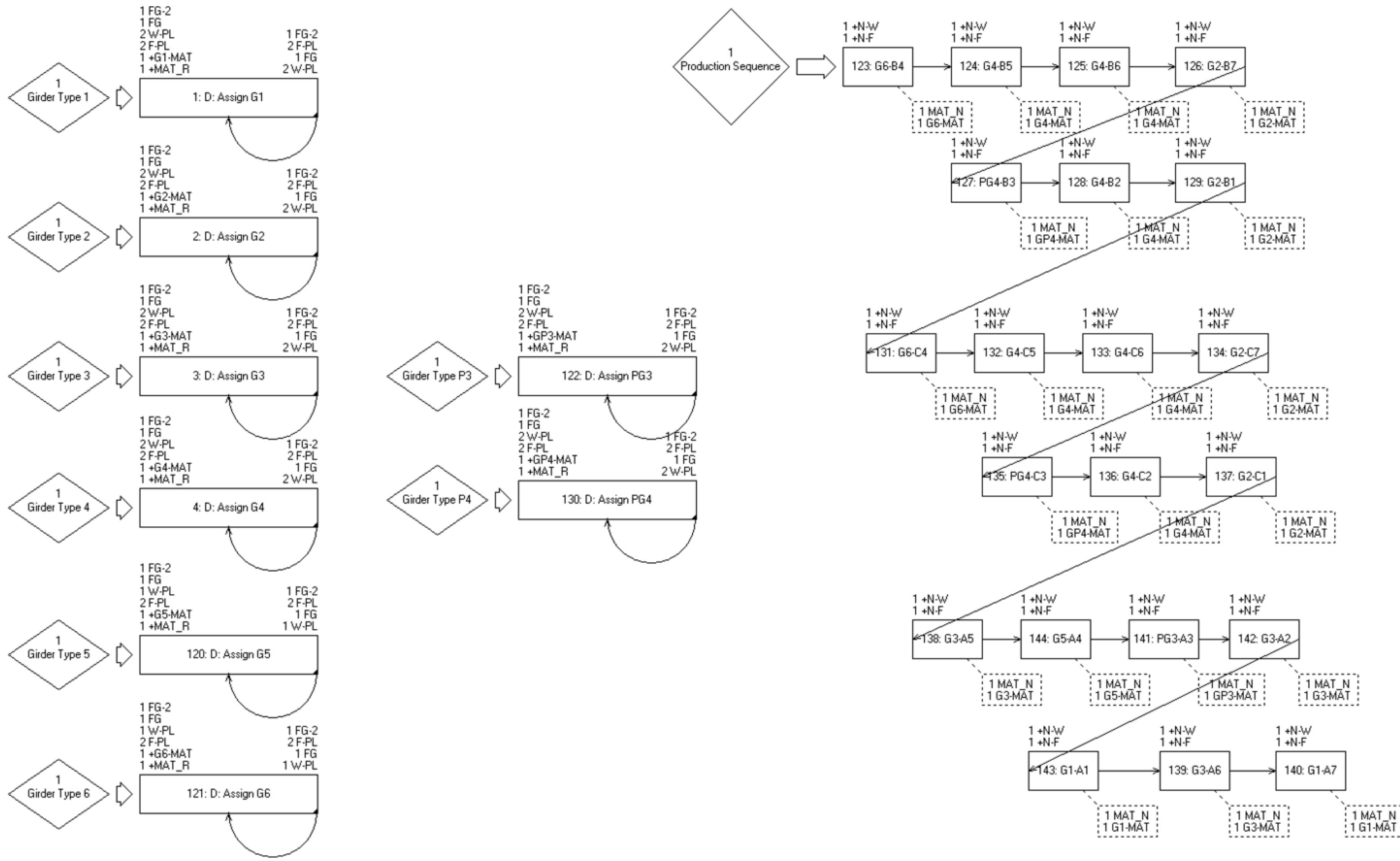


Figure C.4: SDESA model of Job Sequence 4.

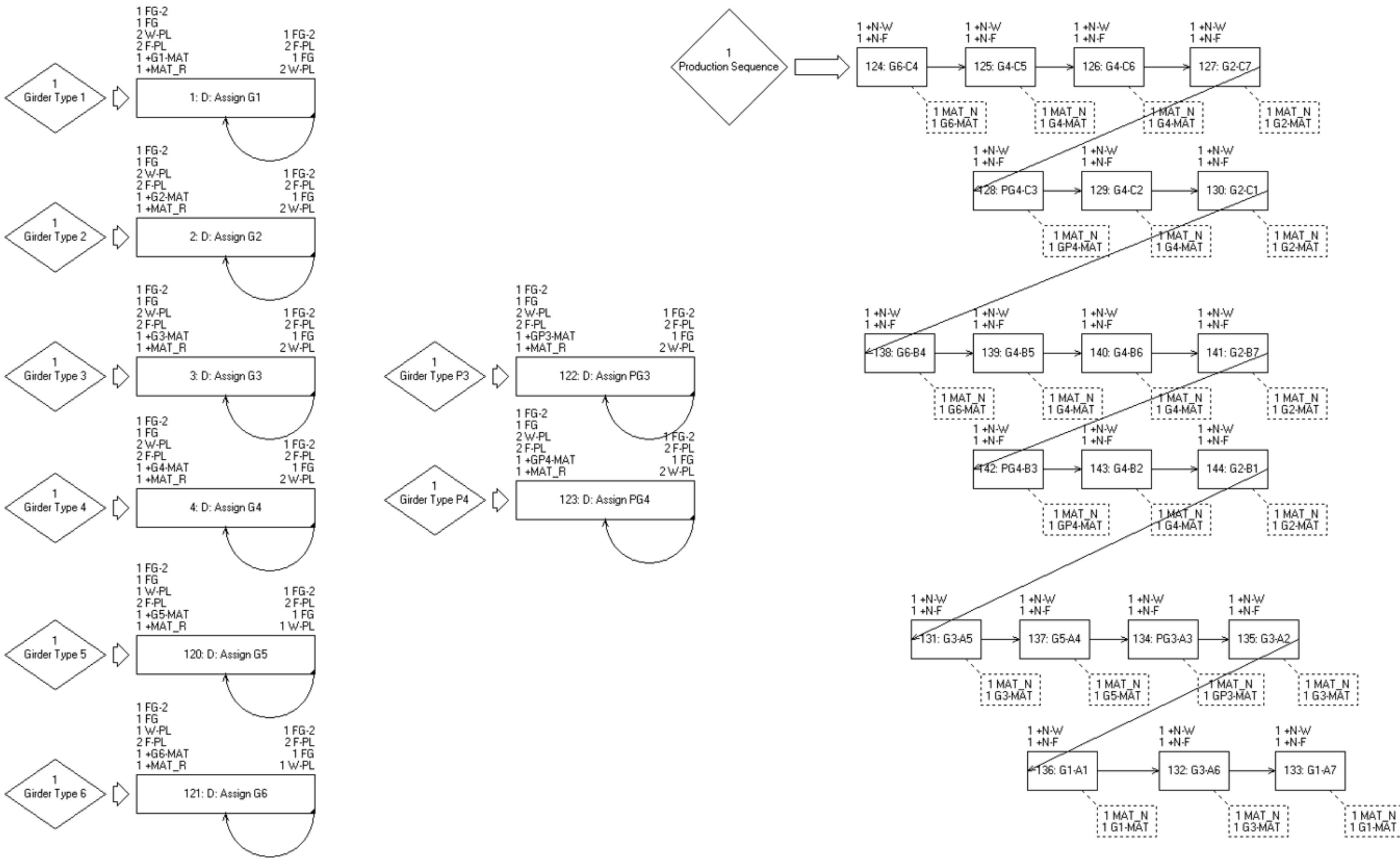


Figure C.5: SDESA model of Job Sequence 5.

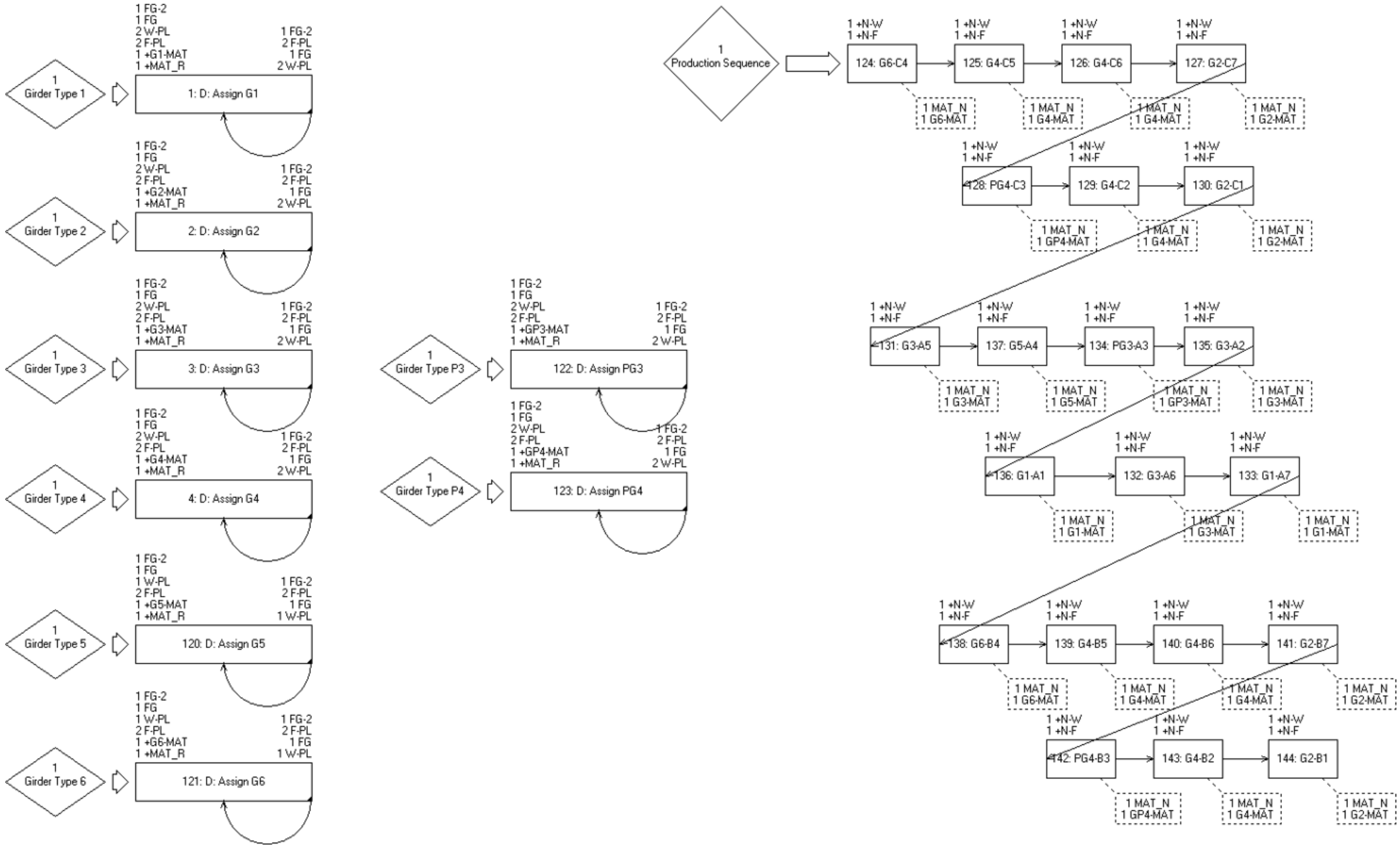


Figure C.6: SDESA model of Job Sequence 6.

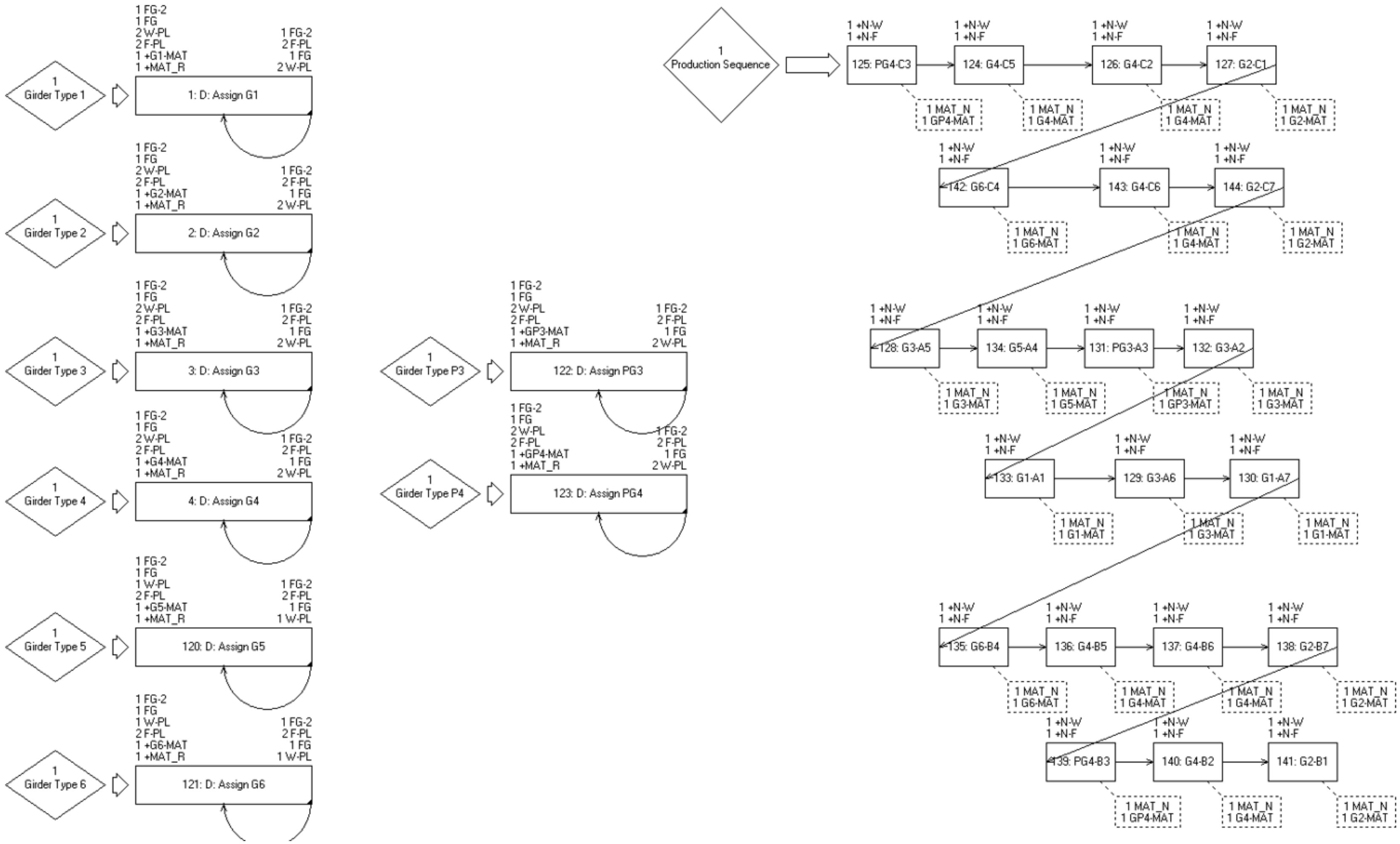


Figure C.7: SDESA model of Job Sequence 7.

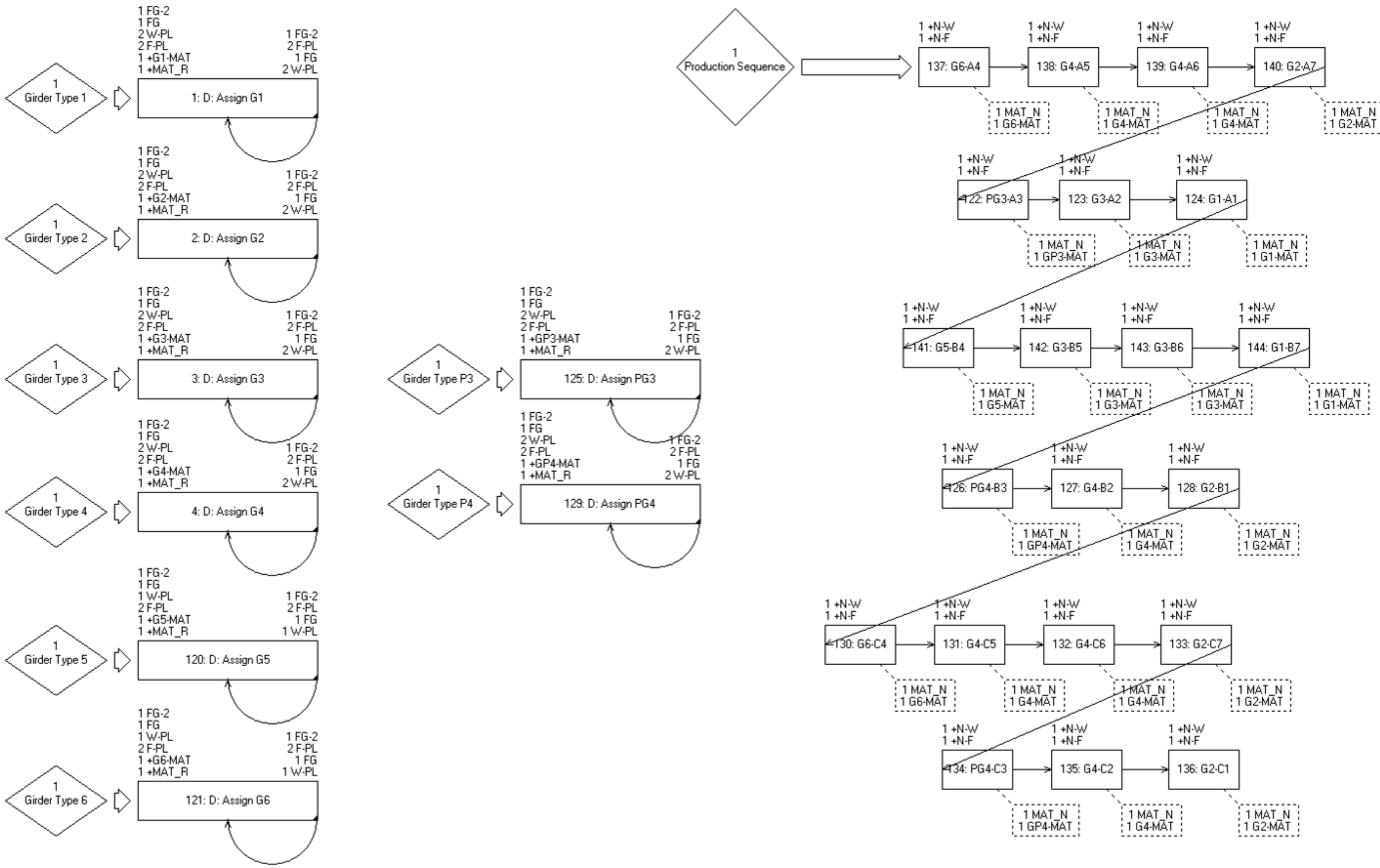


Figure C.8: SDESA model of Job Sequence 8.

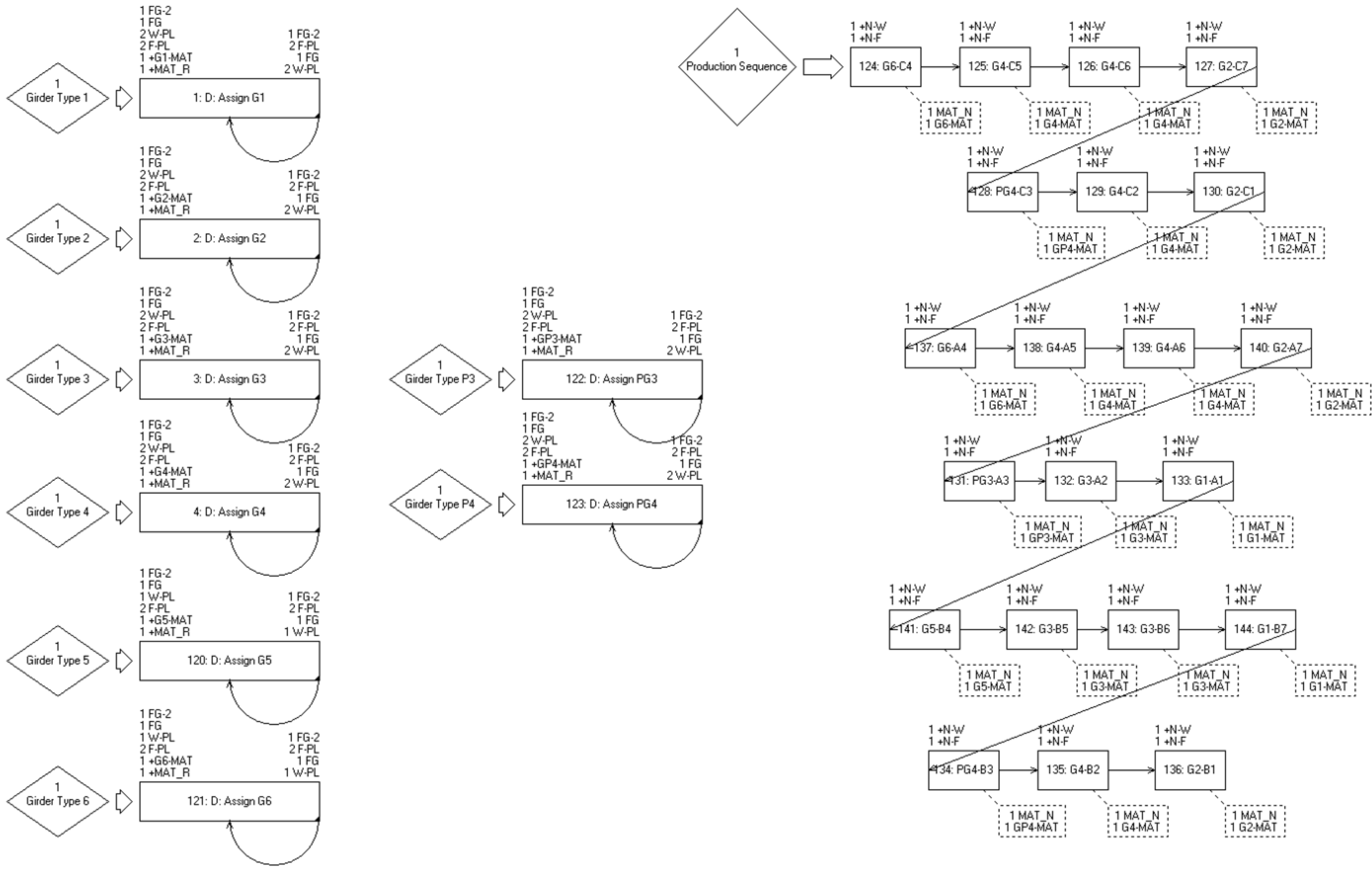


Figure C.9: SDESA model of Job Sequence 9.

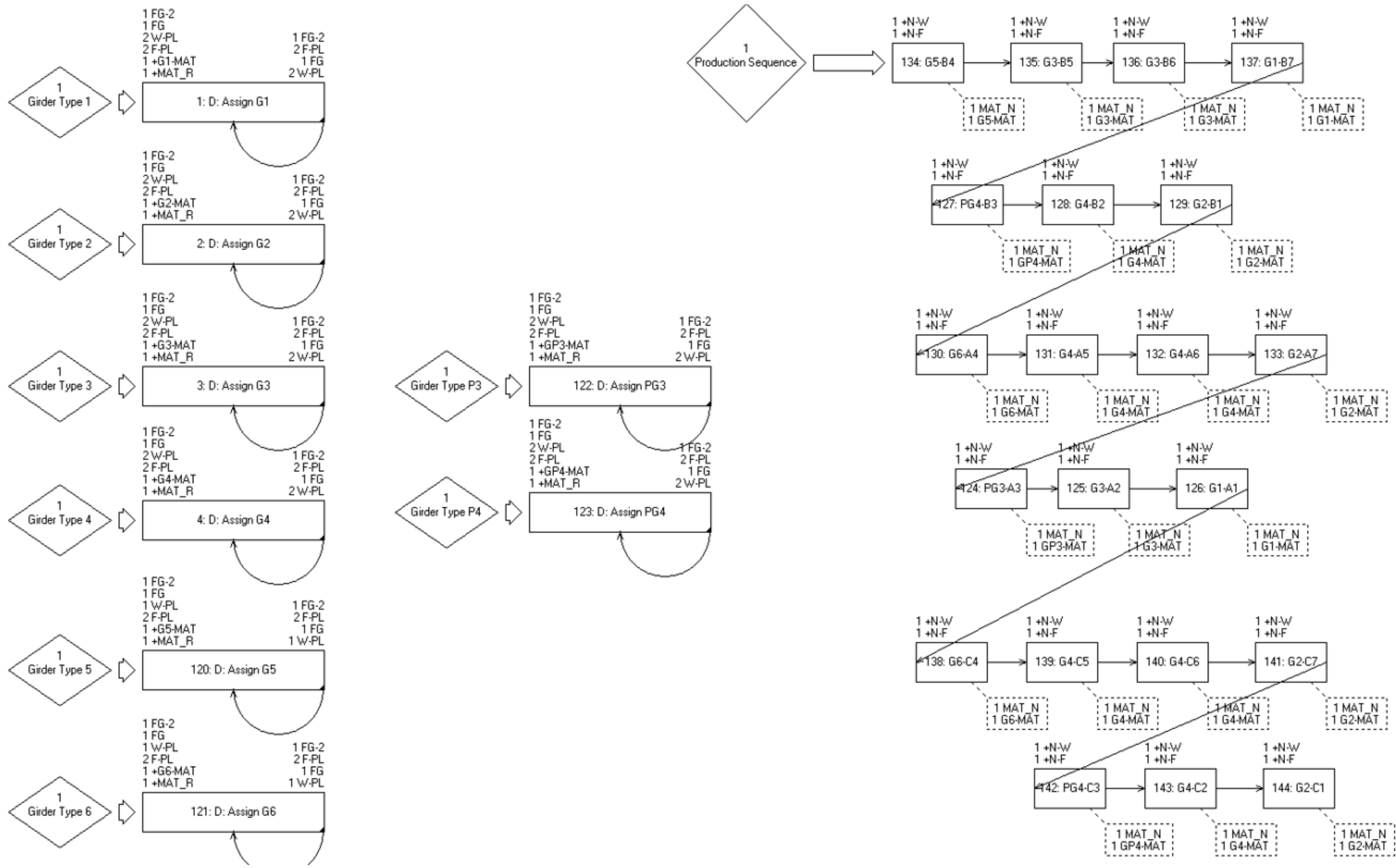


Figure C.10: SDESA model of Job Sequence 10.

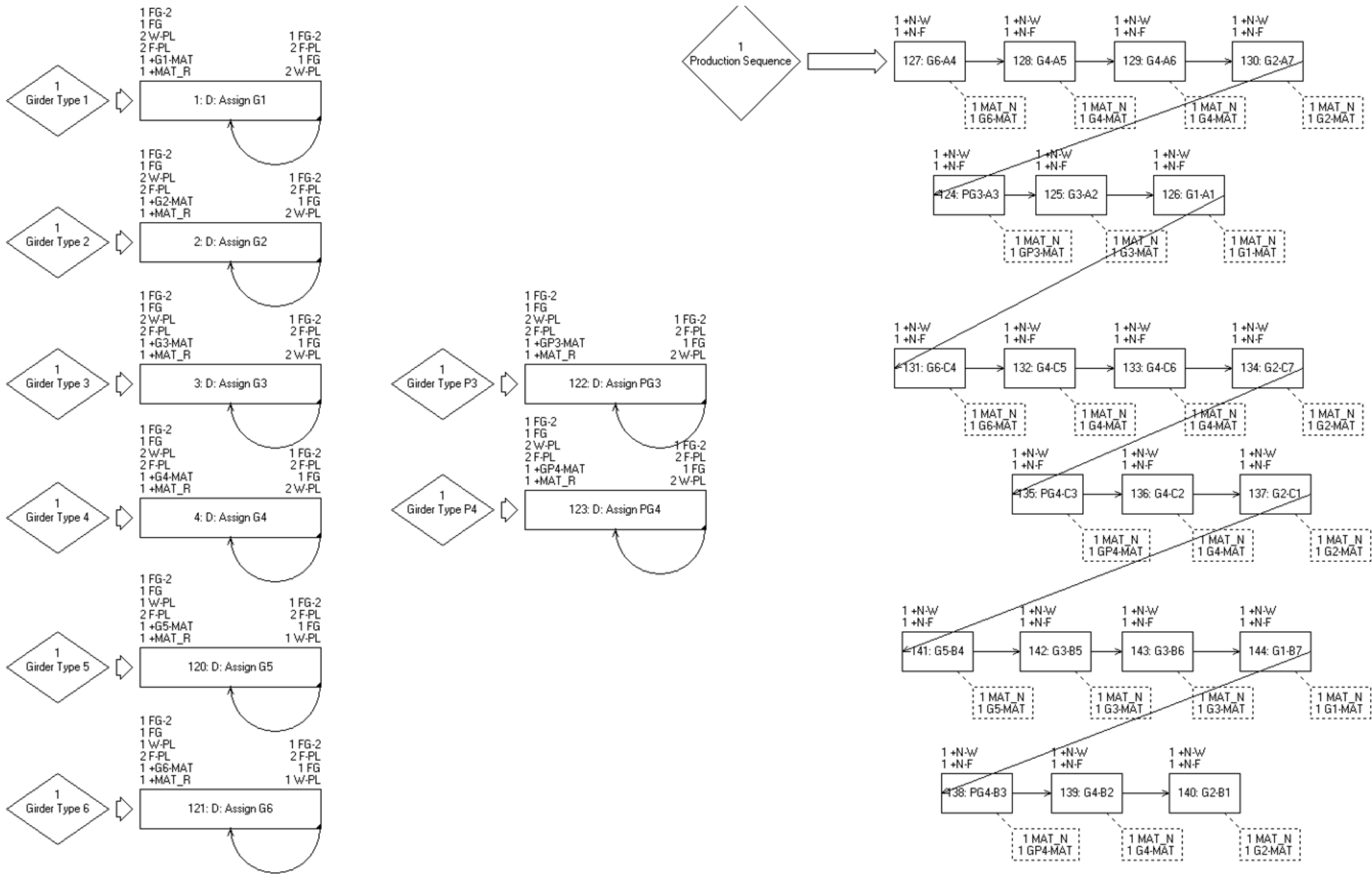


Figure C.11: SDESA model of Job Sequence 11.

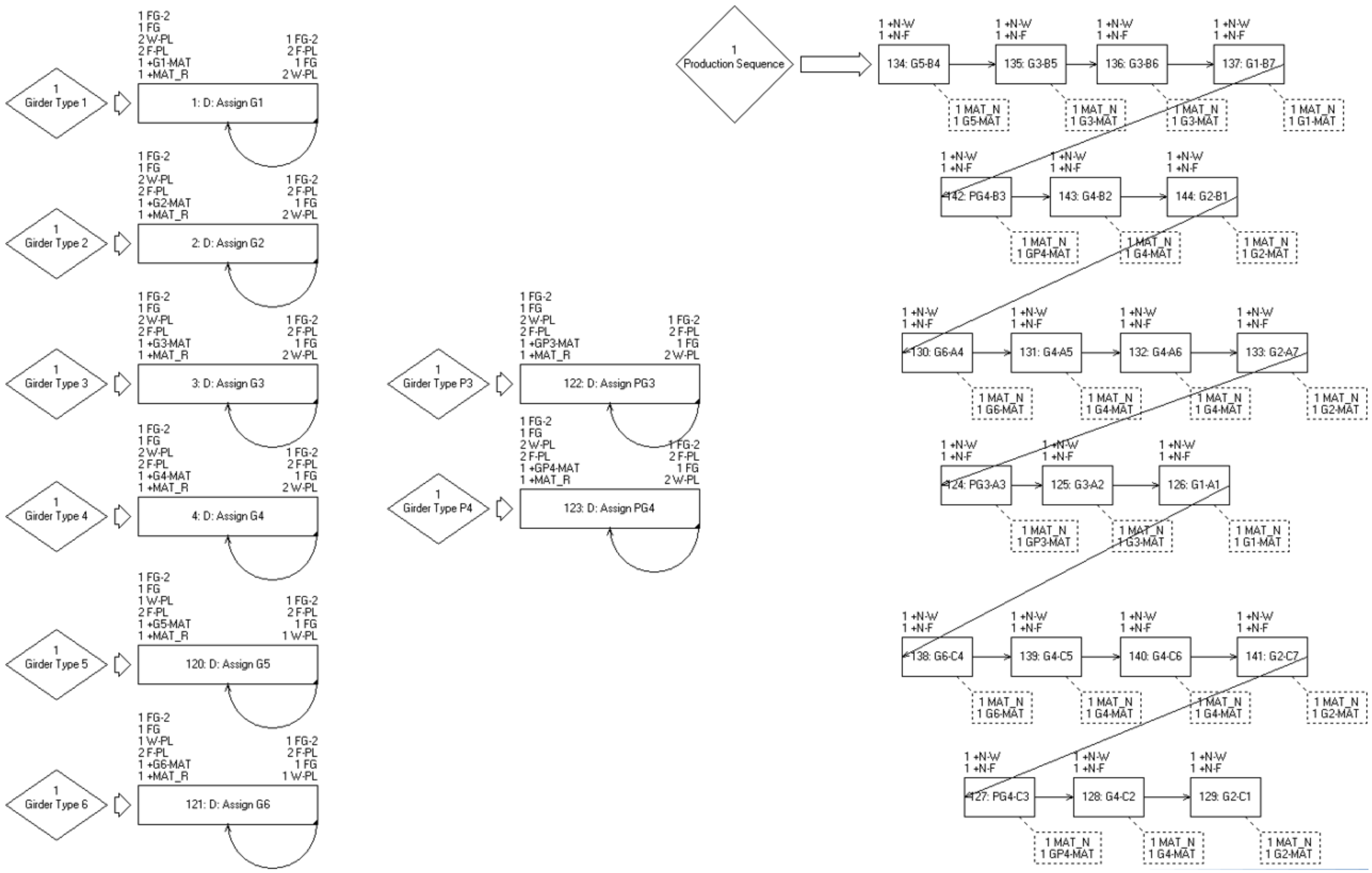


Figure C.12: SDESA model of Job Sequence 12.

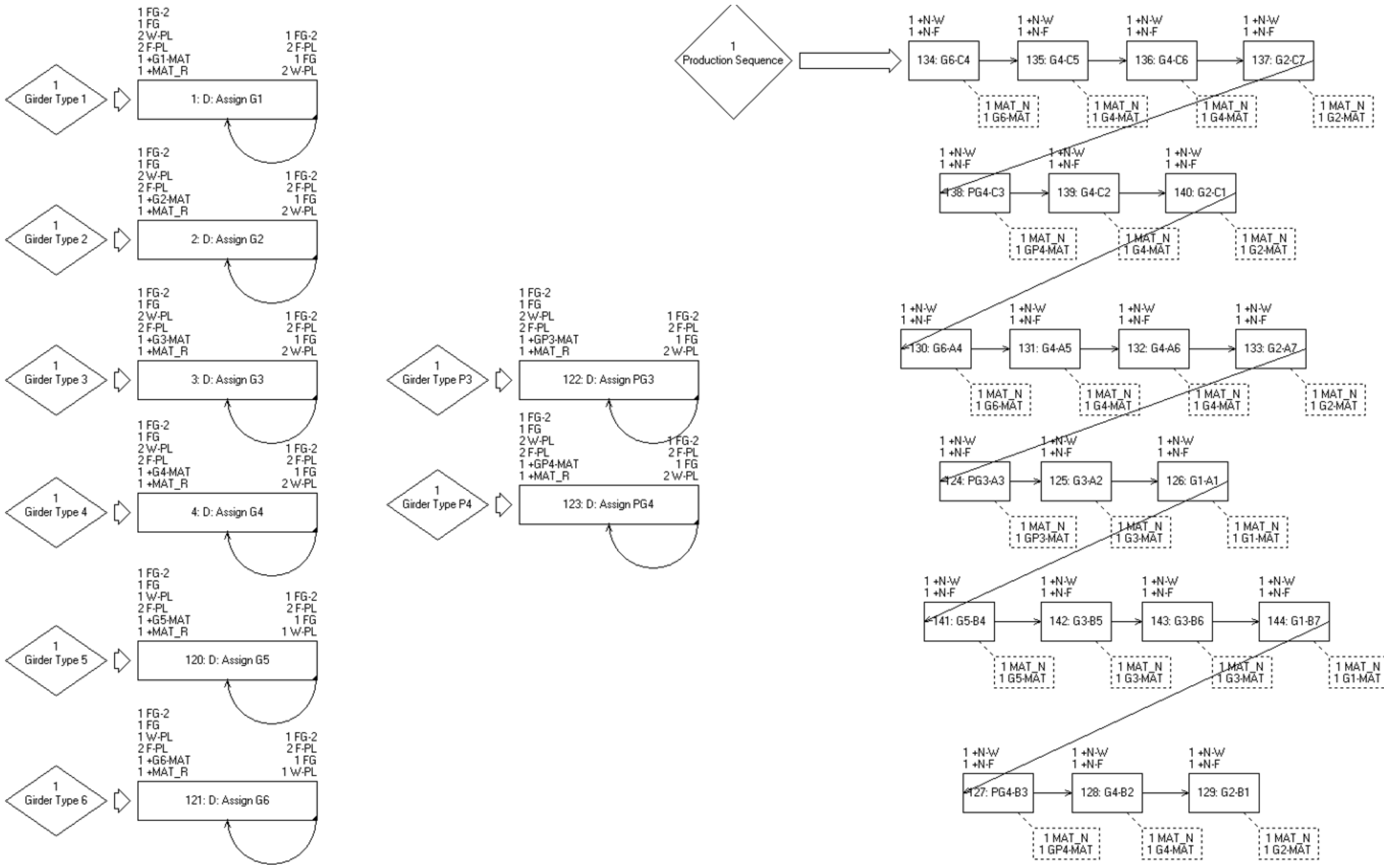


Figure C.13: SDESA model of Job Sequence 13.

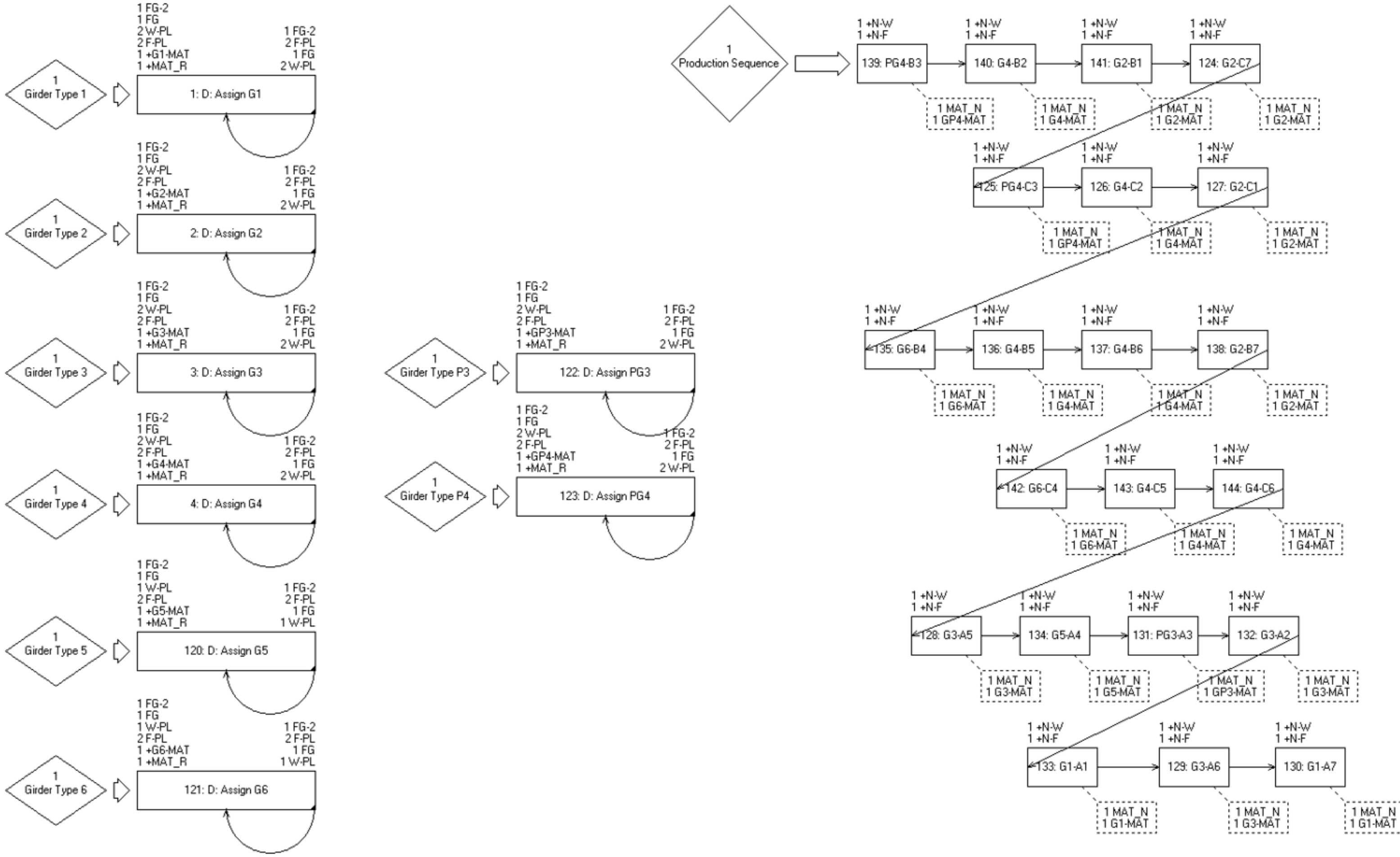


Figure C.14: SDESA model of Job Sequence 14.

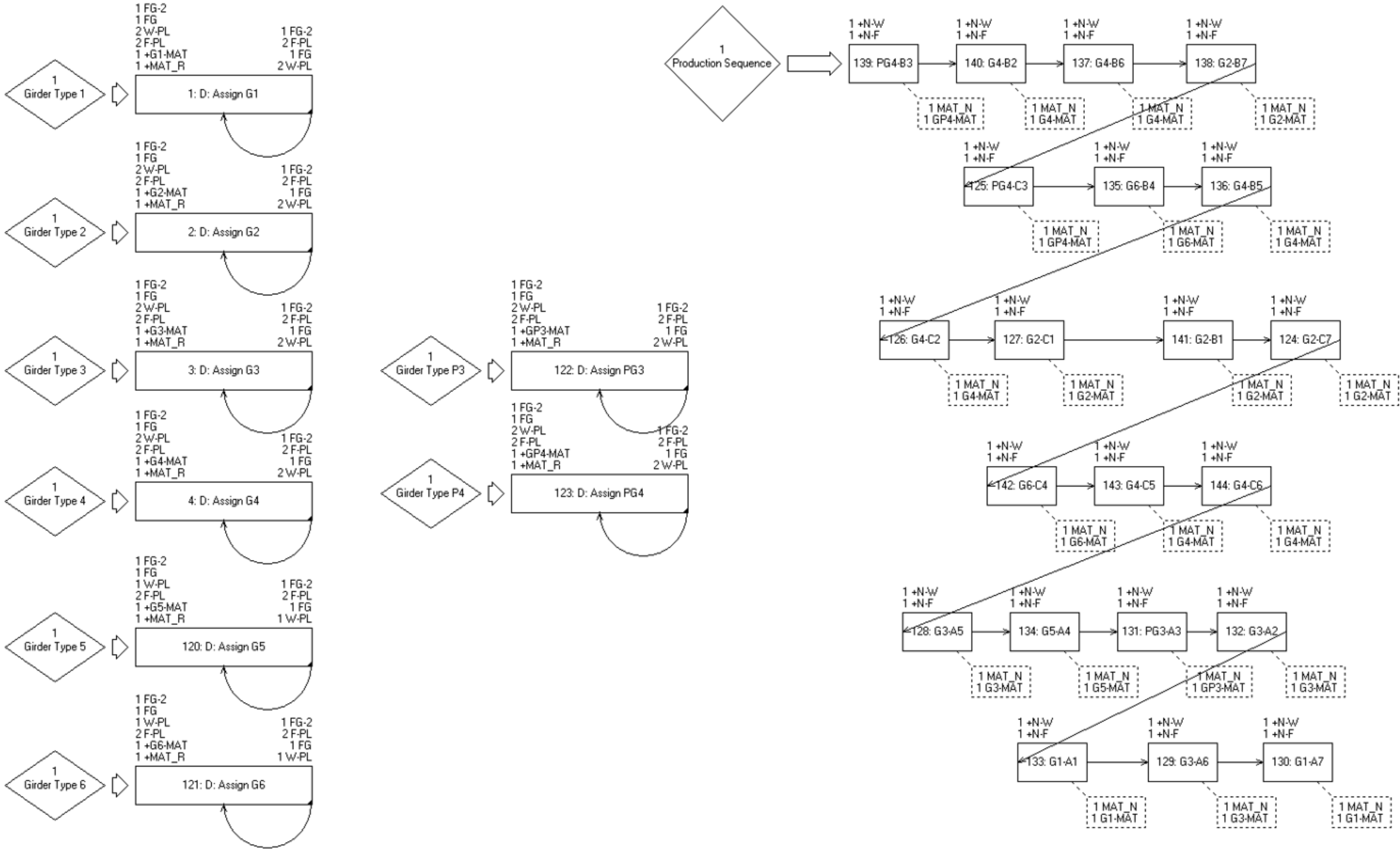


Figure C.15: SDESA model of Job Sequence 15.

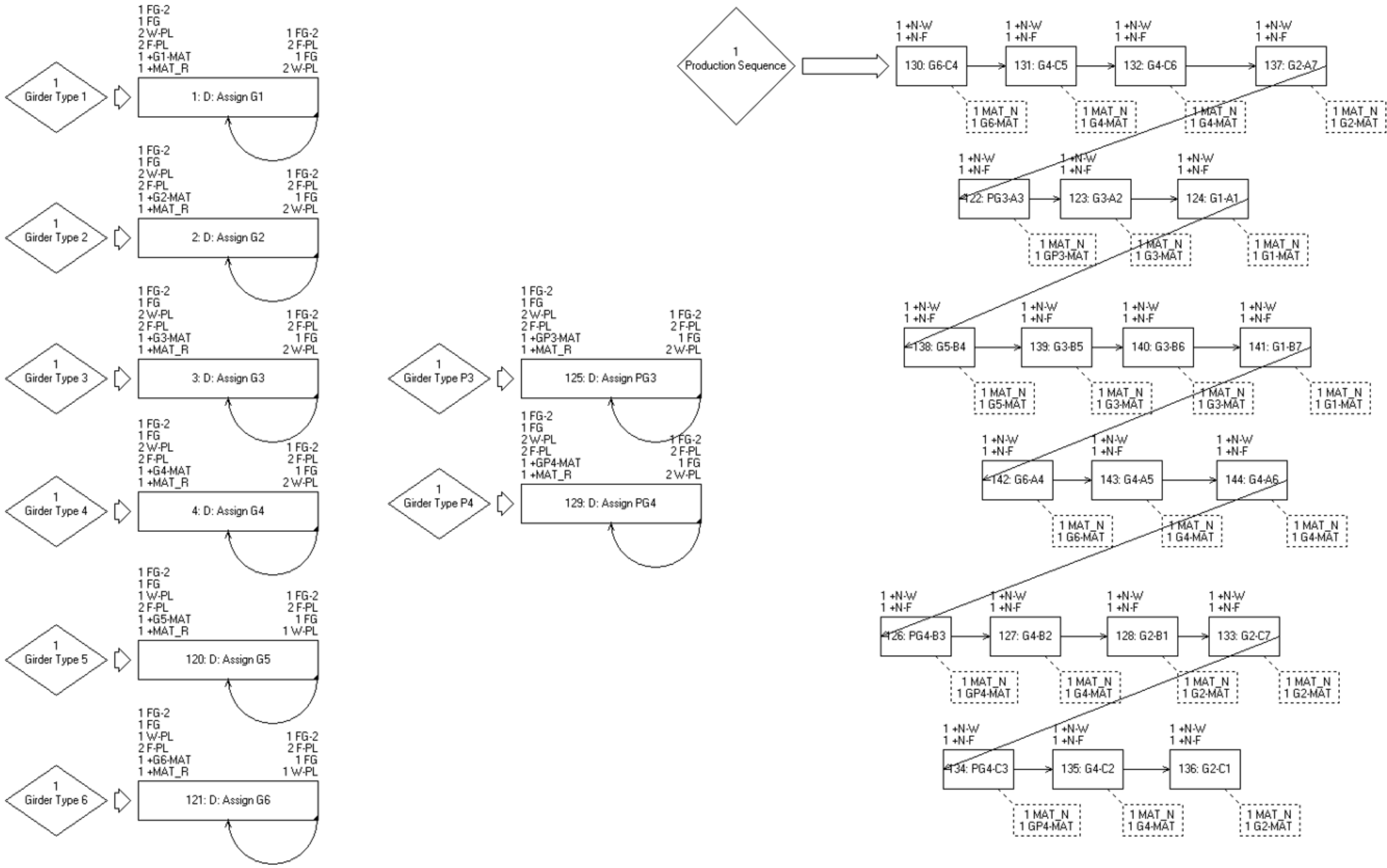


Figure C.16: SDESA model of Job Sequence 16.

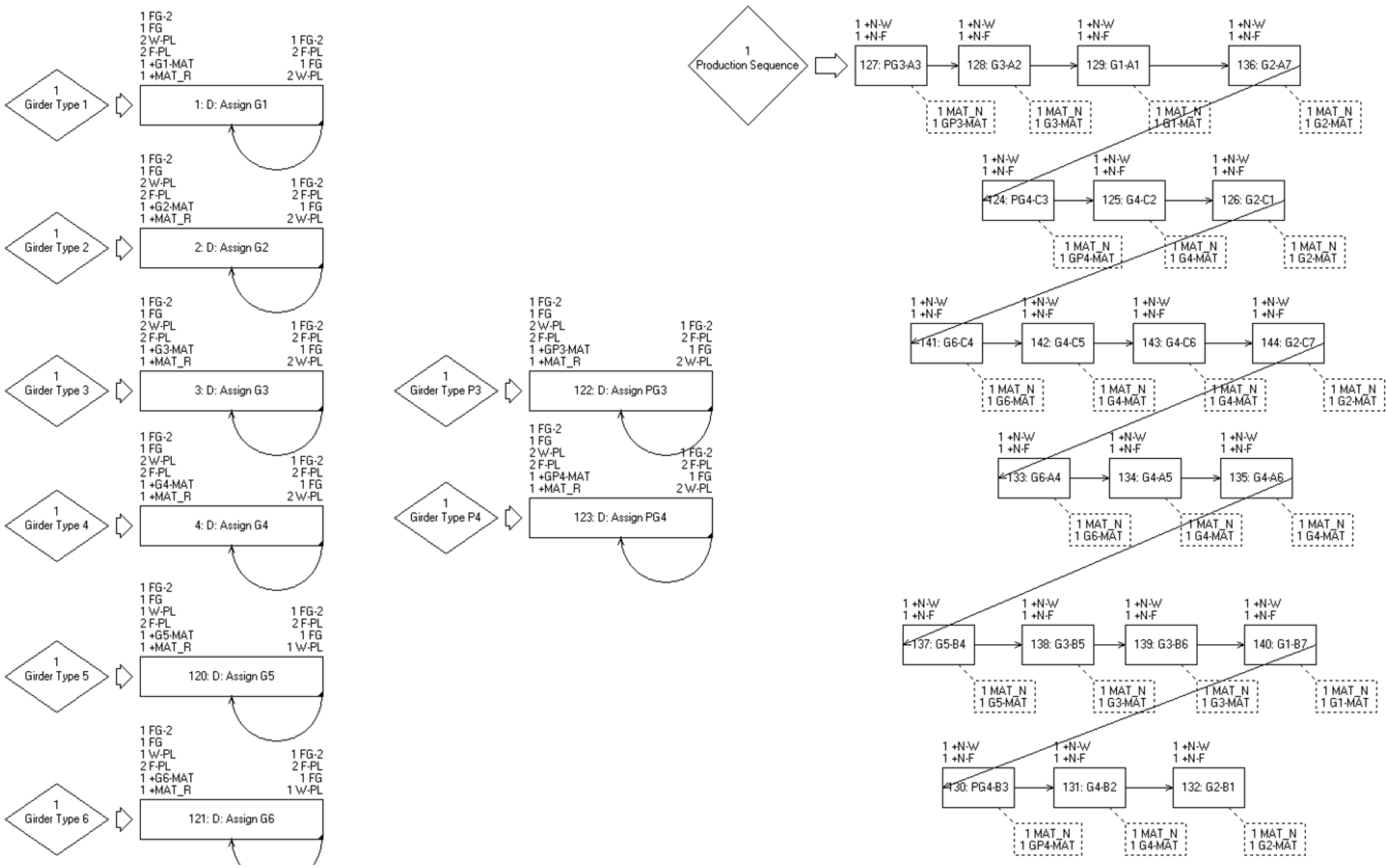


Figure C.17: SDESA model of Job Sequence 17.

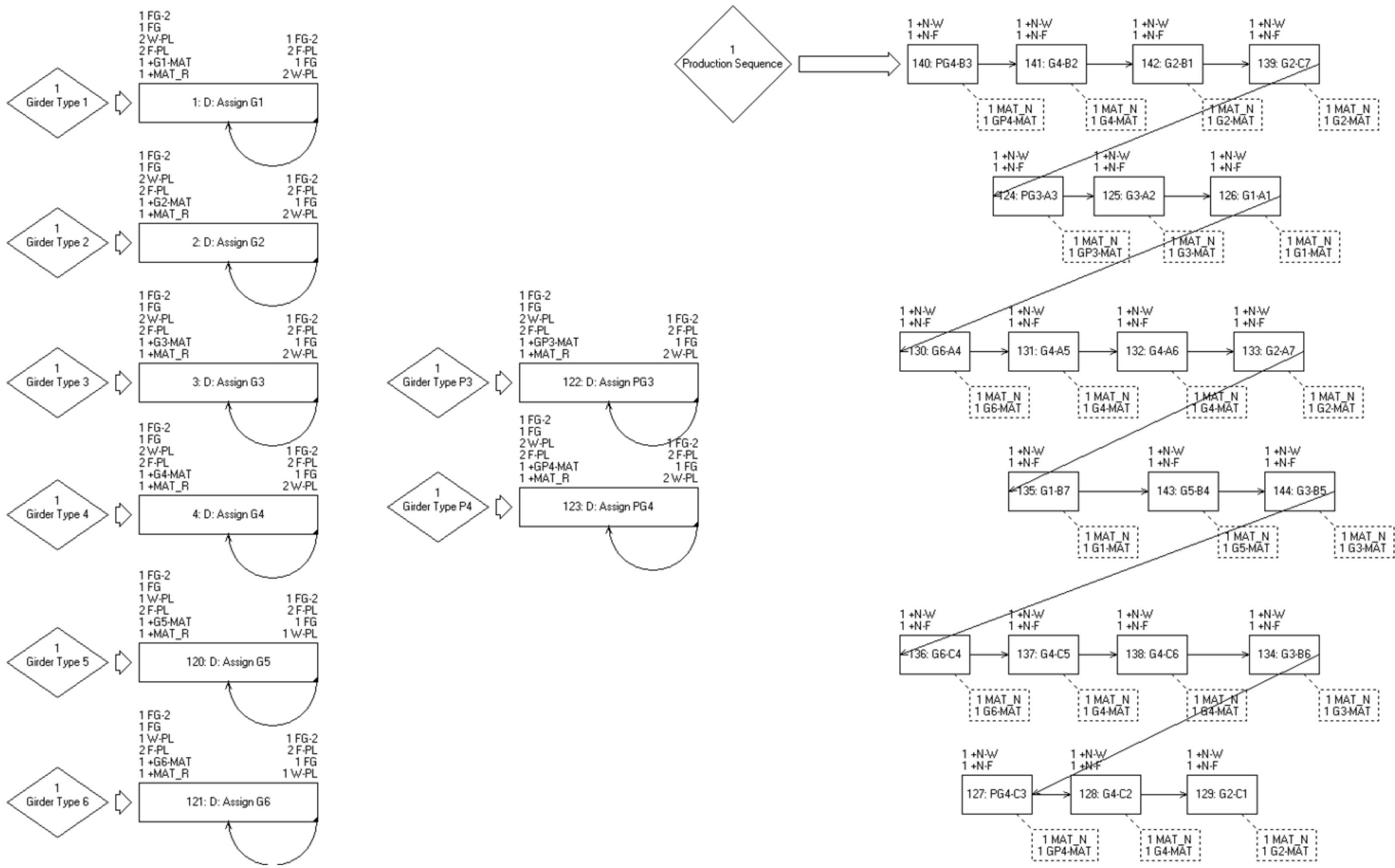


Figure C.18: SDESA model of Job Sequence 18.

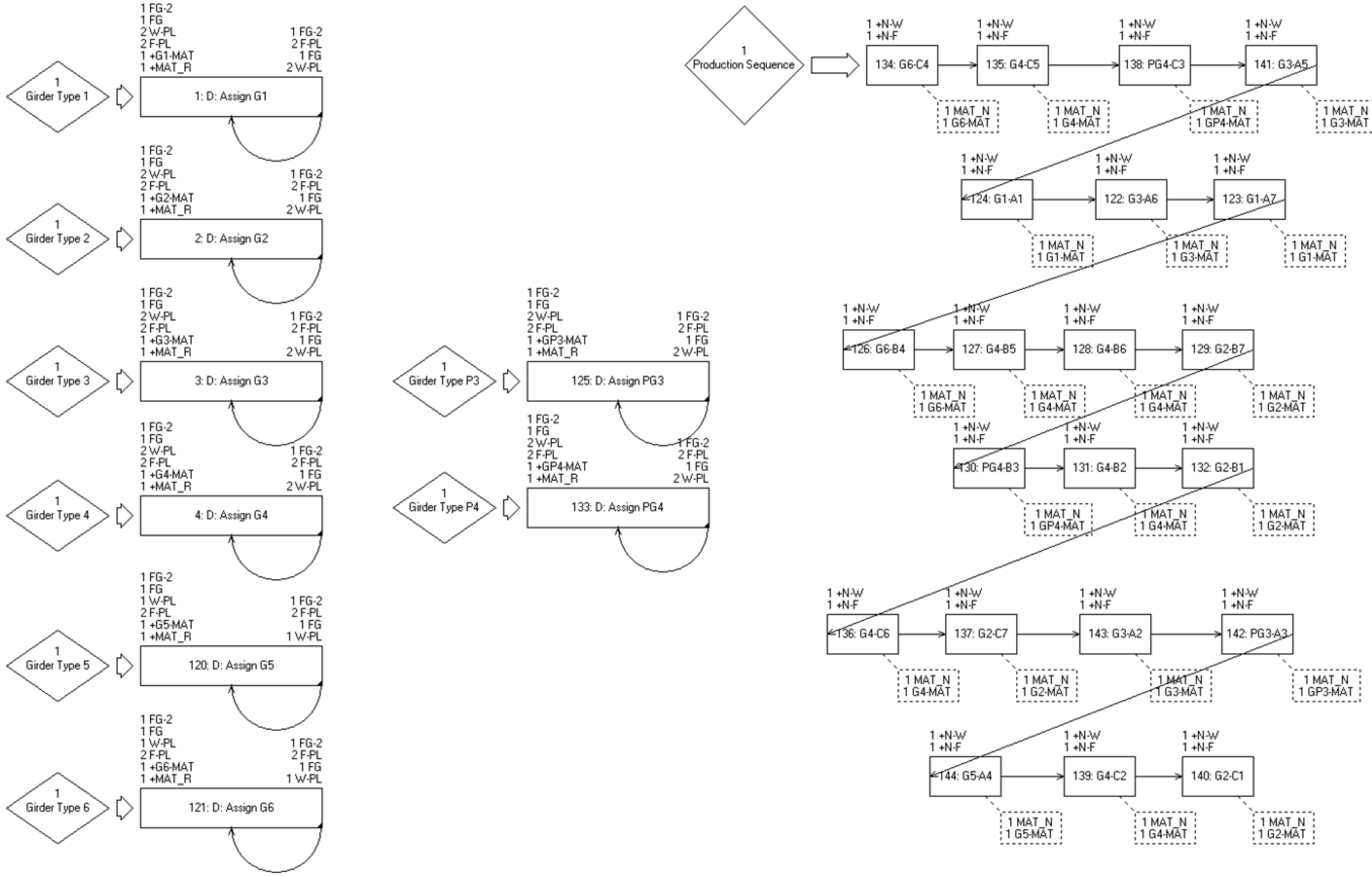


Figure C.19: SDESA model of Job Sequence 19.

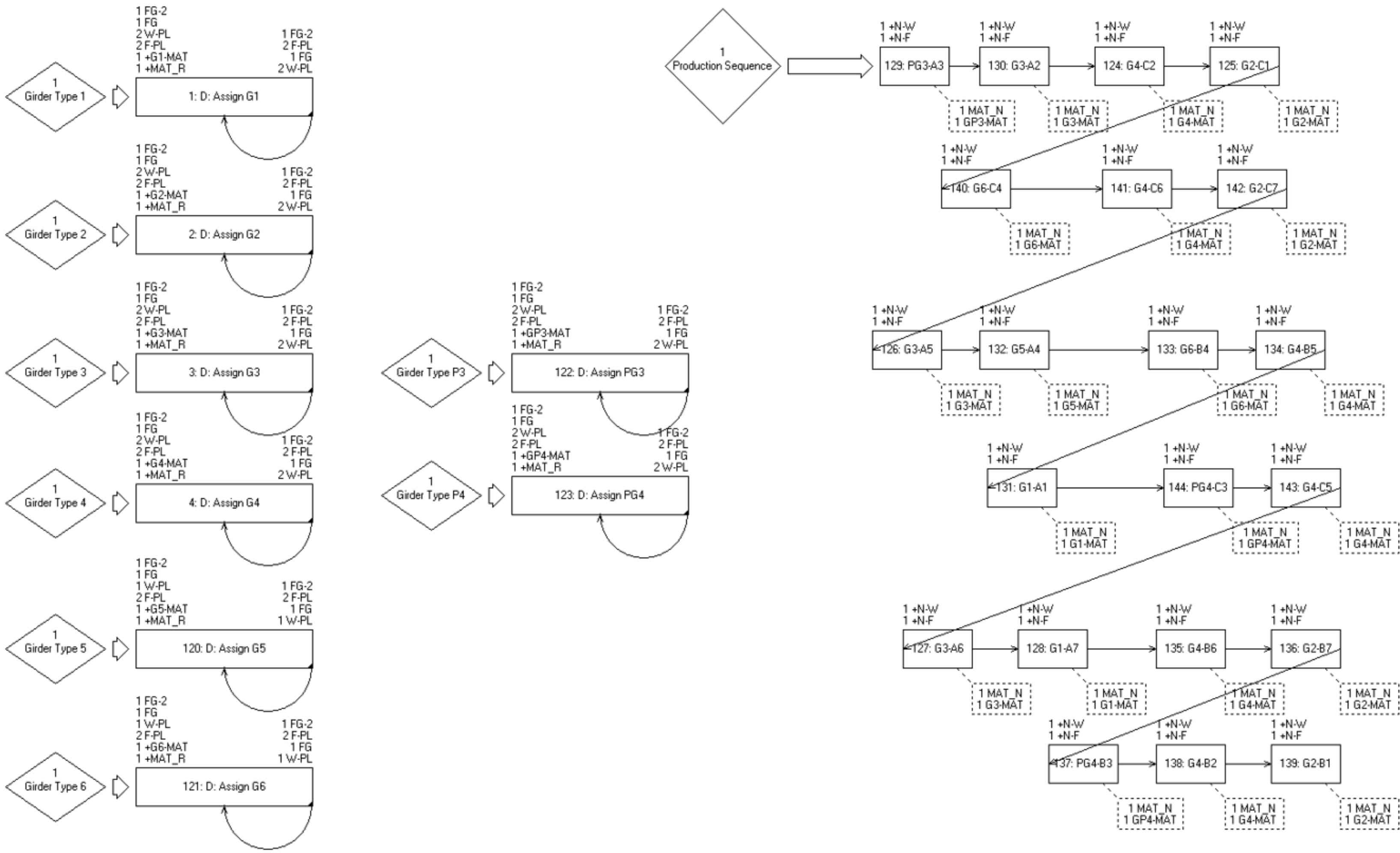


Figure C.20: SDESA model of Job Sequence 20.