A SCHEDULING MODEL FOR INDUSTRIAL PROCESS MANAGEMENT: AN INNOVATIVE APPLICATION OF CROSS-LAMINATED TIMBER (CLT) MANUFACTURING

by

Bruno de Araujo Carneiro

Civil Engineer, Universidade de Brasilia, Brazil, 2003

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A SCHEDULING MODEL FOR INDUSTRIAL PROCESS MANAGEMENT: AN INNOVATIVE APPLICATION OF CROSS-LAMINATED TIMBER (CLT) MANUFACTURING

Submitted by Bruno de Araujo Carneiro in partial fulfillment of the requirements of the degree of Master of Applied Science in Civil Engineering.

Examining Committee:

Dr. Kasun Hewage, School of Engineering

Supervisor

Dr. Rehan Sadiq, School of Engineering

Co-supervisor

Dr. Shahria Alam, School of Engineering

Supervisory Committee Member

Dr. Abbas Milani, University of British Columbia

University Examiner

Abstract

Manufacturing have been constantly challenged to increase process productivity while maintaining quality, safety and production risks at a reasonable level. Engineered wood products is one of the most thriving and dynamic manufacturing sectors in British Columbia, which is also confronted with declining productivity levels. Cross-laminated timber (CLT), an engineered wood product used in the construction industry, have been consistently growing in North America in the past few years. Despite its market relevance, wide technical applicability and performance, and although literature is vast and comprehensive in the field of applied manufacturing scheduling, CLT flow shop production lines are yet to be tackled. CLT manufacturing process involve customized panels and an extraordinary variety of features that can be incorporated into CLT products, leading to unknown process times, presenting an increased complexity to this system's schedule optimization. This thesis outlines the development and methodology of a scheduling algorithm for customizable CLT panels manufacturing. The proposed scheduling algorithm relies on empirical process time estimation models for each production stage to generate the required inputs, based on a list of required panels, their characteristics and features. The algorithm uses discrete event simulation and dispatch rules to generate a heuristic solution to the flow shop problem, aiming to minimize the average bundle finishing time and the total number of job shuffles in the buffer areas. Next, the scheduling algorithm is encapsulated in a scheduling tool which is applied to emulate a real production plant. The outputs of the scheduling tool provide crucial insight for production planners, allowing managers to make informed decisions to properly schedule concurring projects, optimizing limited resources in the plant, counting on a systematic, daily-generated production work order for each stage. Multiple work orders can be updated as desired with the proposed scheduling algorithm.

Lay Summary

Manufacturing industries have been constantly challenged to increase process productivity while maintaining quality, safety and production risks at a reasonable level. Cross-laminated timber (CLT), an engineered wood product used in the construction industry, have been consistently growing in North America in the past few years. This thesis describes the development of a manufacturing scheduling algorithm to determine the most efficient production sequence for customized CLT panels manufacturing to reduce time and resources wasted in plant with unnecessary panel shuffles. The outputs of the algorithm provide crucial insight for production planners, allowing managers to make informed decisions to properly schedule concurring projects, optimizing limited resources in the plant, counting on a systematic, daily-generated production work order for each stage. Multiple work orders can be updated as desired with the proposed scheduling algorithm.

Preface

I, Bruno Carneiro, developed the research concepts presented in this thesis, and conducted the relevant analyses. All CLT manufacturing process time estimation models and scheduling algorithm development and validation were conducted by myself under the supervision of Drs. Kasun Hewage and Rehan Sadiq. Dr. Manjot Kaur and Mr. Rukmal Liyanage provided valuable contributions to the data collection process on field.

This project was approved and funded by Mitacs and Structurlam Products L.P. under a collaborative research grant. In addition, the project was approved by Behavioral Research Ethics Board - UBC Okanagan under the minimal risk amendment (UBC BREB NUMBER: H17-03262).

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List of Abbreviations

GDP	gross domestic product
CLT	cross-laminated timber
CNC	computerized numerical control
SCHER-CLT	Scheduling Heuristic Rule-Based Simulation Model for CLT Products
APA	Engineered Wood Association
ANSI	American National Standards Institute
ISO	International Organization for Standardization
FQC	finishing, and quality control
FFSP	flexible flow shop problem
SPF	spruce-pine-fir
PRF	phenol-resorcinol formaldehyde
EPI	emulsion polymer isocyanate
PUR	one-component polyurethane
MC	wood moisture content
RDI	relative deviation index
NEH	Nawaz-Enscore-Ham heuristic algorithm
JIT	just in time
CAD	computer aided design
ASM	assembly manufacturing
AM	additive manufacturing
SM	subtractive manufacturing
PBA	CNC router cutting machine
FCFS	first come, first served
FIFO	first in, first out
LCFS	last come, first served
LIFO	last in, first out
FASFS	first arrival at shop, first served
SPT	shortest process time
LPT	longest process time

LWKR	least work remaining
MWKR	most work remaining
FOPNR	fewest number of operations remaining
GOPNR	greatest number of operations remaining
MTWF	most total work first
LTWF	least total work first
EDD	earliest due date
ALL	smallest allowance
SL	smallest slack
CR	smallest critical ratio
ALL/OPNR	smallest ratio of allowance per number of operations remaining
SL/OPNR	smallest ratio of slack per number of operations remaining
SL/WKR	smallest ratio of slack per work remaining
SL/ALL	minimum ratio of slack per allowance
ODD	earliest operation due date
OSL	minimum operation slack
OCR	minimum operation critical ratio
NINQ	least number of jobs in the queue of its next operation
WINQ	minimum work of its next operation (only jobs on queue)
XWINQ	minimum work of its next operation (jobs on queue and expected)
LA	look ahead
ALTOP	alternate operation
MOD	modified operation due date
ATC	apparent tardiness cost
CR+SPT	critical ratio + shortest process time
SL/RPT+SPT	slack remaining per remaining process time + shortest process time
RR	Raghu and Rajendran
DES	discrete event simulation

Acknowledgements

First, I would also like to thank Dr. Kasun Hewage, who was the first to trust in me, and guided me through this return to the school after 13 years of industry experience. Dr. Hewage, thank you for giving me this opportunity and teaching me the "full package" during my time here in UBCO and provided me access not only to state-of-the-art facilities and education, but also getting me involved in valuable industry projects. I will be forever grateful for your knowledge, wisdom, guidance and motivation.

Secondly, I would like to thank Dr. Rehan Sadiq for his advice as my co-supervisor, and all the research team at the Life Cycle Management Laboratory, for their friendship and support.

Lastly, the cooperation and funding provided by Mitacs and Structurlam Products LP was crucial for the successful completion of this study. I would also like to thank Mr. Andre Morf, Director of Operations, Structurlam Products LP. His and Structurlam's Okanagan Falls Plant's staff support was decisive in the success of this project.

Dedication

To my Families.

The very first one, that which gave me birth, unconditionally loved and guided me so I could become the man I am today.

The second one, mentors and friends those who embrace me amongst them, as one of their own, and made me feel loved and welcomed, supporting me every step of the way.

And finally, the one which me and Cecilia built. You are the reason all this was possible. To Cecilia, the love of my life, to Melissa, my first-born sweet daughter, and to Leonardo my youngest beloved son. I would not be able to do it without you.

Chapter 1: Introduction

1.1 Background

Manufacturing is a highly-skilled and highly-technical sector that represents almost 10 percent of Canada's total GDP (Canada Statistics 2017). Manufacturing directly employs 1.5 million Canadians, contributing to a share total of 10% of the Canadian economy, according to Statistics Canada (2017). This sector is constantly developing new technologies. In fact, the manufacturing sector is the largest investor in research and development in Canada, having invested nearly $6.8 billion in researching and developing new products and technologies (Industry Canada 2015).

Canada's manufacturing sector has been observing a recovery period since the economic downturn in 2008. From all subsectors in the industry, wood manufacturing has shown the best performance in the "bounce-back-growth" showing positive results in many indicators such as total GDP, nominal sales, capacity utilization and investment growth (Burleton et al. 2014).

In fact, the advanced (or secondary) wood manufacturing sector is an important player to Canada's economic performance and labor market. Employing over 80,000 skilled workers, the sector is expected to grow and add at least 7,000 more workers by 2020. Nevertheless, there are many concerns regarding the education and qualification of the labor market to fulfill the sector's needs (Conference Board of Canada and Wood Manufacturing Council 2016).

In 2017, the secondary wood industry in Canada generated over $5.9 billion in GDP, representing a 3.6% increase when compared to 2016 (Natural Resources Canada 2017). Wood products manufacturing revenues reached a total $29.9 billion in 2016, showing an increase of 9.2% from 2015 values. At the same time, energy, water and vehicle fuel consumption in this sector have increased by 4.3%, showing a steady growth trend (Statistics Canada 2018).

Despite its steady growth, and although wood product industry sales have increased more than 10% from 2016 to 2017 (Canada Statistics 2017), labor productivity has decreased in the sector. According to the latest released report, manufacturing productivity decreased 1.3%, compared to a 0.1% overall reduction for the Canadian economy (Government of Canada 2016). The engineered wood manufacturing market is a dynamic and important sector, especially in British Columbia, the strongest engineered wood product manufacturing province in Canada, with a sector GDP of over $760 million in 2016 (Government of Canada 2016).

Cross-laminated timber (CLT) is an engineered wood product used in the construction industry. Originally developed in Europe, and applied for over 25 years, instances of CLT applications have been consistently growing in North America in the past decade. The product consists of light wood board layers assembled perpendicularly to one another and glued together with high performance adhesives in a mechanical process. This specific configuration empowers the product with remarkable mechanical properties, fire resistance capabilities, and seismic flexibility, granting potential for mid- to high-rise construction (Natural Resources Canada 2016). The advantages of CLT are most often obtained in multi-story buildings and in unconventional long spans for wood construction (Yeh et al. 2012). Additionally, embodied characteristics intrinsic to wood products make this technology suitable for sustainable, carbon-positive construction (Laguarda Mallo and Espinoza 2015). Even though there might be worries regarding how environmentally safe CLT is due to the usage of formaldehyde-based adhesives in its gluing process, there are environmentally friendly and viable alternatives such as emulsion polymer isocyanate (EPI) and polyurethane (PUR) based adhesives (Grøstad and Pedersen 2010; Messmer 2015). Moreover, Life Cycle Assessment studies have shown that CLT is environmentally superior when compared to other construction technologies such as cast-in-place concrete or steel (Buck et al. 2015; Robertson et al. 2012).

CLT is a light and easy material to work with, lowering construction costs due to smaller foundations and substructures (Canadian Wood Council 2017). CLT is also well suited for preassembled and modular construction, reducing construction time and work on-site (Kasbar 2017). Additionally, wood construction and designing are appropriate choices for reusing, recycling and energy generation recovery purposes of building materials at the end of their life cycle (Howe, Jeff, Steve Bratkovich, Jim Bowyer, Matt Frank 2013).

Finally, mass timber buildings (CLT included) represent approximation of people and building users with the natural environment. A study revealed that people feel happier, healthier and more productive when connected to nature (David Fell and FPInnovations 2003).

1.1.1 Research gap and motivation

In a highly competitive market, wood paneling manufacturing experiences are clearly defined by markets and buyers, limited technological change and mass consolidation of production practices and supply chains among the largest players (Leach 2018). In a mature industry, research and development is crucial to generate competitive leverage, increasing productivity, profit, and market share.

One of the best advantages CLT products bring to the construction and engineered wood market, is also one of its biggest challenges. Considering its limitations, CLT allows for customized projects and unconventional features to be incorporated in the structural body of a building, increasing assembly agility and construction efficiency. However, the manufacturing process of customized CLT panels is a complex procedure that demands pristine coordination among plant management, shop floor workers, plant layout and production equipment. Each of those agents' performance are highly impacted by how each CLT panel (job) is scheduled to enter each production stage in the plant.

Productivity is even more impacted when specific loading and unloading sequences are considered. Clients may require specific loading sequences to facilitate the unloading and assembly process in the construction field. Under these specific conditions, the job scheduling order matters even more. Improper production schedules may cause unnecessary panel job shuffles in the buffer areas, leading to wasted time and resources, more risk exposure, and ultimately, costing more money.

Although the literature is vast and comprehensive in the field of applied manufacturing optimization (Ahari et al. 2011; Basu et al. 2014; Bossmann et al. 2008; Liu et al. 2013b; Qi et al. 2017; Schatz et al. 2017; Soury et al. 2009; Zaier and Abdo 2012), CLT production chains are yet to be modeled. A number or studies have tackled production schedule optimization in applied manufacturing, however, CLT manufacturing processes involve customized panels and an extraordinary variety of features that can be incorporated in CLT products, leading to unknown process times, sequenced loads, and presenting an increased complexity to a system's schedule optimization.

Currently, there is no practical, real-life, applicable scheduling model to simulate CLT manufacturing process and account for plant limitations, management priorities, variable process times, process constraints and delivery requirements at the same time. Most previous studies on manufacturing scheduling focus on mathematical theoretical algorithms developed to achieve various time-related objectives (Choi et al. 2011). Additionally, a classical optimization approach to the scheduling problem for a complex practical application like this is not feasible. There are just too many variables, rules and constraints to consider in an analytical solution. Due to the complexity of the real problem, it is virtually impossible to model and solve the scheduling problem in an analytic manner (Kang and Choi 2013). Therefore, it is important to develop a simulation model capable of estimating the production process time for each production stage and to provide a feasible and efficient schedule solutions to the manufacturing of customizable CLT panels using an empirical approach to model the production process.

1.2 Objectives

The main objective of this research is to develop a production scheduling and rescheduling model, for the customizable CLT panel manufacturing industry. The proposed scheduling model shall consider real production constraints, equipment and labor limitations. The specific sub-objectives are outlined below:

1. Identify CLT panel metrics and characteristics, production stages batching constraints, real process times and required labor and equipment, that will be considered in the simulation algorithm;
2. Develop a customized CLT panel production process map to identify bottlenecks, production limitations and improvement potential, plant layout, material handling and storage constraints relevant to CLT production scheduling;
3. Develop four production process time estimation models, one for each manufacturing stage of customized CLT panel production line;
4. Develop a scheduling and rescheduling algorithm for customized CLT panel manufacturing.

The deliverables of this research will aid production planners and plant managers in defining a production schedule and field work orders for customizable CLT panel manufacturing.

The model, translated into the Scheduling Heuristic Rule-Based Simulation Model for CLT Products (SCHER-CLT), is encapsulated in an Excel-based scheduling tool. The scheduling model is generalizable and applicable to different plant setups, product specifications and production management scenarios.

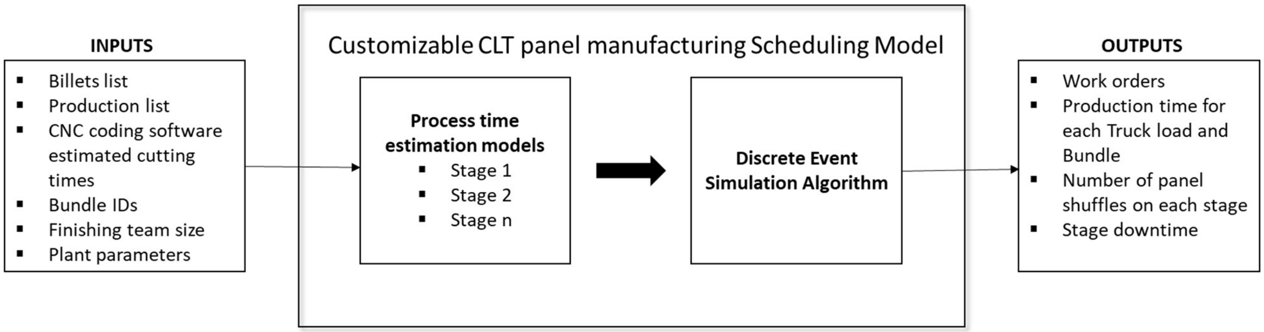


Figure 1-1 - Customizable CLT panel manufacturing Scheduling Model organization

The simulation algorithm applied to the scheduling problem is applicable to other manufacturing set ups and/or different products, as long as they are subject to similar production stages, rules and scheduling constraints. Figure 1-1 shows how the process time estimation models and scheduling algorithm compile the proposed customized CLT panel manufacturing scheduling model.

1.3 Study methodology

The focus of this research is to provide a feasible solution method to customizable CLT panel job scheduling problem, adaptable to different plants and production scenarios provided by the end user, under sequenced load and limited buffer conditions. The aim of the scheduling algorithm is to minimize the number of job shuffles at the buffer areas and the average bundle completion time. As discussed earlier, there is no specific scheduling solution algorithm to address customizable CLT panel manufacturing, accounting for these specific product and plant constraints.

The scheduling model demands a variety of project-related inputs such as panel dimensions, loading and project assembly sequence, and plant-related parameters such as buffer area and production stage capacity and current status. The simulation algorithm relies on process time estimation models and scheduling dispatching rules for each production stage. Both process time estimation models and dispatching rules, were developed based on comprehensive production process observation, field and management personnel expert opinions.

To achieve this main goal, the objectives outlined in section 1.2 were achieved in multiple research phases. The main inputs and outputs for each phase and their interrelations are outlined according to the diagram shown in Figure 1-2.

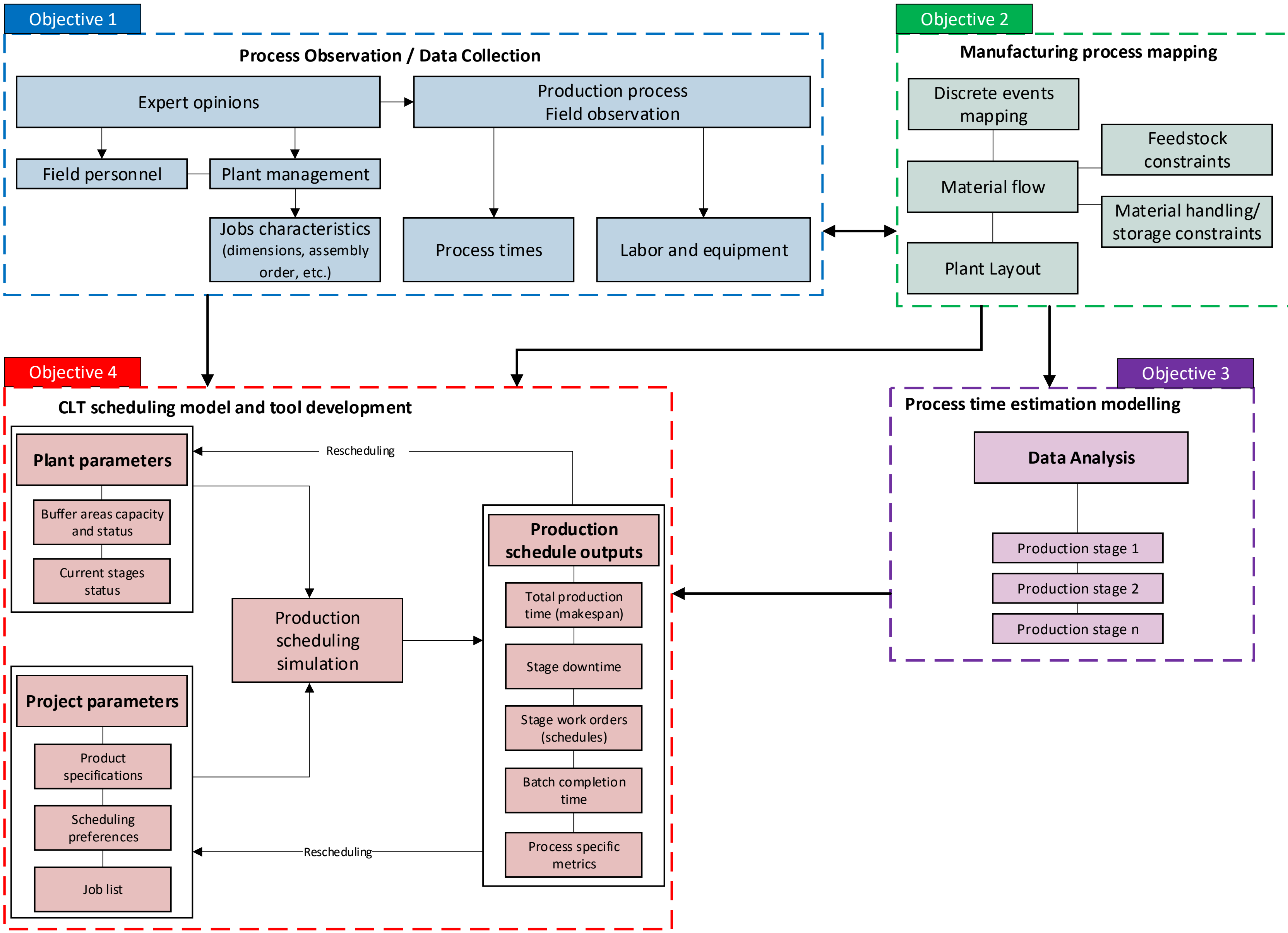


Figure 1-2 - Study objectives, inputs, outputs and interrelations diagram

Objective 1 comprises the data acquisition process, including expert opinions and the production process field observations. Project parameters, process time, labor and equipment employed in production were considered.

Objective 2 consisted of the production process mapping and parameter identification. First, all CLT production stages in the plant were identified and the production constraints of each stage defined. Next, the plant field and warehouse were mapped and the production stages in the scope of this research were placed. The material flow was observed, and the most significant events in the production process were identified.

Objective 3 counted on the inputs provided by Objectives 1 and 2 which were developed simultaneously. The collected data from field observations in Objective 1 allowed for regression analysis to be performed and to develop the process time estimation models for each production stage. The process time estimation models provided reliable, plant-specific process times for every job (CLT panel) in a project, given a set of panel characteristics, equipment, and labor definitions. The outputs of the time estimation models (i.e., process times for each job on each stage) work as inputs to the scheduling algorithm. The process mapping simultaneously provided the necessary information regarding plant organization, equipment and buffer capacity, and labor performance, necessary to develop the scheduling algorithm. Each previous phase contributes to the final goal.

Objective 4, which relied on outputs from objectives 1-3, was comprised of defining the production rules and identifying the logical decisions for each step of the studied process.

The combination of each production stage's constraints, capacity, and limitations, with the logical decisions for intermediate storage placement, and job scheduling for each time step composes the empirical scheduling algorithm. The scheduling algorithm is generalizable (i.e., it can be applied to any CLT production set up, as the input parameters are configurable and can be changed to account for different plant settings such as different buffer area capacities).

The detailed methodologies for each of the four sub-objectives listed above are described in Chapter 3 (for objectives 1, 2 and 3), and in Chapter 4 (for objective 4).

Finally, the scheduling model was bundled into a user-friendly Excel-based tool. The production simulation tool provides production schedules for each stage as the main outputs. Each job in the project can be tracked as it progresses in the production line. Every production task or logistic event (such as panel shuffles and temporary stacking at buffer areas) are tracked and listed in specific production schedules. As the scheduling simulation progresses, different project metrics, such as total makespan, stage downtime, number of panel shuffles, and bundle or truckload production time, are computed and reported. During production, whenever the plant manager feels it necessary, new plant and unfinished jobs databases might be re-fed in the tool for rescheduling.

1.4 Thesis outline

This thesis is organized into five chapters. Following this introduction, Chapter 2 presents a literature review of CLT specifications and production processes, manufacturing scheduling problems and process time estimation models, as well as a discussion of different solution methods previously used in literature.

Chapter 3 outlines the development of the process time estimation models for each CLT manufacturing production stage scoped in this thesis. A detailed description of a customized CLT panel manufacturing process, mapped in a real-world plant set up, is also shown and discussed in Chapter 3.

Chapter 2: Literature review

In this chapter basic concepts regarding CLT specifications and production processes, manufacturing scheduling problems formulations and solutions, as well as manufacturing process time estimation models are discussed. Important product characteristics of CLT and its manufacturing process, which may have influence regarding the scheduling problem, are explained. A few possible approaches for the development of manufacturing process time estimation models are described. Finally, the current body of knowledge regarding manufacturing scheduling problems, feasible solutions and modeling approaches are explored.

2.1 Cross Laminated Timber (CLT)

Cross Laminated Timber is an engineered wood product composed of perpendicularly assembled wood board layers glued together with structural adhesives through mechanical methods. CLT is a very versatile product accepting several project-dependent assembly options such as exterior walls, separation and partition walls, floors and roofs (Crespell and Gagnon 2010). Figure 2-1 is a schematic representation of a CLT panel.

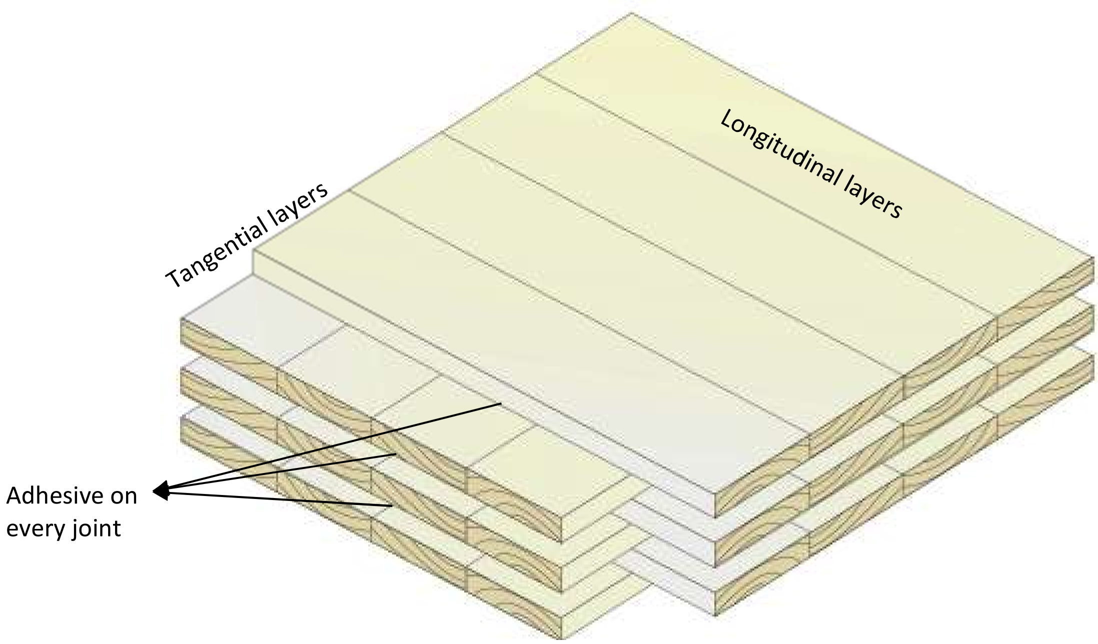


Figure 2-1 - Schematic representation of a CLT panel - modified from (Crespell and Gagnon 2010)

CLT manufacturing and construction in Europe have experienced extraordinary growth rates. New northern European plants are being installed in Finland and Sweden, as existing German, Austrian and British factories are being enhanced to increase capacity (Jauk 2017). Despite the concentration of production in western Europe, North American factories have been continuously investing and starting new projects. The United States (US) and Canada have been investing substantial amounts in CLT research, and in 2018, at least two large scale projects are expected to be realized in North America (Jauk 2017). In 2017, Natural Resources Canada (NRCan) released the Green Construction through Wood (GCWood) Program to foment the use of engineered wood in construction projects in Canada. The program provides financial incentives up to 100% of the incremental costs associated with designs, approvals, construction materials and methods, for the demonstration of innovative mass timber buildings (Natural Resources Canada (NRCan) 2017).

This growth trend is delivered through the combination of new CLT-related businesses and the expansion of existing manufacturers (Pei et al. 2016). Currently four different manufacturers operate CLT production lines in North America: two in Canada, and two in the US. Both Canadian factories focus on structural/architectural uses of CLT, as the US-based companies have a diversified production of structural/architectural applications as well as CLT panels for temporary roads and heavy industry purposes (Grasser 2015).

Recently, the world's tallest wood building was completed in Vancouver, BC. An 18-story student housing apartment building located at the University of British Columbia, Vancouver Campus. The structural CLT panels used in the floors were manufactured by Structurlam, one of the Canadian manufacturers, located in Penticton, British Columbia. The whole structure of the building was completed in only 70 days, showing how productive field activities can be when working with modular wood components.

CLT-related applied research in North America has basically focused on technical aspects of the product such as structural performance, serviceability, fire performance and product set up variations (Pei et al. 2016). The product's sustainability credentials were taken as extremely valuable when choosing to adopt CLT as a construction material (Jones et al. 2016). A US-wide survey revealed that almost 70% of 351 architecture firm professionals believe that CLT's environmental performance, structural performance and aesthetics is excellent or good, when compared to other construction materials (Laguarda Mallo and Espinoza 2015). In Europe, a similar study revealed that manufacturing issues such as optimization of computerized cutting, perforation rates of connections, and modular fabrication are suggested research topics regarding

CLT (Espinoza et al. 2016). Customizable CLT manufacturing process management and production scheduling are yet to be tackled by applied research.

2.1.1 Product regulation

In 2012 the growth of CLT in the North American market reached a point where a product standard had to be developed to qualify it for engineering design. The first performance-based CLT standard developed in North America was a collaboration of APA (Engineered Wood Association) and FPInnovations (Pei et al. 2016).

The developing process started in 2010 in a bi-national (US and Canada) effort to release an ANSI (American National Standards Institute) approved standard, the ANSI/APA PRG 320 – Standard for Performance-Rated Cross-Laminated Timber. Whereas ANSI/APA PRG 320 is based on European experience and manufacturing process, the standard considers the North American lumber resource (native species), manufacturing preferences and user-oriented criterion (Yeh et al. 2012). The standard provides dimensions and tolerances, performance requirements, test methods, quality assurance and trademarking for CLT panels, addressing the following main topics, according to (ANSI and APA 2017; Yeh et al. 2012):

- Panel dimensions and dimensional tolerances – dimensional requisites and tolerances for thickness, squareness and straightness;
- Component requirements – lamination options (lumber or structural composite lumber) lumber species, lamination sizes, moisture limits, adhesives and joints requirements;
- Performance criteria – panel layup requirements, custom grades, stress classes, appearance classifications;
- Qualification and product marking – plant and product qualification requirements, test methods and performance requirements for end-specific qualifications;
- Quality assurance – process control, finished product inspection attributes.

Discussions to prepare an ISO (International Organization for Standardization) standard for CLT were initiated in 2010, after approval from the ISO task group on Timber Structures (ISO TC 165) (Mohammad et al. 2012). However, an ISO equivalent to the ANSI/APA standard is still under development.

2.1.2 Customizable CLT panel manufacturing process

A handful of studies have described, explained and standardized CLT manufacturing processes, in Europe, North America and Asia (Brandner 2014; Flatscher et al. 2016; Liao et al. 2017).

Industry-sponsored fact sheets and information materials superficially and profoundly described the production process, highlighting the production stages, panel layup options and factory quality and production control procedures (Crespell and Gagnon 2010; Gagnon and Pirvu 2011). Customizable CLT production consists in manufacturing structural-, mechanical- or architectural-grade CLT panels according to client-specific production data. Each part in the project will have specific features such as cuts, chamfers, drills, holes, aside from its specific geometry (form, length, width, thickness), structural grade, visual grade, etc. The essential production process remains the same, however, due to differences in each panel configuration, process times and production constraints and parameters may change from panel to panel.

In the next sections the general CLT manufacturing process is going to be described, and the main production parameters outlined. Understanding the production process of critical operations, in depth, is crucial in order to map, model and simulate the manufacturing procedure, and thus improve productivity (Kumar and Phrommathed 2006). A customizable CLT production line is represented according to Figure 2-2, and described below, following the guidelines presented in (Wang et al. 2011) and (Brandner 2014).

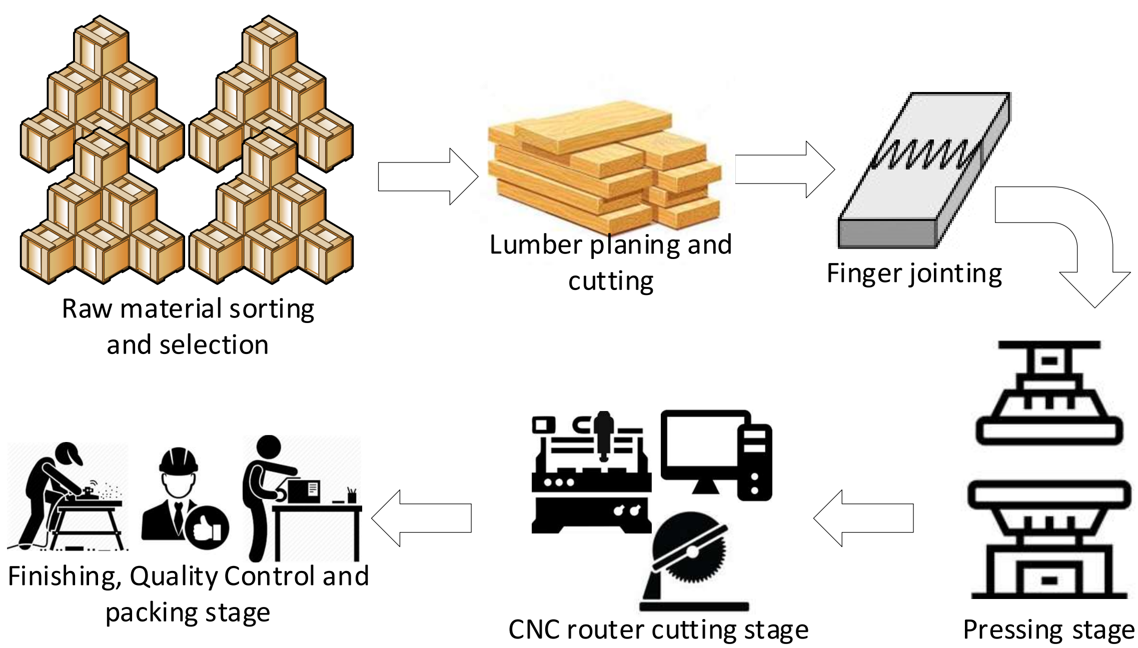


Figure 2-2 - Illustrative scheme of a general CLT production line

2.1.2.1 Raw materials

Raw materials needed for CLT production are essentially lumber and adhesive. CLT may be manufactured from a wide array of species in North America. Although Canadian and U.S.

regulations are different (CSA O141 and PS 20, respectively), lumber selection for CLT production purposes are primarily from structural dimension lumber or boards. Species mostly used in the Canadian market are spruce-pine-fir (SPF) and Douglas-fir (Structurlam 2016). Adhesives traditionally used for other engineered wood purposes may be adopted for CLT applications. Structural-classed adhesives that may be used include phenol-resorcinol formaldehyde (PRF), emulsion polymer isocyanate (EPI) and one-component polyurethane (PUR). Each plant configuration, panel setup, and lumber/adhesive couplings, may have specific ideal production parameters that should be reached to maintain product standards and quality (Gagnon and Pirvu 2011).

Table 2-1 outlines important characteristics of wood bonding adhesives. One-component polyurethane adhesives are vastly used, both in Europe, as well as in Canada, due to its higher safety and zero formaldehyde emission levels (Scalet 2015).

Table 2-1 - Wood bonding adhesive characteristics - modified from (Gagnon and Pirvu 2011)

Item	Units	Adhesive		
		PRF	EPI	PUR
Cured adhesive color		Dark	Light	Light
Component		Liquid, two components	Liquid, two components	Liquid, single component
Solids content	(%)	50	43	100
Wood moisture content (MC)	(%)	6 - 15%	6 - 15%	more than 8%, optimal 12%
Target application rate	(g/m^2)	375 - 400 (75 - 80 lb/msf)	275 - 325 (55 - 65 lb/msf)	100 - 180 (20 - 35 lb/msf)
Assembly time	(min)	40	20	45
Pressing time	(min)	420 - 540	60	120
Applied pressure	(psi)	120	120	120 – 200
Relative cost comparison (Grøstad and Pedersen 2010; Messmer 2015)		$	$$	$$$
Environmental performance (Grøstad and Pedersen 2010; Messmer 2015)		poor	good	average

2.1.2.2 Preliminary stages

In preliminary stages, raw material sorting, selection and control is performed. CLT raw material (wood boards) are inspected, selected, planed, cut and finger jointed. In industrial custom CLT plants, primary lumber selection, drying and grouping are made directly from the wood board suppliers. Raw materials come to the plant in adequate conditions to start being processed. A moisture content of 12% (+/-3%) and ideal wood temperature should be targeted as the bonding performance and curing time of adhesives are affected by both parameters.

After a first visual inspection on the unwrapped material, raw lumber boards are then planed (or surfaced). This process consists of removing a very thin layer of wood from both faces of the board, ensuring dimensional consistency, as well as removing oxidized material and ensuring better bonding conditions (Julien 2010).

Finally, the lumber boards are then cut to the desired length, according to the application (longitudinal or tangential layers). Depending on how long the intended panels are, longitudinal finger jointing may be required. Finger jointing is an economical method to increase longitudinal dimensions but maintaining the target strength at the main section of the board. Finger joints may be edgewise (fingers showing in the larger sectional dimension) or flatwise (fingers showing in the narrow face), as illustrated in Figure 2-3. The advantage of flatwise jointing is basically aesthetics, as no joints would be visible in the surfaces of the panel (Flatscher et al. 2016). It may be needed to apply special adhesives to the joints aiming to minimize stress concentrations in the fingers. Additionally, the coincidence of joints with wood knots may also cause reduced stress resistance (Flatscher et al. 2016).

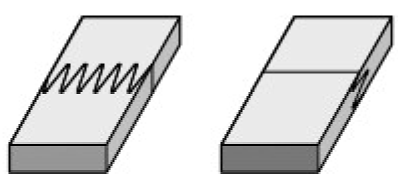


Figure 2-3 - Edgewise (left) and flatwise (right) finger jointing - extracted from (Brandner 2014)

2.1.2.3 Pressing stage

The next step in CLT production process is to glue the wood board layers together. The most influential factors affecting mechanical proprieties, and therefore, overall panel quality are the adhesive spread rate and pressing strength and time (Liao et al. 2017). Each of these factors must be carefully defined depending on which CLT application and configuration is intended.

First, the selected glue is applied in a through-feed process with parallel lines of application heads with direct supply of adhesive. After each layer, the adhesive application process is repeated. Adhesive application should occur within 24hrs of the planing process to ensure surface receptibility and dimension stability of the wood. The surface bonding procedure should happen with no disruptions to avoid adhesive pre-curing processes before pressing.

The actual panel pressing may be performed through hydraulic press equipment, vacuum press equipment or even utilizing screws, staples or nails. Nevertheless, the bonding pressure generated by mechanized means is considerably higher. Between hydraulic and vacuum presses, the former can generate much higher vertical and side pressure. The main variables defining the bonding process are defined to guarantee complete adhesive wetting of the glued surfaces, as well as to allow a specific bond line thickness. Additionally, vertical hydraulic presses may allow for more than one panel to be pressed together (Julien 2010), greatly increasing process productivity. Longer than prescribed pressing times do not impact adhesive bonding quality.

2.1.2.4 Computerized numerical control (CNC) router cutting stage

Up to the previous stage, customizable and standard industrial CLT panel production is essentially the same. Form this point on, the production process incorporates customizable features to CLT panels aggregating value. Drilling, cutting, milling and trimming are performed by computer-aided equipment, allowing maximum cutting accuracy and detail. CNC router machines are capable of processing large-sized CLT panels using tools (molding cutters, saws, chain saws, etc.), and following specific sequential instructions provided by a computer code (Gagnon and Pirvu 2011).

CLT process centers composed of one or more CNC machines may be assembled parallelly, depending on the production volume and market demands, allowing for a continuous production line. Different process centers may allow for distinctive features among each other, granting flexibility and covering several market applications (Flatscher et al. 2016). This stage may not be necessary, depending on product application and panel characteristics.

2.1.2.5 Finishing, quality control (FQC) and packaging stage

The last stage in the production line will provide the final details and finishing touches to customizable CLT panels. In this phase, minor repairs, face sanding, as well as features which are not executed by the CNC, are carried out manually. Quality control, packaging and labeling are also performed at this stage. Measurable attributes, dimensional requirements and tolerances are checked. General quality attributes such as surface finish type (sanded or stained), finishing consistency, labeling, splinters, corner damage, among others, are inspected. In some custom-focused production set ups, surface sanding may be performed by industrial sanding machines prior to the CNC cutting stage (in case that stage is present).

Finally, panel labelling, and packaging are executed. Labelling is important to ensure the correct product category, part and specification is being delivered and installed. Labelling also identifies the manufacturer and indicates that quality-assurance procedures have been made.

Factory wrapping is important to protect finished panels from direct moisture, and light mechanical damages. Several panels are packed together as bundles, following strict loading and truck shipping constraints. Product packaging is also closely related to the truck loading and transportation procedures of finished panels to site, as well as the assembling vs loading/unloading order required for construction (Structurlam 2014).

2.1.2.6 Material handling, loading, unloading and storage

Although finished product handling may be considered a special-cause variation aspect for CLT production (Grasser 2015), on a smaller scale, material handling, loading, unloading and storage may also impact CLT quality. Moreover, material handling procedures have significant impacts on overall process and plant productivity (Kulak 2005).

According to Structurlam's material handling guidelines (Structurlam 2017):

- CLT panels are usually shipped on flat deck trucks following the installation order for each part in the project. Sequenced loads are a valuable resource for space-constrained construction sites as the CLT panels may be unloaded directly to their assembly positions;
- Package bundles are usually separated by dunnage pieces allowing for forklift or crane unloading;
- Panel handling should be made with fabric or plastic belts with corner protection. Chains and cables may be used with appropriate blocking or padding to protect panels from damage;
- Storage location should allow for air flow around panels and avoid precipitation and UV damage.

All precautions and requirements described for the finished product must also be taken in the plant environment when dealing with unfinished products. As panels are stored separated by dunnage pieces, forklifts may be used to move and shift more than one panel from a stacking pile to another with just one single operation (depending on forklift weight capacity and panel geometry).

2.2 Production process time estimation modelling

Process times for each job is arguably the most important input / parameter for manufacturing scheduling modelling (Liu et al. 2013a; Zhu et al. 2013). Analytical scheduling methods are extremely data-dependent, especially for parameters closely related to the objectives of the optimization problem. Basically, all time-related project metrics and optimization objectives are dependent on the process time of each job in each stage of the scheduling problem. Process time is also considered as one of the most important factors to estimate the total production cost of products (Niazi et al. 2006).

However, the build time of products in real-life industrial manufacturing systems is a complex parameter depending on machine-, process-, and product-specific variables. Whereas manufacturing scheduling studies usually assume that the process times for the scheduled jobs in their demonstration cases are known parameters, this is hardly the case in real-life situations. Unless a previously defined process time calculation methodology has been developed for the products and processes at hand, plant management will not be able to foresee, in a systemic way and within a reasonable error margin, the manufacturing time of their products on each production station.

Manufacturing processes may be classified in additive (e.g., 3D printing) or subtractive (e.g. CNC router cutting) techniques. Assembly techniques may be employed to complex structures and combined to additive or subtractive in hybrid approaches (Zhu et al. 2016). According to the method described in section 2.1, the customizable CLT panel manufacturing process is a hybrid assembly and subtractive system.

In literature, build time estimation models have been developed for assembly, additive and subtractive manufacturing techniques (ASM, AM, and SM, respectively). Several modelling approaches have been applied, depending on the production method, significant variables and data availability. Boothroyd et al. (2011) developed a data intensive assembly time estimation method based on empiric evidence from field observations in assembly plants (Boothroyd et al. 2011). Each part received code parameters to identify characteristics such as length, thickness, and symmetry, among others. Two subcomponents of the estimated assembly time were calculated based on parts' parameters: the handling time and the insertion time for each part. Namouz and Summers (2013) proposed a different approach for the ASM time estimation model (Namouz and Summers 2013). The Complexity Connectivity Metrics (CCM) method uses several graphic complexity metrics to estimate the assembly time of a product. The relationship between the complexity metrics and the assembly time was first established by a linear regression model, and then, expanded to a trained artificial neural network to improve predictive capability (Miller et al. 2014; Namouz and Summers 2014). The complexity metrics are composed of 29 different graphically-determined parameters to represent how difficult each part is to be mounted in one another. The developed model, if applied in a systemic architecture during the design phase of products, may be capable of incorporating assembly time analysis in computer-aided design (CAD) models (Mathieson et al. 2010).

Like SM, AM productivity has improved through time, however, one of the most important drawbacks of AM are still the long build times observed in those processes (Han et al. 2002). Researchers from Greece developed two build time estimation models for thermal extrusion additive manufacturing, one analytical and one empirical model. The analytical model relied on kinematic analysis of the path, velocity and acceleration determined by the part design and equipment employed in the manufacturing process. The empirical build time model considered the geometric features of the part and the extruded filament to define the total surface area and distance the machine has to cover. Based on the extrusion velocity and the allowed percentage fill for the part, the total build time is calculated. When compared to real production times, the analytical model deviated about 1.7%, and the empirical 4.2% (Komineas et al. 2018). Other analytical (Zhu et al. 2016) and empirical (Zhang et al. 2015) approaches for AM build times also relied on geometric characteristics of the produced parts and employed equipment productivity parameters.

Regarding SM process time estimation models, four different categories might be found in literature, according to Liu et al. (2013):

1. Estimation based on material removal rates – considers the amount in volume or weight from the mother piece that is removed during the cutting process;
2. Process time based on CNC software system estimation tools – calculates the cutting time based on the machine feed rates and total path length of operating tools;

3. Estimation based on CNC cutting code (features) and machine characteristics – both empirical and analytical approaches might be employed to define the relationship between machine feed rate, tool path and production time;
4. Artificial intelligence-based models – relies on complex reasoning and modelling techniques to predict machining time based on object characteristics, empirical data and uncertainty analysis.

Regarding estimation based on material removal rates, Hbaied et al. (2011) investigated the roughing time for pocket machining as a ratio of the removed material rate and the pocket volume. The method considered five components to total production time: cutting time at standard work feed rate, cutting time at rapid feed rate, time to change tools, time to unload and load tools, and auxiliary time related to operation uncertainty (unproductive time due to machine preparation, production planning and adjustment (Hbaieb et al. 2011).

In feature- and machine characteristics-based SM process time estimation, Liu et al. (2013) proposed a feature-based method to estimate cutting CNC time. The model identifies the basic features from a CAD model and generate a code list of processes based on each parts' geometry. Following, based on machine characteristics, a specific machine code is generated, defining sequence, parameters, used tools, and machine speed for each operation. Finally, the process time is calculated based on the previously defined parameters (Liu et al. 2013a).

Considering the shift from well-defined (deterministic) to ill-defined (stochastic) parameters in the flat plate processing industry, Jahan-Shahi et al. (2001) proposed a fuzzy-based model to estimate production cost and time. Non-process variables effects on activity time variation were studied and empirically-determined allowances were found to twenty different variables. Following, these variables and allowances were used to subjectively generate multi-valued fuzzy sets. The fuzzy sets were then applied in an estimation algorithm to calculate the production cost and time for each part cut from a plate (Jahan-Shahi et al. 2001).

Analyzing the ASM, AM and SM process time modelling techniques described above, is possible to note that there is no one-fits-all rule to determine which method should be used. The modelling method of choice is influenced or sometimes even determined by data availability constraints and modelling objective. Some techniques result in easily developed and applicable models with modest data requirements but provide rough estimates. However, depending on how the model is being applied, highly precise process time data is not necessary. Other modelling approaches might result in very precise models but require virtually impractical amounts of product- and equipment-related information. The "ideal" model should be tailor-made to the desired application and provide no more than the necessary precision of the forecast information. At the same time, the model should only demand reasonable and easily acquired input data.

2.3 Manufacturing scheduling problems

Manufacturing, in a classical definition, is the process of converting raw materials into finished products on a large scale, employing human-aided or autonomous transformation processes. Standardization and repetition in manufacturing aim to improve the quality and reliability of mass-produced products, as well as the overall productivity of the process. Job production order and allocation of plant resources, or manufacturing schedule (Gen and Lin 2014), is crucial to improve productivity in the system and optimize costs (Sun and Yu 2015). Additionally, frequent changes and unreliable production schedules significantly impact process productivity and may cause quality problems (Vieira et al. 2003).

Scheduling problems consist in defining the job processing sequence and allocating resources to perform manufacturing tasks, pursuing specific objectives. These objectives are directly or, sometimes, indirectly impacted by the chosen schedule and can be expressed as a function of job completion times, or even metrics relating to energy consumption or production costs, and, among others, possible metric combinations.

Thus, countless research exercises, academic and industrial studies were dedicated to defining and standardizing job scheduling problems, evaluating and improving job scheduling mechanisms, aiming to achieve a variety of objectives, applicable to numerous theoretical and real-case situations. Manufacturing scheduling problems are usually divided in the following categories:

2.3.1 Flow shop

A flow shop problem is a process system in which the task sequence for each job is the same and previously specified. For example: assume that in a three-machine production system the production sequence is machine one, then machine two, then machine three. Thus, in flow shop problems, every job in that production system must follow the same sequence. Additionally, most studies consider that in flow shop systems, no job should, in ordinary conditions, revisit any stage (Emmons and Vairaktarakis 2013).

A particular type of the flow shop problem is the permutation flow shop in which the order each job is processed on each machine is the same in every step of the production process.
Hybrid flow shop problems incorporate additional constraints and limitations to the manufacturing model such as intermediate limited job buffers, additional parallel resources, job batching, etc.
A flexible flow shop problem implies that some tasks can be performed by more than one single resource, i.e., parallel machines, and these resources can be identical, uniform or unrelated (Zandieh and Gholami 2009).

- *Identical parallel machines* – in the flexible flow shop problem (FFSP), whenever parallel machines have exactly the same processing times and operation procedures for similar jobs, they are regarded as identical machines. About 80% of FFSP in literature focus on identical parallel resources (Lee and Loong 2019).
- *Uniform parallel machines* – resources which run with different speeds (i.e. different output in terms of completed tasks per unit of time) but have the same operational procedures and constraints. Therefore, the process times for similar jobs are proportional and dependent on the running speed of each parallel machine (Mirsanei et al. 2011).
- *Unrelated parallel machines* – sometimes, especially in real-world applications, newer machines with different capacities are added to a production line to either balance each stage outputs or to increase the total production system productivity (Ribas et al. 2010). In unrelated machines the processing times of each job depend specifically on which machine it is going to be processed, due to differences in the machines themselves.

Most studies simplify the scheduling problem assuming that there is enough space on intermediate buffer areas to stock intermediate jobs. Nevertheless, in real-case applications, that is hardly the case. In real world applications, limited buffer capacity must be accounted for. Whenever an intermediate buffer is full, job delays and stage blocking implications may occur (Li and Pan 2015).
Moreover, each stage process times may be affected by the actual processing sequence determined by the schedule. In that case, sequence dependent process time schedules, are even harder to be optimized (Pinedo 2008).
Additionally, job batching, or lot streaming refers to combining jobs to enter production stages and advance as a group. This constraint increases the complexity of the problem, as more

analysis must be made in order to define the best combination of jobs to join the batched stage together, besides the scheduling order itself (Paolucci and Sacile 2005).

Finally, the flow shop problem may be applied in deterministic or stochastic manners. Deterministic scheduling problems assume that job and resources parameters are known and do not account for possible unknown variations in these attributes. Stochastic or robust models assume that jobs and resources parameters are not known in advance, except for an indicative distribution of their true values. Each of these parameters will become known after the completion of the scheduling process and the actual occurrence of the production (Pinedo 2008).

Figure 2-4 represents a hybrid m-machines flexible flow shop.

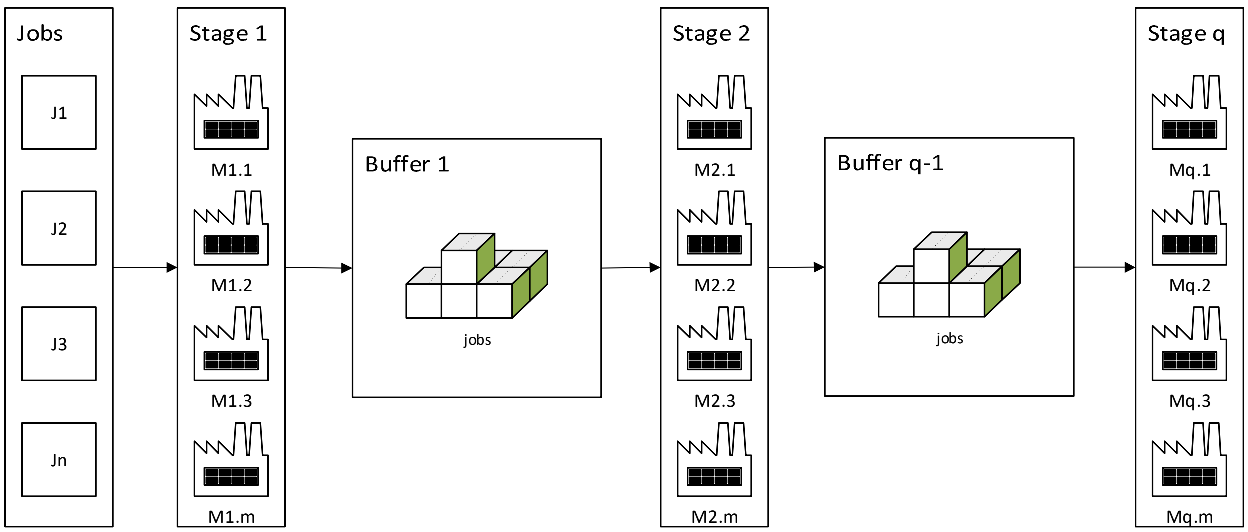


Figure 2-4 - Representation of a generic n-job, m-machine and q-stage hybrid flexible flow shop problem

Several studies are focused in exploring new constraints that may be applicable to a real case scenario and represent them in a modeled scheduled problem. However, flow shop problems with variable buffer capacities and sequenced job load constraints were explored. A permutation flow shop problem considering transportation time and sequence dependent setup time for each stage, and simultaneously minimizing total makespan and energy consumption was studied in 2017 (Lu et al. 2017). Previously, Sawik (2012) proposed three mixed-integer programming scheduling solutions considering no added constraints, batching and cyclic scheduling. Total processing time, buffer allocation and machine downtime were compared (Sawik 2012). A hybrid flow shop with identical machines and sequence-dependent setup times to minimize makespan (Mirsanei et al. 2011), or focusing in the bottleneck stage (Liao et al. 2012) were also explored in literature. Yalaoui et al. (2013) dealt with a hybrid flow shop with pre-assigned jobs, non-identical parallel machines and non-compatibility between certain jobs and certain machines, aiming to minimize the total tardiness time (Yalaoui et al. 2013). Shahnaghi et al. (2016) adopted two robust models to solve a flow shop system with batching in uncertain times and job sizes to minimize the maximum tardiness (Shahnaghi et al. 2016).

On the other hand, other studies focus directly in a real-life production line and try to mimic its constraints to a simplified model, “fitting” the real production process in a flow shop problem, such as a two-stage hybrid flow shop problem to solve the manufacturing scheduling of composite aerospace components. Limited buffer, waiting time and tools/molds constraints were used in both stages of every production cycle (Azami et al. 2018). Long production lines have also been modeled like a sixteen-stage process with sequence-dependent setup times and batching to minimize weighted tardiness in a steel manufacturing company with a large number of different products (Voß and Witt 2007). Gholami-Zanjani et al. (2017) studied a printed circuit board assembly line, modelling it to a sequence dependent flow shop with uncertain process and setup times, minimizing weighted mean flow time. Sun and Yu (2015) studied the steelmaking casting process considering batching constraints and variable processing times, aiming to minimize the total weighted completion time (Sun and Yu 2015). Jun and Park (2015) addressed the transformer industry, modelling the production system as a hybrid flow shop with nighttime and simultaneous work constraints minimizing the total tardiness (Jun and Park 2015).

2.3.2 Open shop

In open shop scheduling problems, like the flow shop model, each job needs to be processed in every production stage, however, the task sequence is not specified and can change from job to job. This model set up allows for such freedom to schedule jobs that, almost all possible schedules are optimal, in terms of total makespan (Emmons and Vairaktarakis 2013). Figure 2-5 depicts a 3-machine and 3-job open shop problem.

Breit et al. (2001) studied a simple two-machine open shop with machine availability constraints to minimize total makespan (Breit et al. 2001). Campos Ciro et al. (2016) analyzed an open shop problem with a multi-skill resource constraint (checking for the number or resources that can perform different tasks), minimizing total flow time (Campos Ciro et al. 2016).

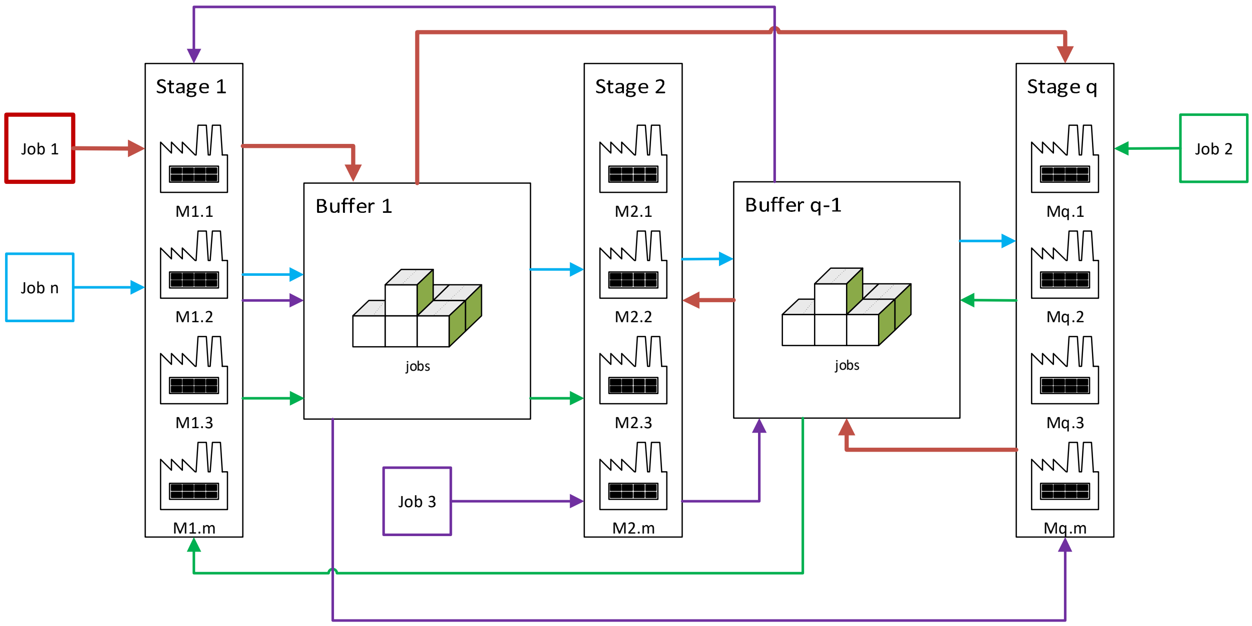


Figure 2-5 - Representation of a generic n-job, m-machine and q-stage open shop problem

2.3.3 Job shop

The job shop model is the broadest manufacturing configuration where every job may be processed in each machine or production stage in a different order, relaxing the limitations imposed by the flow shop and open shop models. Consequently, due to the exponentially increased combination of possible schedules, the job shop model is considered the most difficult type of scheduling problem. Figure 2-6 represents a generic job shop manufacturing model. Jong et al. (2014) and Jong and Lai (2015) addressed the plastic injection mold manufacturing system and modelled it as a job shop, non-polynomial scheduling problem, to minimize total makespan (Jong et al. 2014; Jong and Lai 2015). Burnwal and Deb (2013) analyzed a theoretical flexible job shop system minimizing the penalty cost due to delay and maximizing machine utilization time (Burnwal and Deb 2013). Mokhtari and Hasani (2017) proposed a general flexible job shop problem to develop an energy-efficient scheduling algorithm to minimize total completion time, maximize total system availability and minimize total energy cost (Mokhtari and Hasani 2017).

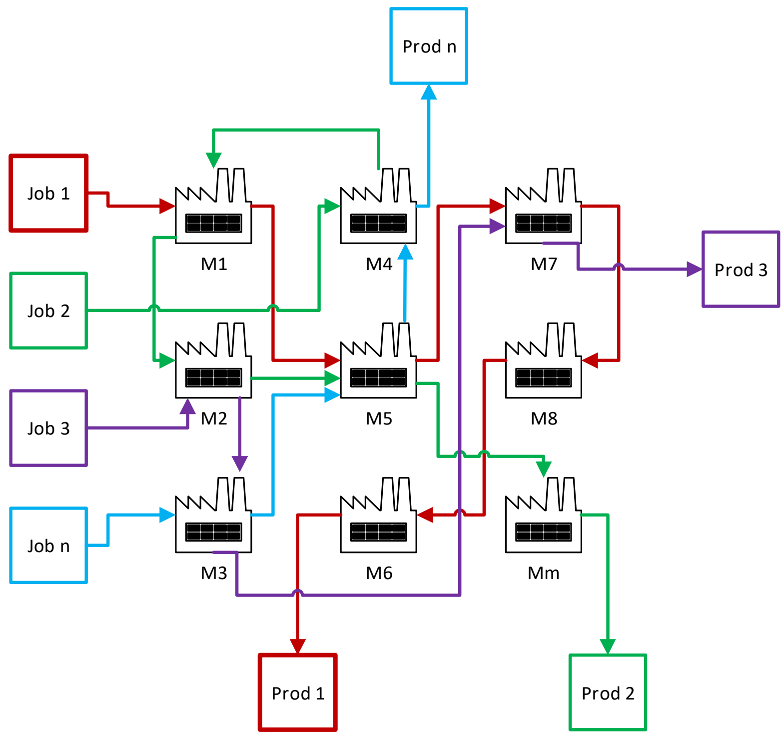


Figure 2-6 - Representation of a generic n-job and m-machine job shop problem

2.4 Scheduling methods

Finding solutions for manufacturing scheduling problems is not an easy task. Finding an optimal solution considering a certain single or a set of objectives is even harder and may not be achieved within reasonable computation time and operational resources. A simple 10-jobs, 3-stages flow shop scheduling problem may have a set of 10! viable solutions. Expanding this same problem to a job shop configuration, the number of viable solutions may be as many as (10!).

Therefore, due to the extreme computational effort to achieve optimal solutions, especially in real-life and large-scale manufacturing problems, the focus has been shifted to find methods and techniques that would reach more feasible, near-optimal solutions.

A multitude of different scheduling methods were developed for over 50 years. Nevertheless, note that no method can completely outperform others in every criterion (i.e. how close the proposed solution is to the optimal, computational time, simplifications and assumptions, etc.). Some applications are better suited to one technique or another. However, regardless of the used technique, simplified theoretical models are hardly applicable to real-life scenarios in industry (Kang and Choi 2013).

To find the quality of the solutions provided by a certain scheduling algorithm ($Method$), their solution metrics should be compared with the ($Best$) and ($Worst$) solutions found by other scheduling algorithms applied to the same problem. This can be determined by the Relative Deviation Index (RDI) (Emmons and Vairaktarakis 2013; Jun and Park 2015; Vallada et al. 2008; Yu et al. 2018) which is stablished as:

$$\boldsymbol{RDI = \frac{Method_{solution} - Best_{solution}}{Worst_{solution} - Best_{solution}} \; 100\%} \qquad \textbf{Equation 1}$$

Finding the best suited method and best modelling technique, considering assumptions and simplifications, have been the focus of research in the last few decades.

2.4.1 Heuristic algorithms

Standard linear programming methods are often limited due to their excessive computational time. Thus, heuristic algorithms are solution-based approaches that focus on finding a feasible, near-optimal solution to scheduling problems, within reasonable computational demands. In constructive or single-pass approaches, a single permutation is found. Interactive heuristics (multi-pass) try to improve on the previously found solution by exchanging jobs in the schedule. Heuristics may involve different methodologies such as single- and multi-pass rule-based scheduling, modified branch and bound algorithms, and local and disjunctive arch search techniques (Kolisch 1995).

The very first known heuristic method for scheduling problems, Johnson's algorithm, was developed in 1954 for the two-stage flow shop problem to minimize makespan (Allaoui and Artiba 2009). This algorithm is an example of constructive heuristics, where the method allows to build a feasible schedule solution from scratch. Improvement heuristics refer to methods that perform operations to improve a solution previously generated. A famous heuristic for the m-machines permutation flow shop problem, Nawaz-Enscore-Ham (NEH), was proposed by (Nawaz et al. 1983).

2.4.2 Metaheuristic algorithms

Although heuristic methods may be able to provide good solutions, they are difficult to be adapted to different problems, due to their rule-based approach. Besides, heuristics are "designed" to provide one single solution in a universe with many feasible schedules. Thus, there is a high probability that better solutions may be found (Jarboui et al. 2013).

Metaheuristics, on the other hand, refers to classical heuristics solutions which can be adapted to several production scenarios and applications. One of the most important metaheuristic capabilities is reaching a global near-optimum solution, instead of being locked in the local optimum of the function being optimized. This is done by temporarily accepting inferior combinations aiming to shift the search to other areas of the universe of solutions (Emmons and Vairaktarakis 2013).

According to Jarboui et al. (2013), there are two main metaheuristic methods:

- *Local search approaches* – based on a given or found solution, derives new solutions by exploring neighboring areas of the search space. Includes methods such as Simulated Annealing (Azab and Naderi 2015; Jungwattanakit et al. 2009; Liao et al. 2012; Mirsanei et al. 2011; Totah et al. 2017), Tabu Search (Baykasoğlu and Özbakir 2010; Jungwattanakit et al. 2009)(Li and Pan 2015), and Cuckoo Search (Burnwal and Deb 2013), among others.
- *Evolutionary methods* – consider a number of similar solutions (family) to mutate and evolve after each iteration into a better solution. The general designation of such methods is Genetic Algorithms. However, several other approaches can be found such as Ant Colony Optimization (Campos Ciro et al. 2016), Particle Swarm Optimization (Liao et al. 2012), and the Artificial Bee Colony Algorithm (Li and Pan 2015), among others.

2.4.3 Dispatching rules

The use of dispatching rules is a heuristic approach to solve job scheduling problems. Dispatch rules are essentially a set of conditions that will determine, which jobs should be scheduled next. These conditions are derived from attributes such as process times, tardiness, total makespan, jobs available in cue, and work remaining, among others. Attributes may be any propriety associated with any of the components in the shop environment (jobs, machines, buffers, etc.). Dispatching rules-directed studies have followed the history of manufacturing scheduling since the early days of operations management. Blackstone et al. (1982) developed a state-of-the-art review and compared dispatching rules including analytical approach, simulation and evaluation criteria. Although impossible to determine a specific rule to outperform the others, the authors verified that that some rules show satisfactory performance in some cases (Blackstone et al. 1982).

In the field of project scheduling, dispatching rules may also be known as priority rules. Priority rules consist in mathematical expressions that will somehow rank the available jobs for scheduling at each stage, choosing the first or last one in the rank. Priority rules are generally labelled with an acronym referring to their basic concept and extremum. For instance, one of the classical, mostly used, and best performing rules in literature for minimizing the mean flow time, mean tardiness and the number of tardy jobs, Shortest Processing Time, is known as SPT (Kolisch 1995). This rule is generally used as benchmark for several scheduling studies (Xiong et al. 2017).

Static dispatching rules are expressions that will return the same priority value for a certain job, no matter what time are they being evaluated. On the other hand, in dynamic rules the priority values and status of jobs changes through time, progress in the production line, position in cue, etc. Depending on the amount of information required and the reach (in terms of how many stages ahead, or behind in the production line) each attribute considered in a rule has, it may be classified as local or myopic (for a small amount of information in a single stage environment) or global (large amounts of information needed in several stages).

Finally, regarding their complexity, dispatching rules may be classified as simple or composite. Simple dispatching rules account for one or two parameters to sort and rank jobs. Composite rules are more elaborate and consider several parameters, resulting in rather complex formulations. Two or more simple rules may also be combined to generate composite rules.

It is important to note though, that balance, scale and nature of different parameters may be an issue in composite rules. Unbalanced rules may be brought to the same scale and account for parameters with different natures by adjusting weights or simply by scaling different priority values.

Table 2-2 shows, formulates and describes a small set of dispatching rules in literature often applied to scheduling problems. In the first section, only simple, basic rules are presented according to (Haupt 1989). In the second section of the table, composite rules are shown, and described. In the formulations shown below, $Z_i(t)$ is the priority value of job i at time step t.

Table 2-2 - Dispatching rules for scheduling problems

Rule	Formulation - $Z_i(t)$	Description and name
	Basic rules	
RANDOM	$min\ (X_{ij})$	X_{ij} is the value of a random variable for stage j of job i. The chosen job has the smallest priority derived from a **random value**.

Rule	Formulation - $Z_i(t)$	Description and name
FCFS or FIFO	$min\ (C_{i,j-1})$	C_{ij} is the completion time step for stage j of job i. Whichever job arrives first at queue has priority. **First come, first served or first in, first out**.
LCFS or LIFO	$max(C_{i,j-1})$	**Last come, first served or last in, first out**.
FASFS	$min\ (r_i)$	r_i is the release time step of job i. Whichever job arrives first at shop has priority. **First arrival at shop, first served**.
SPT	$min\ (p_{ij})$	p_{ij} is the process time for stage j of job i. The job with the **shortest process time** will have priority.
LPT	$max\ (p_{ij})$	The job with the **longest process time** will have priority.
LWKR	$min\left(\sum_{q=j}^{m(i)} p_{iq}\right)$	m is the total number of machines in the production line, and q is the index of remaining stages (1,2…m). The job with the **least work remaining (i.e. sum of the process times of all jobs in queue)** will be selected.
MWKR	$max\left(\sum_{q=j}^{m(i)} p_{iq}\right)$	The job with the **most work remaining** will be selected.
FOPNR	$min\ (m_{i-j+1})$	**Fewest number of operations remaining**.
GOPNR	$max\ (m_{i-j+1})$	**Greatest number of operations remaining**.
MTWF	$max\left(\sum_{j=1}^{m(i)} p_{ij}\right)$	Select the available job with **most total work first**.
LTWF	$min\left(\sum_{j=1}^{m(i)} p_{ij}\right)$	Select the available job with **least total work first**.
EDD	$min\ (D_i)$	D_i is the due date (delivery time step or date) of job i. Select the available job with the **earliest due date**.
ALL	$min\ (D_i - t)$	t is the current time step. The available job with the **smallest allowance** is selected next.
SL	$min\left(D_i - t - \sum_{q=j}^{m(i)} p_{iq}\right)$	Choose the job with the **smallest slack**.

Rule	Formulation - $Z_i(t)$	Description and name
CR	$min\left((D_i - t)\Big/\sum_{q=j}^{m(i)} p_{iq}\right)$	Select the job with the **smallest critical ratio**, which is the job allowance divided by the work remaining.
ALL/OPNR	$min\left(\frac{D_i - t}{m_i - j + 1}\right)$	**Smallest ratio of allowance per number of operations remaining**.
SL/OPNR	$min\left(\frac{D_i - t - \sum_{q=j}^{m} p_{iq}}{m_i - j + 1}\right)$	**Smallest ratio of slack per number of operations remaining**.
SL/WKR	$min\left[\left(D_i - t - \sum_{q=j}^{m} p_{iq}\right)\Big/\left(\sum_{q=j}^{m} p_{iq}\right)\right]$	The job with the **smallest ratio of slack per work remaining** will be chosen next.
SL/ALL	$min\left[\left(D_i - t - \sum_{q=j}^{m} p_{iq}\right)\Big/(d_i - t)\right]$	Select the job with the **minimum ratio of slack per allowance**.
ODD	$min\ (d_{ij})$	**Earliest operation due date**, where d_{ij} is the due date of job i at stage j.
OSL	$min\ (d_{ij} - t - p_{ij})$	**Minimum operation slack**.
OCR	$min\ \left((d_{ij} - t)/p_{ij}\right)$	**Minimum operation critical ratio**.
NINQ	$min\ (N_{i\ ,j+1(t)})$	$N_{ij(t)}$ is the number of jobs in queue at stage j, at the time step t, for job i. The job chosen is the one which has the **least number of jobs in the queue of its next operation**.
WINQ	$min\ (Y_{i\ ,j+1(t)})$	$Y_{ij(t)}$ is the total work of waiting jobs at time t in the queue containing stage j of job i. The job chosen is the one which has the **minimum work (i.e. sum of the process times of all jobs in queue) of its next operation**.
XWINQ	$min\ (Y'_{i\ ,j+1(t)})$	$Y'_{ij(t)}$ is the total work of waiting and expected jobs at time t in the queue containing stage j of job i. The job chosen is the one which has the **minimum work (i.e. sum of the process times of all jobs in queue and expected) of its next operation**. A job is expected to arrive soon if, at time t its preceding stage is already being performed.

Rule	Formulation - $Z_i(t)$	Description and name
LA	$max\ (Z_i(t))(i \in \{P \cup R\})$	$Z_{i(t)}$ is the priority value of job i at time step t (may have a specific function). R is the set of jobs currently in queue of stage j. P is the set of jobs currently processed in stages preceding stage j. Choose the highest priority among the jobs in the current stage queue, and the jobs currently processed on earlier stages. **Look ahead**.
ALTOP (might be considered as a composite rule)	$$Z_i(t) = min \sum_{\substack{h \in R \\ h \neq i}} min\left\{D_h - (t + p_{ij)} - \sum_{q=j}^{m(h)} p_{hq}\ ; 0\right\} - min\left\{D_i - (t + p_{ij}) - \sum_{q=j+1}^{m(i)} p_{iq}\ ; 0\right\}$$	Where h is the selected job. This rule chooses the job which would result at the smallest sum of tardiness (negative lateness) for all jobs in the queue due to the selected job h. **Alternate operation**.
	Composite rules	
MOD (Baker and Kanet 1983)	$Z_i(t) = min\big(max\ [d_{ij}\ , p_{ij} + t]\big)$	The **modified operational due date**. In this rule, the operational due date is used until the job is operationally late (i.e. when the finish time step of job i in machine j is higher than its due date on that same stage d_{ij}). After that, the earliest finish time of the operation ($p_{ij} + t$) is treated as due date.
ATC (Vepsalainen and Morton 1987)	$$Z_i(t) = max\left\{\frac{1}{p_{ij}} \exp\left[max\left(\frac{D_i - \sum_{q=j+1}^{m(i)}(W_{iq} + p_{iq}) - t - p_{ij}}{k\bar{p}}\right); 0\right]\right\}$$	**Apparent tardiness cost**. In this rule, W_{iq} is the waiting time of job i at stage q. k is a look ahead parameter used to scale the slack depending on the number of competing jobs (i.e. the load level of the shop), and $\bar{p}$ is the expected processing time of an operation.
CR+SPT (Anderson and Nyirenda 1990)	$d'_{ij} = CR.p_{ij}$ $Z_i(t) = min\big(max[d'_{ij}\ ;\ p_{ij}]\big)$	This rule modifies the operational due date as a multiple of the process time and the critical ratio of a job. **Critical ratio + Shortest process time**.
SL/RPT + SPT (Anderson and Nyirenda 1990)	$$d'_{ij} = \left(SL/\sum_{q=j}^{m(i)} p_{iq}\right).p_{ij}$$ $Z_i(t) = min\big(max[d'_{ij}\ ;\ p_{ij}]\big)$	The operational due date for this rule is given as the ratio of the slack by the total remaining process time. **Slack/remaining process time + Shortest process time**.
RR (Raghu and Rajendran 1993)	$$\eta(m) = \frac{total\ service\ time}{total\ service\ time + total\ free\ time}$$ $$W_{nxt} = \sum_{i=0}^{n} \begin{cases} Z_h > Z_i \rightarrow p_{ij} \\ Z_h \leq Z_i \rightarrow 0 \end{cases}$$ $$Z_{ij}(t) = min\big(SL/RPT.\exp(-\eta)\, p_{ij} + \exp(\eta)\, p_{ij} + W_{nxt}\big)$$	**Raghu and Rajendran**. The proposed rule applies a combination of the SL/RPT + SPT with different weights. The weights are a function of the utilization level of a machine m given by η. W_{nxt} is the expected waiting time of job i at the next stage and is the sum of the process times of all jobs whose priorities are higher than the priority of job i.

Xiong et al. (2017) evaluated the performance of 20 different simple and composite rules, in a simulation-based job shop problem with batch release and technical precedence constraints, with respect to tardiness-related functions. The study confirmed literature results regarding classical rules performance. According to the researchers, SPT is well known as an effective rule to minimize mean flow time, mean tardiness and number of tardy jobs, and SL/OPNR is often adopted as a benchmark for tardiness-related measures. Both EDD and SPT are reported to achieve close-to-optimum results in many scheduling problems involving due dates (Xiong et al. 2017). Modified operational due date (MOD) was evaluated as one of the best heuristics when intermediate operational due dates are considered (Parthanadee and Buddhakulsomsiri 2010). Sharma and Jain (2015) applied nine different dispatching rules to a dynamic job shop problem with sequence-dependent setup times. The rules were assessed in terms of makespan, mean flow time, maximum flow time, mean tardiness, maximum tardiness, number of tardy jobs, total setups and mean setup time. Results showed that the setup time constraint significantly affected the performance of dispatching rules. Rules that account for setup time logic such as JMEDD (Job with similar setup time and modified earliest due date), and JSSPT (Job with similar setup time and shortest setup + process time) performed better than those which did not account for the setup time attribute (Sharma and Jain 2015). Similar results were reported when comparing basic dispatching rules with setup time-oriented rules in a dynamic job shop problem with sequence-dependent setup times. The problem was solved using simulation based metamodels (Vinod and Sridharan 2009).

The rule proposed by Raghu and Rajendran (1993), later regarded as RR, considers the process time, slack and the waiting time for the next stage. The weights assigned to each component are dynamic (vary according to the process time and slack of each job). Simulations showed that the rule enhances the scheduling performance in terms of flow time, tardiness and root mean square tardiness (Raghu and Rajendran 1993).

Ruiz and Maroto (2005) compared a wide array of dispatching rules, many heuristics and metaheuristics methods for the permutation flow shop problem. A total of 25 different algorithms were coded and compared to the Taillard benchmark problem for the permutation flow shop (Taillard 1993). Dispatching rule-based algorithms performed very poorly against Taillard's problem, and the best results were given by the NEH (Nawaz et al. 1983) heuristics (Ruiz and Maroto 2005).

Later, Vallada et al. (2008) coded and compared 40 algorithms under a common data set of 540 problems. Results indicate that heuristics based in genetic algorithms performed better in terms of the evaluated metric (total tardiness) as well as CPU processing time. Unfortunately, dispatching rules in general exhibited poor performance (Vallada et al. 2008).

2.4.4 Simulation-based scheduling

Computer simulation-based scheduling consists of trying to mimic the behavior of a real manufacturing system in a controlled, digital environment. The characteristics of the real system are coded in a software that will both, simulate and schedule jobs as time progresses.

There are several arguments to why sophisticated analytical methods normally are not applicable to real problems. According to Pinedo (2008), a number of differences between real world scheduling and theoretical problems are worth mentioning, among others (Pinedo 2008):

1. In theoretical problems, the number of jobs to be scheduled are usually fixed. Real-life applications must be flexible enough to schedule an undetermined number of jobs. In fact, industry practice deals with constant rescheduling problems as new jobs keep joining a busy production line;
2. Most analytical models do not account for preferences. However, in industry applications, some jobs are more suitable to be assigned to a specific machine, or to be combined with other jobs with the same characteristics;
3. Most mathematical problems focus in optimizing single objectives or a previously defined set of metrics. In real-life problems, different objectives might be chosen for different situations, or consider a large number of concurring objectives simultaneously;
4. Job priorities change constantly in real-life scenarios. A low-priority job might suddenly become a high-priority job due to uncertainty factors;
5. Process times are usually stochastic metrics and might change over time due to learning or deterioration. When human labor is applied, this behavior is further potentialized.

As complex real-world systems are usually beyond analytical method capabilities, discrete event simulation (DES) was created in the manufacturing industry and has been widely applied in a variety of sectors. Therefore, simulation becomes a feasible way of modelling complex manufacturing systems (Kang and Choi 2013).

In DES models, the scheduling is performed under a chronological sequence of events. After each discrete event, a new decision is made virtually changing how the system will respond in the next decisions (Gentile et al. 2005; Ingalls 2002). A DES structure flowchart is shown in Figure 2-7.

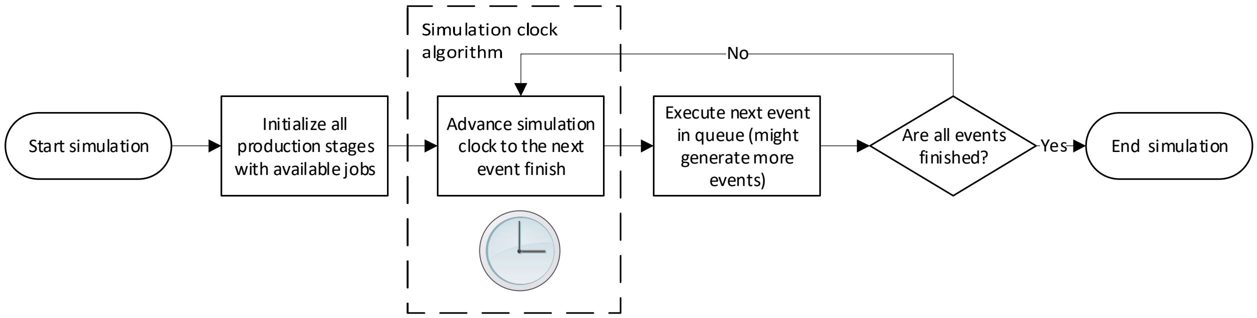


Figure 2-7 - General discrete event simulation flowchart

As computer technology advances and the capabilities of simulation-based algorithms continue to grow, it becomes possible to reduce computation time and allow for real-time rescheduling applications (Jeong and Kim 1998). Simulation-based scheduling is generally closely related to dispatching rules heuristic approaches.

Min Hee Kim and Kim (1994) proposed a scheduling framework for flexible manufacturing systems which relied on a real-time control system paired with a rule selection module and a simulation mechanism. After each discrete event, a simulation is performed employing each rule in the dispatching rule set. With the outputs of that simulation, the rule selection module will choose the best rule for each performance measure (Min Hee Kim and Kim 1994). The schedule quality in several metrics can be greatly improved by employing an adaptable rule selection mechanism capable of switching the priority rules at specific decision points in the algorithm (Aufenanger et al. 2008).

Gupta and Sivakumar (2005) used DES to simplify the scheduling problem into single job selection problems at each event in the simulation to minimize average cycle time and average tardiness and maximize machine utilization. The scheduling algorithm showed superior results when compared to common dispatching rules in literature (Gupta and Sivakumar 2005).

A number of studies developed rule-selection simulations and automatic generation of scheduling rules to improve the performance of scheduling algorithms. Freitag and Hildebrandt (2016) described a simulation-based optimization to create improved dispatching rules for a specific semiconductor manufacturing application (Freitag and Hildebrandt 2016). Korytkowski et al. (2013) proposed an evolutionary heuristic to determine the priority strategies and allocate dispatching rules accordingly aiming to maximize the performance of a complex manufacturing system (Korytkowski et al. 2013). Choi et al. (2011) developed a decision-tree based rule selector to choose from a set of dispatching rules in a real-time scheduling hybrid flow shop problem (Choi et al. 2011). Decision trees can be built according to various approaches such as field activities observation, experts' knowledge or historical data.

Several studies applied DES-based algorithms to solve real-life scheduling problems in industry. Vaidyanathan and Park (1998) applied a DES to a coffee manufacturing process, generating production schedules for each stage. The simulation applied EDD dispatching rule to sequence jobs aiming to minimize the number of tardy jobs (Vaidyanathan and Park 1998). Parthanadee and Buddhakulsomsiri (2010) also used dispatching rules in a simulation model to determine the production schedule for two stages in a canned fruit industry case study, aiming to minimize flow time and the average number of tardy jobs (Parthanadee and Buddhakulsomsiri 2010). Lin and Chen (2015) presented a simulation-based approach to a hybrid flow shop problem in a real-life semiconductor back-end assembly facility, attempting to achieve minimum flow time (Lin and Chen 2015).

2.5 Summary

Production scheduling management is a crucial factor to achieve higher productivity levels in manufacturing systems. Production schedules are affected by a multitude of factors such as product specifications, production processes and constraints, client's demands, and so on. In the engineered wood manufacturing industry, an important sector of Canada's economy, customized CLT panel production lines have evolved and now represent a substantial parcel of the market with significant growth potential. However, even though the system has been applied in Europe for a long time, no dedicated scheduling study was dedicated to modelling CLT production lines. Several approaches have been used to manufacturing production scheduling. However, complex systems and production constraints are seldom modeled to simulate a real production environment. The more general and analytical the model is, more simplifications and adaptations must be made to simulate system. One of the alternatives to maintain a reasonable complexity and reality level, and at the same time, provide the necessary computation feasibility, is Discrete Event Simulation (DES).

To apply DES, several production inputs must be provided. Arguably the most important input necessary for manufacturing scheduling are the process times of each job on each production

stage. In the customizable CLT panel industry, process times are variable and dependent on each job characteristics and plant production capacity (equipment, machinery and labor).
Additionally, production process time models must be adapted and applicable to specific plant and production characteristics. Several modeling techniques have been applied to manufacturing systems and process time estimation. Linear programming analysis, empirical analysis, evolutionary and regression models, to name a few. Nevertheless, no customizable CLT panel process time model has been developed.

The body of knowledge explored in this review provides the necessary knowledge regarding customizable CLT panel manufacturing processes, production process time estimation models, manufacturing scheduling problems and scheduling methods and techniques. A holistic approach to the customizable CLT panel manufacturing scheduling management is proposed, combining tailor-made empirical time estimation models, production process mapping and DES scheduling to improve process efficiency.

Chapter 3: Process time estimation modelling

To further enhance the knowledge regarding CLT manufacturing process and acquire the necessary production data to develop process time estimation models for each stage, and provide inputs for the production scheduling model, a CLT manufacturing plant was studied.

The field observations (time study and video recording), and process mapping conducted at a customizable CLT panel manufacturing plant located in Okanagan Falls, British Columbia, are described below. Furthermore, the data analysis procedure is described, and the process time estimation models results, discussed.

3.1 Background

The main objective of the developed models is to provide reasonably precise estimate jobs process times for customized CLT panel manufacturing, delivering necessary inputs for the scheduling model. In the field of project management, it is well documented that decision support tools and models should follow six basic guiding principles: realism, capability, flexibility, ease of use, cost and easy computerization (Meredith and Samuel J. Mantel 2012; Souder 1973). In real-life applications, decision support tools must be pragmatic and "to the point". The model should be essentially easy to operate, and processing time and requested input parameters should not be unfeasibly long or hard to acquire.

Therefore, the process time estimation models developed in this study merely rely on input parameters that already were part of the regular production process. No input-acquiring activities were introduced in the process, granting the model necessary flexibility, ease of use, low cost and feasible computerization.

System observation and process mapping techniques have been widely used in operations management studies for several reasons. From productivity improvement to complete business re-engineering, empirical techniques were developed and applied in many research and industry projects (Flynn et al. 1990). Industrial operations are dynamic, therefore, demanding for dynamic process improvement methods (Grünberg 2003).

A standard and systematic approach for empirical operations research study model follows a five-step road map, as proposed by (Flynn et al. 1990):

1- Establish the theoretical foundation of the study – whether it is theory building or verification;

2- Select a research design – several research designs might be chosen, from panel study, to focus group, field experiment, single or multiple case study, among others;
3- Define a data collection method – similarly, several techniques might be used, depending on data constraints and availability (e.g. historical literature data, observations, interviews or questionnaires);
4- Implementation – establishes the requirements and operational measures to implement the research design and data collection method;
5- Analysis and validation – defining the better suited statistical technique to analyze the gathered information, as well as approaches to validate the study and its reliability.

In this study, new manufacturing time estimation models are being built. For that reason, the necessary background knowledge about the process and its intricacies need to be explored. Steps one and two were achieved through process mapping. Process mapping is an acknowledged method to achieve industrial processes improvement. The technique consists in analyzing the production flow to identify drawbacks and improvement opportunities that might, or might not, result in modifications in the process, plant, and operational parameters (Soliman 1998). It's a widely recognized approach that provides reliable unbiased information, for a relatively cheap cost (Biazzo 2002), used in many industrial applications such as waste management (Rybicka et al. 2015), and enterprise resource planning (Okrent and Vokurka 2004).

Process maps, in combination with the field observations and expert engagement, allowed to holistically evaluate the process sequence and plant layout implications on the production process. Interrelations among production stages inputs and outputs were captured, and a thorough understanding of the limitations and constraints introduced to the problem by the specific plant layout and configuration, was acquired. Plant layout design plays a fundamental roll in material flows and plant productivity, involving equipment and machinery positioning, field personnel logistics, and buffer areas organization (Nyemba and Mbohwa 2017). Ultimately, improved results may be achieved in terms of total production time or processing time. The process mapping approach proved itself efficient on improving production throughput in a furniture manufacturing company (Nyemba and Mbohwa 2017).

The process mapping study also laid foundations for the third and fourth steps on this empirical study, defining the constraints and requirements for data acquisition. According to Hewage

(2007), two of the most effective observation methods for industrial manufacturing activities are the following (Hewage 2007):

- *Time study* – initially developed to understand, measure, standardize and improve tradesmen's work, this method proposed by (Gilbreth 1911), suggests tracking the time spent for each activity performed by workers in the production process, and;
- *Video recording* – observation method where the actual presence of the researcher at the work environment is not required. The work process is continuously observed, allowing for higher amounts of collected data, in a much less tedious way and with minimal researcher influence in the observed activities. However, it is imperative that the researchers guarantee that the privacy of the observed workers is maintained, and that information is gathered in an ethical way.

Jackson et al. (2004) proposed a different "scheduler-dependent" scheduling model for industrial operations based on tasks, roles and monitoring, through extensive empirical study of industry schedulers, observation-based methods and decision inquiries. In this study, the methodology applied to the field observations was a combination of both observation techniques described above, with the addition of industrial order-to-delivery process mapping (Jackson et al. 2004).

Finally, for the fifth step, analysis and validation, regression analysis was performed. In this study, jobs' process times are means to achieve a reasonable production schedule, and from a multitude of single processes times acquired in the data collection process, regression models were developed for each activity identified in the production process map.

Regression is a powerful approach to forecast the behavior of particular responses depending on a set of independent variables collected in the empirical study (Pesarin and Salmaso 2010). Regression analysis is also capable of providing understanding on roles of variables and confounding factors of the modeled process (Lee and Whitmore 2006). However, the application of regression techniques without evaluating the performance and quality of predictions may lead to unrealistic results (Picard and Cook 1984).

There are several approaches for regression validation. Among others, data-splitting, repeated data-splitting, jack-knife technique and bootstrapping are methods of internal validation, where the regression model is tested with a subset of the data originally collected (Arboretti and Salmaso 2003). Data-splitting is a simple validation technique, in which the collected data is divided in two groups, one for model training, and one for validation (Picard and Berk 1990).

One of the biggest advantages of data splitting is that the validation procedure must be done only once. The samples for model training and validation must be random and their sizes reasonably distributed so the relationship between predicted and real values can be projected with good accuracy (Harrell et al. 2005).

3.2 Methodology

Combining empirical studies methods, observation techniques, process mapping and regression analysis, customizable CLT panel manufacturing process time estimation models were developed.

The first stage of the study consisted in understanding the production process through experts' information and process mapping. During the data collection phase, the plant was visited nine times. Data collection activities on the shop floor were performed in six occasions, the other three being dedicated for plant management meetings to acquire preliminary knowledge of the production process and scrutinize the perceptions acquired after field observations.

Four IP cameras and one computer server were installed at the plant for 49 days. The cameras were first installed June 1st, 2018 and the server was removed on July 19th, 2018. The cameras were carefully placed on spots where the three focus stages could be observed, and production related activities could be properly tracked. Camera 2 was installed close to the pressing stage, observing the loading, glue spreading, pressing and unloading processes. Camera 1 was placed at the CNC stage, focusing in the cutting process. Camera 4, also focused at the CNC stage, but more specifically in the loading, unloading, machine and billet preparation procedures. Finally, camera 3 captured activities performed at the FQC stage, including the logistic involved in moving and flipping panels around, manual finishing, quality checking and packaging of products.

Unfortunately, some unforeseen occurrences disturbed data collection during the observation period. Two interruptions could have been avoided (caused by interferences with the computer server), and a third unavoidable interruption was caused due to a large-scale power outage in the plant. From those 49 days, a total of 28 full days of footage were collected for each observation point installed by the researcher. Additional data was acquired through a factory security camera which also captured activities performed in the FQC stage. A total of 17 full days of footage were captured from the factory security camera labeled as camera 10.

As the plant kept normal operations during the observations, there were interruptions in production of some stages (due to maintenance, equipment breakdown, or other unforeseen events) at certain times and those gaps are reflected in the data collection. Throughout the field observations, fragments of fourteen different projects were captured, resulting in a heterogeneous database of complex and simple, long and short, and big and small projects. However, due to the aforementioned disruptions in the footage, and because several projects were being produced simultaneously at the plant, no project was completely observed, i.e. from the very first job at the first production stage to the last job on the last stage.

Once information as gathered in field, all footage was stored in a secure server in the University of British Columbia – Okanagan Campus, and carefully watched. Main process activities were selected for each production stage after brainstorm sections and discussions with plant management experts. A time study was conducted to capture the process time for as much data points as possible for each stage-specific selected activity described in the following Section 3.3.

3.2.1 Case-specific production process mapping

Customizable CLT production consists in manufacturing structural or architectural grade CLT panels according to client-specific production data. Generally, clients provide 2D architectural, structural and specialty engineering designs. These designs are then converted into a tridimensional work model able to generate a CLT production list and a bill of materials.

The list of CLT panels is then nested into CLT billets to optimize material consumption, i.e. one or more CLT panels with the same grade, visual requirements, stress class and thickness are fitted into a large billet. CNC cutting codes are then generated to determine how the billets will be processed in a CNC cutting machine at the plant, to separate the billets in the actual CLT panels. The process up to this point does not necessarily need to be performed at the manufacturing plant and is usually developed in a design office, at a different location.

Once material consumption is optimized and the cutting codes are generated, the billets and parts lists, and the CNC router cutting codes are sent directly to the PBA machine at the plant for production. Plant management will define the production schedule based on the assembly priority and truck load plan for each CLT panel which are also provided in the billets and production list. The production flowchart of the studied plant is depicted in Figure 3-1. The flowchart shows the high-level stages from the 3D modelling of clients' designs all the way to the loading and shipping of products. This thesis's scope is concentrated on the highlighted stages, specifically to the processes related to CLT pressing, cutting, finishing, quality control and packaging.

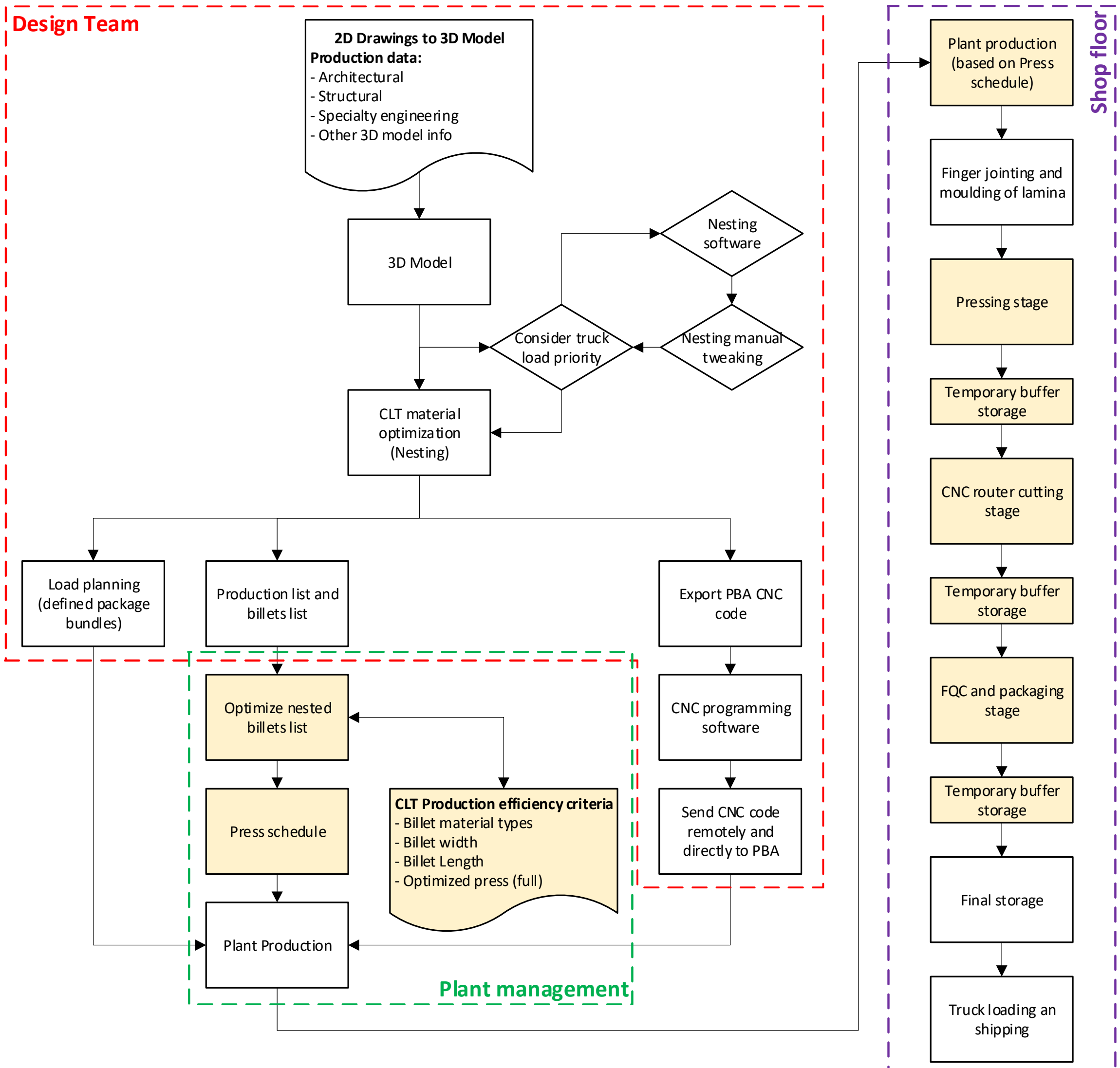


Figure 3-1 - Okanagan Falls plant production flowchart

After the production planning is done and the job schedule is defined, the actual physical manufacturing process is commenced. The sequence shown in the last portion of Figure 3-1 matches CLT manufacturing processes in specialized literature and described in Section 2.1.2. The "As Is" production layout map was developed after several meetings and discussions with plant management, as well as field observations and brief conversations with field personnel and it is shown in Figure 3-2. Although the process map situates preliminary, post-finishing stages and different product manufacturing areas, only the studied activities were effectively analyzed.

Nevertheless, the plant layout organization, even for products or stages not considered in the scope, might have impacts on the CLT production line.

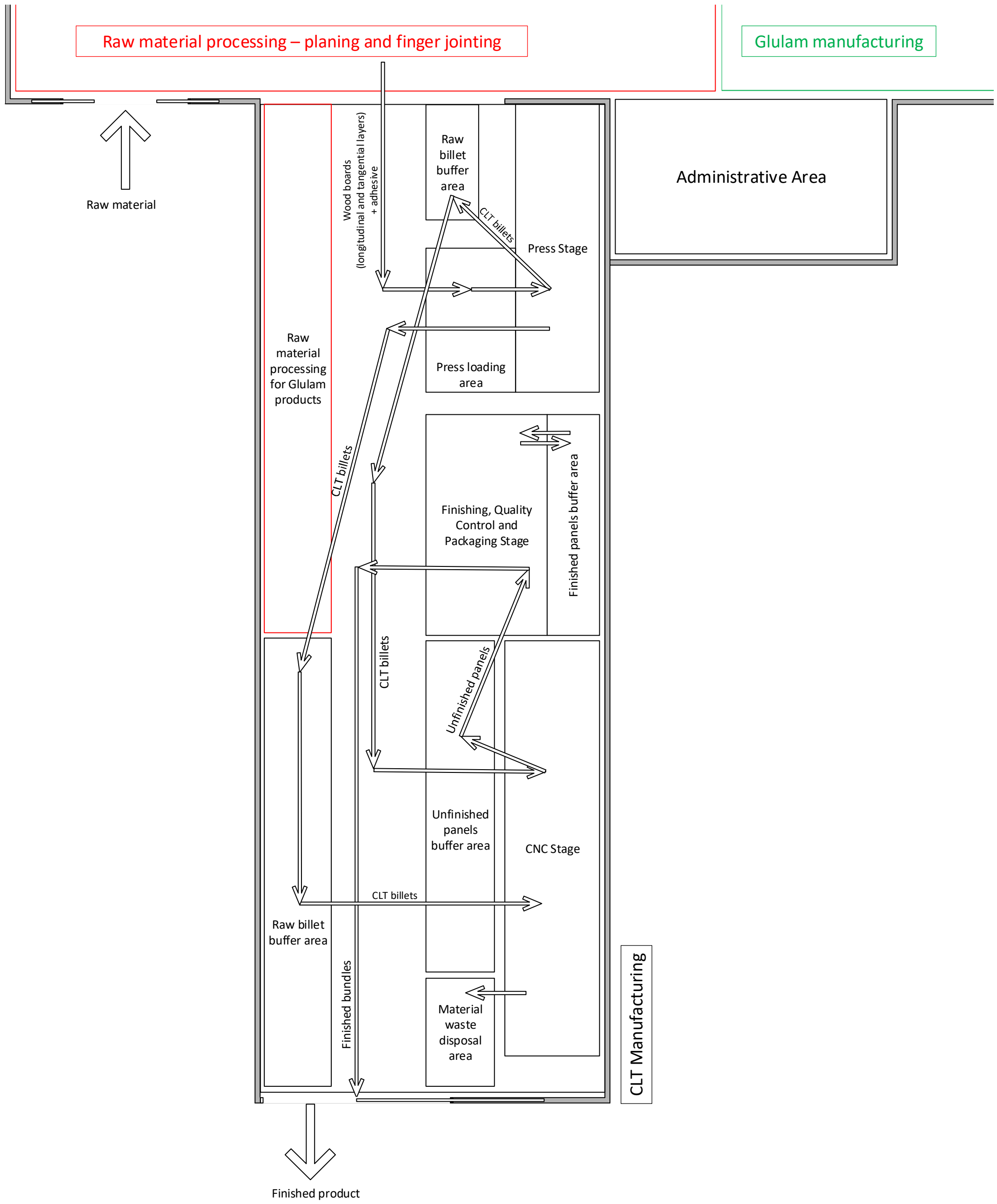


Figure 3-2 - Okanagan Falls CLT production layout map

3.2.1.1 Preliminary stages

The plant in Okanagan Falls processes two different engineered wood products, CLT and Glulam (glued laminated timber beams). This section describes only the CLT production process. In the studied plant, CLT panels are classified based on their material composition and thickness. The finger jointing and planing schedule, although not included in this study, depends on the press schedule, since diverse billets series (see Figure 3-3) require different configuration setups for planing and finger jointing stages. Thus, the press schedule needs to account for different material types, avoiding switching back and forth between different layups or combining billets with different product series in the same press cycle.

CrossLam® CLT Series	Grade	Face Layers	Major Layer (L)	Minor Layer (T)	Layer Thickness (mm) L	T	L	T	L	T	L	T	L	Panel Depth (mm)
87 V	V2.1	SPF #2& Btr	SPF #2& Btr	SPF #3& Btr	35	17	35							87
139 V					35	17	35	17	35					139
191 V					35	17	35	17	35	17	35			191
243 V					35	17	35	17	35	17	35	17	35	243
105 V	V2M1.1	J-Grade Dfir L3		SPF #2& Btr	35	35	35							105
175 V					35	35	35	35	35					175
245 V					35	35	35	35	35	35	35			245
315 V					35	35	35	35	35	35	35	35	35	315
87 E	E1M4	MSR 2100 1.8E SPF	MSR 2100 1.8E SPF	SPF #3& Btr	35	17	35							87
139 E					35	17	35	17	35					139
191 E					35	17	35	17	35	17	35			191
243 E					35	17	35	17	35	17	35	17	35	243
105 E	E1M5			SPF #2& Btr	35	35	35							105
175 E					35	35	35	35	35					175
245 E					35	35	35	35	35	35	35			245
315 E					35	35	35	35	35	35	35	35	35	315

L = Longitudinal Layer (Major Layer)
T = Tangential Layer (Minor Layer)

Figure 3-3 - Okanagan Falls plant conventional CLT panel laypus

3.2.1.2 Pressing stage

The pressing stage is the first workstation considered in the scheduling algorithm. Regarding material flow, the press stage represents the first material transformation in the CLT production process, where single boards of different dimensions (for tangential and longitudinal layers) are combined with gluing adhesive to make a CLT billet. The studied plant uses a hydraulic press, by far the most productive stage in the process. The plant only used PUR adhesives in the pressing stage. The hydraulic press is capable of pressing billets as wide as 9.9 ft (3 m), and as long as 39.8 ft (12.19 m). The equipment is also capable of pressing up to 10 layers of conventional CLT panels. One of the plant's management production criteria is to maximize the press yield for each cycle by grouping billets together in the press. This approach maximizes the stage productivity, minimizing the energy consumption vs productivity ratio. Considering that conventional CLT panels have either 3, 5, 7, or 9 layers according to Figure 3-3, each press cycle can yield up to 3x(3-layer billets), 2x(5-layer billets), 1x(3-) + 1x(5-layer billets), 1x(7-) + 1x(3-layer billets), or 1x(9-layer billets). Although billets also might be pressed individually in some situations, this practice is avoided.

Observations and field personnel account for a maximum production rate of no more than 15 presses per day, constrained by process time or buffer area conditions. Press limitations do not allow for billets of different widths to be processed together. Whereas, variations in length are possible, it is preferable to maintain the same length on each cycle as to facilitate the loading and set up procedure, as well as increasing productivity on the preliminary stages.

The loading procedure is highly automated. The positioning and alignment of single boards is made on a previous conveyor table with the help of two workers. The aligned boards for each layer are then transferred to the press table with a vacuum crane, where the adhesive is applied, also automatically.

The unloading process demands more labor intervention. Due to the positioning of the press table, the unloading process must be executed with the conventional warehouse crane, demanding the installation of anchor points. These anchor points need to be removed for storage before the next stage. In the case of three layers billets, a vacuum crane can also be utilized in the unloading process. However, the vacuum crane does not have the necessary range to transfer raw billets to the main buffer area across the service corridor, nor the strength to support large and heavy billets. Therefore, billets unloaded by the vacuum crane are placed on the loading conveyor table from where it is then stored in the buffer areas with the help of a forklift.

As the pressing time shows hardly any variation, the loading and unloading times vary depending on how many layers and billets are being processed on each cycle, and the size and weight of the billets. These variations will be taken into consideration in the press time estimation model.

3.2.1.3 CNC router cutting stage

The second stage in the CLT production line consists of cutting the raw billets in smaller panels. After the 3D model is created based on the client's designs, all CLT panels in the project are combined in billets to minimize material waste. The material optimization takes into account the assembling order of each panel at the construction site. Thus, after the billets are pressed, the panels in each billet have to be cut according to 3D model. This process is executed with a Computerized Numerical Control (CNC) cutting machine, also known as PBA or panel cutting machine.

This stage is apparently the slowest in the production line. Depending on how many CLT panels are combined in each billet and on how many cutting, drilling, and other processes they require, the CNC process time can last for hours. The CNC process time is also impacted by how many tool changes and panel repositioning must be performed, and how the PBA operator adjusts the machine during the cutting process.

Due to process time optimization procedures for this stage itself, it is not possible to specify the completion order of multiple parts in a billet, nor determine if one panel would be ready before all cutting processes in the billet are completed. Operator's discretion and technique are also a factor. Therefore, a conservative approach was adopted, considering that the CNC finish time for every part in a billet is equal to the summation of cutting times for each part in the same billet.

It was observed that, not rarely, the cutting process is interrupted during some billets. One single process code is programmed in the PBA and then executed in multiple similar billets, avoiding extra set up times. Once this first process is completed on all similar billets, the next process is programmed and executed in each billet, and so forth until all processes are executed on all similar billets. Additionally, interruptions are frequently made to attach small panels to the cutting table, as well as panel repositioning and checking dimensions.

Loading and unloading procedures in this stage are made with a vacuum crane. Depending on the size and weight of transferred billets, conventional crane and anchor points might be employed. As the main buffer area for raw billets and the unfinished panel buffer area are located adjacent to the CNC machine, loading and unloading operations are performed efficiently, maximizing the CNC operation time range. The unloading process is slightly more complex, since several smaller parts need to be positioned and stacked on top of each order, due to buffer area limitations. The amount of waste produced also impacts the unloading process, as some waste pieces are just too small to be removed by the vacuum crane, but a little too large to be handled manually. In those cases, workers need to chainsaw waste in smaller pieces and carry them out by hand to the waste disposal area.

3.2.1.4 FQC and packaging stage

The final stage of the production process is entirely executed by human labor with hand tools. Depending on the level of detail and design complexity in a part, some features must be made by hand through manual drilling, cutting, grinding, etc. Visual and shape inspections, and dimensions measurements are performed on each piece to guarantee that it is up to factory standards and client specifications. The number of visual faces on the panel also affects the amount of work each part demands. As sanding and manual framing processes can be carried out on both faces of a panel, the parts are constantly flipped and turned over with the help of a crane. Once panels are finished, they must be stored accordingly in a buffer area or left in the finishing area for their package bundle mates. Obviously, each bundle can only be wrapped up and sent to truck loading procedures once every panel in that package is completed. It is extremely unproductive if a finished panel sits in the finishing or buffer area for a long time waiting for their mates.

Framing productivity is highly impacted by the shape and size of the panels, as the finishing area is limited. Therefore, applied labor must be carefully balanced with the complexity and size of panels at hand. The framing crew uses either a conventional warehouse crane or with a forklift to load panels to the finishing area, move them around as needed, and unload the package bundles once they are finished. Material handling quality and safety measures such as corner protection and fabric or plastic belts for panel moving, are mostly observed at this stage.

Package bundle wrapping may be considered an independent stage, separated from the FQC stage. However, as both activities share the same work area, buffer area, equipment, and manpower, and are highly dependent on each other, package wrapping was considered as a sub-process of the FQC stage. Nevertheless, the two activities do not happen in a continuous manner for most panels. Finished panels usually need to wait until their mates are also finished, so all of them can be wrapped together in a single package bundle.

3.2.2 Identified processes and production variables

The undertaken literature review (Chapter 2) and data collection provided the necessary background and understanding of the problem to identify relevant production processes and variables, as shown in Table 3-1. The identified items are divided in job-related variables, production activities, feedstock- and stage-related variables, and material handling and storage variables.

Some of the identified variables were not directly considered in the process time estimation models. That is one of the reasons why empirical models were used, derived from real process times: to capture the underlying behavior of some of the identified variables such as the material type (type of wood and adhesive), plant layout, material flow and equipment, without directly considering them in the predictive equation. With this approach, simple and reasonably accurate models were developed.

It is important to mention that the aforementioned characteristics are plant-specific, therefore, valid to the developed models and modeled production plant.

Table 3-1 - Identified processes and production variables of customized CLT panel manufacturing

Job-related variables (billets and parts)	
Priority parameters	Truck load ID
	Package bundle ID
Dimensions and geometry	Width
	Length
	Number of layers
	Billet/part waste %
Other parameters	CNC software estimated process times
	Number of visual/sanded faces
	Number of parts in billet

Production activities	
Pressing	Loading
	Pressing
	Unloading
	Waiting/setup
CNC	Loading/setup
	Cutting
	Shifting/tool changes
	Waiting/setup
FQC	Loading
	Finishing and Quality Control
	Flipping and shifting
	Packaging

Feedstock- and stage-related variables
Material type
Press batching constraints
FQC team size
Number of FQC work areas

Material handling and storage variables
Number of buffer areas
Buffer area capacity (stacked panels)
Material flow
Plant layout
Loading/unloading equipment

3.2.3 Model development

Multivariate regression analysis was applied to the collected and generated metadata for each stage, according to the sections below. Predicting the process times of jobs in a manufacturing environment demands the development of empirical relationships that may tie the necessary time taken to produce a job in a certain stage with products' and job's characteristics, as well as with plant and equipment capacities. Empirical modeling was the selected due to the complexity of the problem. As most production constraints were considered in the models, an analytical mechanistic model was not reached. Multivariate linear regression has been widely applied in several fields (Sadiq et al. 2018). In this study, linear regression was applied due to its simplicity, straight-forwardness, easy and wide applicability.

After watching over 3,000 hours of footage, a robust database of process times was created for each of the three production stages. The measured times for the selected activities were further scrutinized to evaluate which job variables had a significant impact on the process times. The process times of the observed activities were compiled with the plant production records for each job. From the plant records, each job was tracked by its unique billet ID or part ID number, and billets and parts characteristics were acquired from production lists made available by plant management for each observed project. As the data was analyzed, different empirical modelling approaches were taken for each production stage, with the help of the statistical analysis software Minitab 18. A data-splitting approach was applied, and seventy percent (70%) of the data was randomly selected and used to develop the models, leaving the last thirty percent (30%) to validate the developed models for each stage.

3.2.3.1 Pressing stage

The process time database for the pressing stage counted with 186 data points. Each data point relates to a job (billet) processed in the press. The 186 observed billets were combined in 104 press cycles, as explained in section 3.2.1.2. Loading, pressing, unloading, and waiting and setup times in between press cycles were measured in this stage, and considered in the pressing time estimation model development. The pressing time output from the model is the summation of the process components described in the next subsections, and according to the equation below:

$$\boldsymbol{p_{i,PRESS} = p_{i,PLT} + p_{i,PT} + p_{i,PUT} + p_{i,PWT}} \quad \textbf{Equation 2}$$

where $p_{i,PRESS}$ is the total pressing stage process time, and $p_{i,PLT}$, $p_{i,PT}$, $p_{i,PUT}$ and $p_{i,PWT}$ are respectively the loading time, pressing time, unloading time, and waiting and setup time component, for the ith billet. All components in the equation above are in minutes (min). Considering job batching at this stage, the total process time should be shared among batch components. Therefore, considering batching implications, the actual total pressing time output is given by the following equation:

$$\boldsymbol{p'_{i,PRESS} = p_{i,PT} + p_{i,PWT} + \sum_{bt}(p_{i,PLT} + p_{i,PUT})} \quad \textbf{Equation 3}$$

where $p'_{i,PRESS}$ is the actual total pressing time in minutes (min), and bt is the batch composed of up to three billets in the press cycle, according to the batching constraints in Section 3.2.1.2.

A) Press loading and unloading times

Due to equipment, activities and plant layout constraints, whenever at least two workers are employed, labor quantity was not considered a significant factor to estimate loading and unloading times. The labor team for this stage consists of only one press operator and one helper. Adding more labor beyond this pair would not increase the process productivity and reducing to one worker only would severely decrease it. First, the loading process, as mentioned before, is almost completely automated. Labor is only used to feed the conveyor belt to align the wood boards, and in this sub process, no more than two workers are needed. Second, during the actual pressing, only the press operator is needed to start the press, and not for the whole time. The sub process of feeding the conveyor belt was performed in parallel, during the press time of a previous cycle, optimizing total process duration. Lastly, the unloading process also demands only two workers. When the vacuum crane is used, one worker operates the crane and another worker uses the forklift to take the unloaded billet to the buffer area. When the conventional crane is used, while one worker attaches the anchor points to lift the billet, the other operates the crane.

On the other hand, billets characteristics such as width, length and thickness, have an underlying influence on loading and unloading time. It is reasonable to consider that the heavier, larger the billets are, more time will be taken to perform loading and unloading procedures. Therefore, the following parameters were considered as explanatory variables: billet width (mm), billet length (mm) and billet thickness (in number of layers).

Using Minitab, linear regression was applied to the dataset, where both billet width and length were considered continuous variables, and the billet thickness (number of layers), categorical.

B) Pressing time

The bonding capacity for CLT panels is basically dependent on the type of wood, type of glue, bonding pressure (strength/area), adhesive spread rate, and pressing time (Liao et al. 2017; Weidman 2015). Considering that all panels produced in the studied plant during the observation period were produced with the same type of PUR adhesive, the same type of SPF wood, must meet the same quality and strength parameters, and were pressed by the same equipment (i.e. same bonding pressure and adhesive spread rate), the pressing time should be virtually the same for all data points.

For that reason, single distribution analysis was made on the observed pressing times to identify the variation and uncertainty level. The observed variation in pressing times was considered to be the error component due to uncontrollable and unmeasured labor-related confounding factors in the process. To deal with this variation, an ordinary fuzzy set was proposed to represent the pressing time of every billet. Fuzzy set theory is widely used in applied engineering problems (Hu et al. 2018) and is a good representation of imprecise knowledge (Jahan-Shahi et al. 2001). However, a crisp value is needed to compose the total pressing time output of the model. The triangular fuzzy number was then defuzzified using the centroid method, calculated by the centroid to the shape defined by the membership function.

$$\boldsymbol{Centroid} = {\int \boldsymbol{x}\, \boldsymbol{\mu}(\boldsymbol{x})\, \boldsymbol{dx}} \Big/ {\int \boldsymbol{\mu}(\boldsymbol{x})\, \boldsymbol{dx}} \qquad \textbf{Equation 4}$$

where, x is the pressing time in the fuzzy set described above, and $\mu(x)$ is the membership value.

C) Waiting time or setup time

In between some press cycles, apparent equipment idle time was observed. Eventually, depending on billets width difference in between cycles, the press table had to be reconfigured resulting in setup times. As the available data was not sufficient to explain the waiting (which is completely random) or the setup time behavior, a similar approach to the pressing time component was adopted.

3.2.3.2 CNC router cutting stage

For the CNC stage, 179 billets were observed, generating 491 parts and waste pieces. Loading and machine setup, and cutting for each billet, and unloading processes for each part or waste pieces were the observed activities for this stage. Since the PBA was rarely idle, waiting or maintenance times were not considered in the model, as there was no consistency in those observed events.

Although CNC process time can be subdivided in loading and setup, cutting and unloading procedures, the loading and unloading procedures are not as influenced by the billets characteristics as they were in the pressing stage. Additionally, as billets are transformed in parts in this stage, unloading procedures durations are much more dependent on the quantity and shape of cut parts and waste material than to the original billet characteristics.

Furthermore, the cutting times are by far the most significant component of the total CNC process time. As explained in Section 3.2.1.3, the cutting time is defined by the quantity and complexity of CNC processes executed in each billet. Billets dimensions, although relevant, are not the main parameters, thus, not capable of explaining the behavior of the observed cutting time. Another significant indicator that can be used for both cutting and unloading components time estimation, is the percentage of waste material produced after each cutting cycle (Ou-Yang and Lin 1997).

For those reasons, additional parameters were added to the analysis, apart to the billet's characteristics (width, length and thickness), and observed process times. The following parameters were added for each data point: number of cut parts from each billet, waste generation percentage, and the coding software CNC machining estimated time.

- *Number of cut parts* – how many parts are originated from each billet that is processed in the PBA. This parameter is acquired from the production lists made available by the plant management;
- *Waste generation percentage* – this parameter is calculated by subtracting the rough volume of each cut part from the total volume of the original billet. This parameter is inputted as an absolute value, i.e. if 2% waste is generated, the input value should be 0.02. The necessary information to calculate this parameter is also available in the production lists;
- *Coding software CNC machining estimated time* – arguably, every CNC coding software has a built-in feature to provide the machine estimated cutting time for the coded processes. However, the process times provided by the software do not account for operator-related interference, nor for any manual processes necessary to complete the job (e.g. intermediate waste removal, panel repositioning, piece anchoring, etc.). Therefore, the software estimated process times are solely an indicator parameter of how complex and time-demanding the process time will be. An additional spreadsheet made available by the designing team provided the software estimated cutting times for each billet.

Using Minitab 18, linear regression was applied to the enhanced CNC dataset. The continuous independent variables considered were billet width and length, number of cut parts, waste generation percentage, and coding software CNC machining estimated time. Billets thickness (number of layers) was used as a categorical independent variable. However, the results of this first regression round were not as expected. The independent coefficient derived for the 5-layer equation was smaller than the one on the 7-layer equation, meaning that for billets with exactly the same dimensions, parts and cutting codes, the total CNC time for the 7-layer would be smaller than the total CNC time for the 5-layer billet, which is incorrect. Similarly, the derived coefficients for billet width and length were negative, meaning that the larger the billets were, the less time it would take to finish the CNC procedure, which is also incorrect.

Therefore, a new regression round was performed without billet width and length as independent variables. Billets' width and length were the least significant variables on the previous regression round, and their removal from the analysis will not jeopardize the results. Finally, three different equations were derived, for 3-, 5-, and 7-layer billets, and the response variable is the total CNC process time for each billet.

3.2.3.3 FQC and packaging stage

The FQC and packaging stage is the most challenging to model, as all activities are directly performed by human labor, and most affected by uncertainty and unknown confounding factors. Even the data collection process was affected by the sometimes random and unpredictable process of finishing panels. Several bundles were wrapped in areas not captured by the observation camera, substantially reducing the total number of data points available for the packaging component.

Another challenge consisted in attempting to track the amount of time employed in working on several panels being finished at the same time, by different workers in the finishing area. Finishing, quality control and packaging activities were constantly interrupted, panels were moved around, and workers frequently changed from working in one panel to another making the tracking process slow and difficult.

For those reasons, no loading and unloading, intermediate panel shift or flipping, nor labor moving times, were tracked. Those processes were considered included in the total finishing or packaging time. The packaging component started as soon as the very first bundle component started being wrapped. Furthermore, as the number of workers was variable on each panel at any given time, both finishing, and packaging times were compiled in (man x minutes), i.e. if two workers spent 15 min finishing a panel each, the total finishing time is 30man x min.

In terms of panels' dimensions, although the plant kept quality control records of all finished panels, it was not possible to identify, from the footage, which panels were being finished or packed at any given time. Therefore, an adjustable 3D model of the finishing area was created using SolidWorks 2018-Student Edition to graphically capture panel's rough dimensions (areas and shapes), according to Figure 3-4 and Figure 3-5. Each square in the grid accounts for 0.25 m^2.

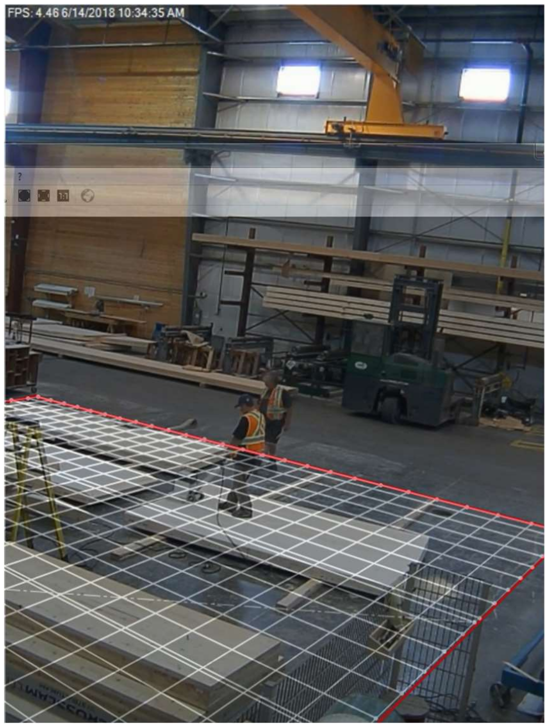


Figure 3-4 - Adjusted 3D grid model for camera 3

Figure 3-5 - Adjusted 3D grid model for camera 10

Although the amount of footage collected for this stage was larger than any other (due to the added footage from camera 10), 122 data points were captured for the finishing component, and only 78 data points for the packaging component.

A) Finishing and quality control time

Not considering skill level, and assuming that all workers have the same average productivity, finishing and quality control process time is essentially dependent on the panel area and whether it has visual faces (to which sanding is required) or not. For this analysis, only standard finishing and quality control interventions were considered, i.e. the time taken to execute features manually (unconventional features which the PBA is not capable of executing) was not considered in the model.

Using Minitab 18, linear regression was applied to the FQC dataset. Rough panel work area was the only continuous independent variable considered for the finishing component. The rough panel work area is calculated by multiplying the rough panel area by the number of faces demanding labor intervention (either 0, 1 or 2). The number of visual faces was considered as a categorical parameter. Hence, three different equations were derived, for 0, 1 and 2 visual faces. The response variable is the total finishing time in man x minutes.

The actual finishing time is going to be weighted by the ratio of the number of panels being finished or packed at the same time and the number of workers in the FQC team. For example, consider that the nominal calculated finishing time of a panel is 60 minutes. If the FQC team is composed of three workers and there is one slot in the work area currently occupied, the next panel's FQC nominal process time is going to be weighted by 2/3, and the total FQC process time for this panel is going to be 40 minutes, according to the equation below:

$$\boldsymbol{p'}_{\boldsymbol{i,FQC}} = \frac{\boldsymbol{p_{i,FQC}}}{\boldsymbol{ts}} . \boldsymbol{Jos} \qquad \textbf{Equation 5}$$

where, $p'_{i,FQC}$ is the actual total FQC process time in minutes (min), and Jos is the number of occupied FQC job slots, including the current panel, and ts is the FQC team size (in men).

B) Packaging time

The packaging component, as mentioned before, shares resources with the FQC component. Intuitively, this the packaging process is mostly dependent on the number and size of panels composing a given bundle. However, it is also known that the wrapping procedures is affected by how many visual faces the panel has, as additional measures must be carried out to protect its visual faces.

Several regression analyses were performed considering the number of visual faces as a categorical parameter, deriving different equations for panels with different visual faces. However, results were not logical, often showing panels with less visual faces taking longer to wrap. One of the reasons for this behavior is the limited database of panels with 2 visual faces (only 5 data points). The second is related to the composition of panel bundles. The time taken to wrap a bundle package is shared among its components, regardless of how many visual faces the panels in that bundle have.

For those reasons, the number of visual faces, although categorical in definition, was used as a limited continuous variable, alongside the rough panel area and the bundle size. The response variable is the total packaging time in man x minutes.

One of the implications of the suggested model is that different panels composing a bundle package might have different nominal wrapping times. Besides that, similar to the FQC component, the actual wrapping time is influenced by the occupied job slots and finishing team size ratio. Addressing these issues, the actual package bundle time is given by the following equation.

$$\boldsymbol{p'_{i,PACK}} = \frac{(\max_{bd} p_{i,PACK})}{ts} . \boldsymbol{Jos} \qquad \textbf{Equation 6}$$

where, $p_{i,PACK}$ and $p'_{i,PACK}$ are the nominal and the actual total packaging time in man x minutes and minutes, respectively, bs is the bundle size in number of panels, bd is the bundle composed of whatever panels are combined in each particular package, and ts is the FQC team size (in men).

3.3 Results

Following the process described in the methodology, this section outlines the modelling results and the derived equations for each customized CLT panel production stage. The estimated process times will provide fundamental inputs for the CLT production scheduling model described in Chapter 4.

3.3.1 Press loading and unloading times

As described in section 3.2.2.1, considering the elected independent variables for regression analysis, billet width (mm), billet length (mm) and billet thickness (in number of layers), both loading and unloading times equations were achieved. Three different equations were derived, for 3-, 5-, and 7-layer billets. Figure 3-6 and Figure 3-7, show the analysis output, residuals plots, and regression equations for Loading Times of 3- and 5-layers categorical values, and Figure 3-8 and Figure 3-9, for the 7-layer category. Note that, for 7-layer billets, logarithmical Box-Cox transformation was applied to improve equation-fitted values.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1610.01	402.503	136.81	0.000
Billet Width (mm)	1	138.95	138.946	47.23	0.000
Billet Length (mm)	1	1.50	1.504	0.51	0.476
Number of Layers	2	923.02	461.511	156.86	0.000
Error	127	373.65	2.942		
Lack-of-Fit	15	52.92	3.528	1.23	0.259
Pure Error	112	320.73	2.864		
Total	131	1983.66			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.71526	81.16%	80.57%	79.43%

Regression Equation

Number of Layers			
3	Loading Time (min)	=	-7.08 + 0.004710 Billet Width (mm) + 0.000080 Billet Length (mm)
5	Loading Time (min)	=	-3.28 + 0.004710 Billet Width (mm) + 0.000080 Billet Length (mm)

Figure 3-6 - Analysis outputs and regression equations for press loading time of 3- and 5-layers billets

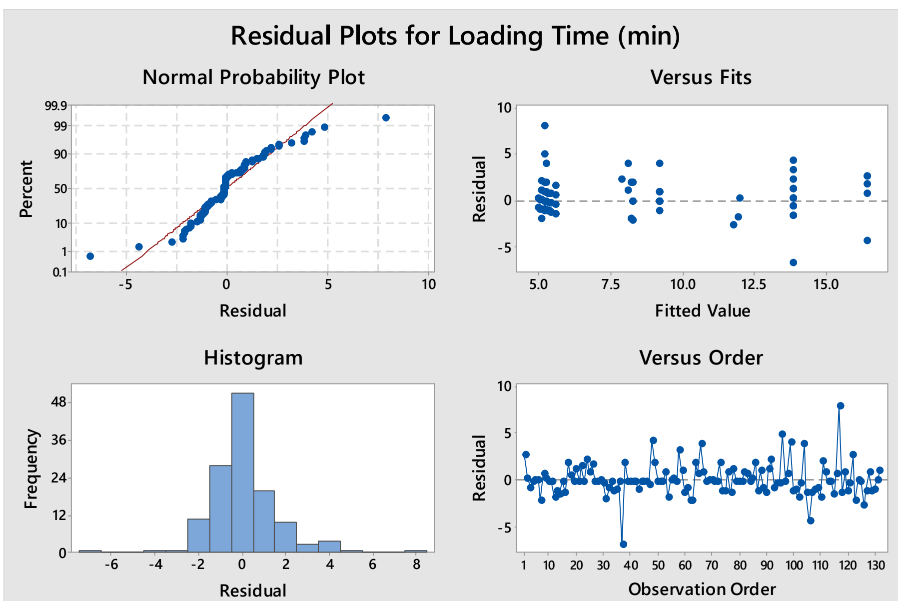


Figure 3-7 - Residuals plots for press loading time of 3- and 5-layers billets

Analysis of Variance for Transformed Response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	21.7211	5.43028	112.65	0.000
Billet Width (mm)	1	2.2166	2.21658	45.98	0.000
Billet Length (mm)	1	0.1350	0.13501	2.80	0.097
Number of Layers	2	10.6548	5.32740	110.52	0.000
Error	127	6.1219	0.04820		
Lack-of-Fit	15	1.1241	0.07494	1.68	0.065
Pure Error	112	4.9977	0.04462		
Total	131	27.8430			

Method

Categorical predictor coding	(1, 0)
Box-Cox transformation	
Rounded λ	0
Estimated λ	0.149428
95% CI for λ	(-0.186072, 0.468928)

Model Summary for Transformed Response

S	R-sq	R-sq(adj)	R-sq(pred)
0.219553	78.01%	77.32%	76.41%

Regression Equation

Number of Layers			
7	ln(Loading Time (min))	=	0.813 + 0.000595 Billet Width (mm) + 0.000024 Billet Length (mm)

Figure 3-8 - Analysis outputs and regression equations for press loading time of 7-layers billets

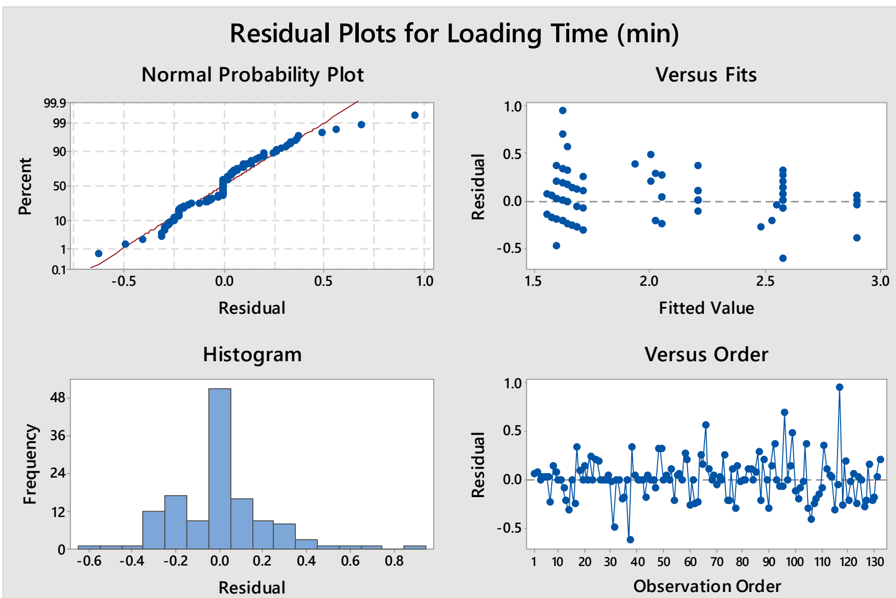


Figure 3-9 - Residuals plots for press loading time of 7-layers billets

Similarly, Figure 3-10 and Figure 3-11 show the analysis output, residuals plots, and regression equations for Unloading Times of 3-, 5-, and 7-layers categorical values.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1925.85	481.462	77.41	0.000
Billet Width (mm)	1	131.87	131.871	21.20	0.000
Billet Length (mm)	1	0.48	0.484	0.08	0.781
Number of Layers	2	1094.11	547.057	87.96	0.000
Error	128	796.12	6.220		
Lack-of-Fit	16	124.61	7.788	1.30	0.210
Pure Error	112	671.51	5.996		
Total	132	2721.97			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.49393	70.75%	69.84%	67.49%

Regression Equation

Number of Layers			
3	Unloading Time (min)	=	-10.23 + 0.00500 Billet Width (mm) + 0.000044 Billet Length (mm)
5	Unloading Time (min)	=	-3.27 + 0.00500 Billet Width (mm) + 0.000044 Billet Length (mm)
7	Unloading Time (min)	=	-1.57 + 0.00500 Billet Width (mm) + 0.000044 Billet Length (mm)

Figure 3-10 - Analysis outputs and regression equations for press unloading time of 3-, 5-, and 7-layers billets

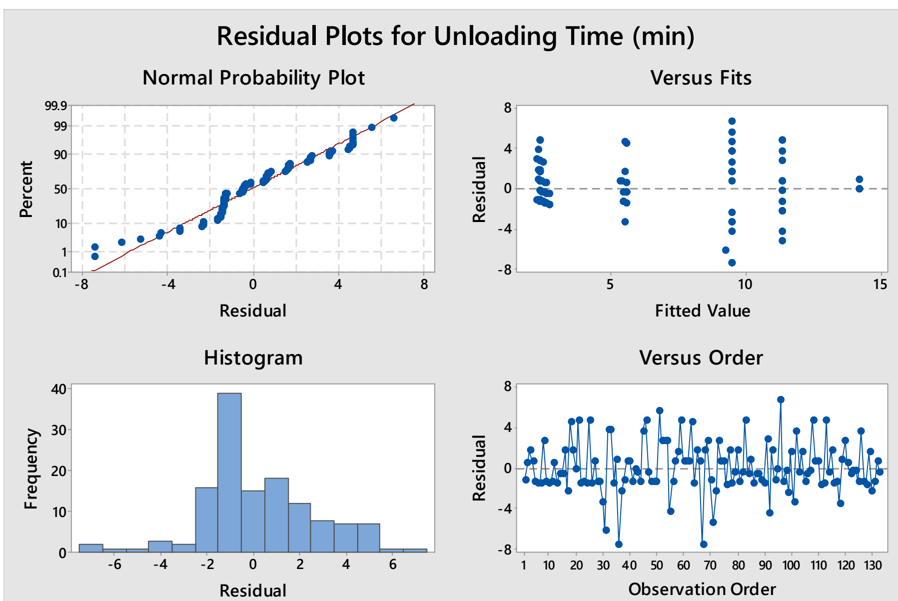


Figure 3-11 - Residuals plots for press unloading time of 3-, 5- and 7-layers billets

From the regression outputs p-values it is possible to see that the billet length is the least significant factor in the model, and could be virtually excluded from the equations, with close to no impacts to the forecasted values. However, there is no indication that this behavior is specific to the sampled analysis. Therefore, to maintain consistency to the idealized model, billet length was kept as an independent variable.

Also note that some of the derived regression equations have negative intercept parameters. This means that, for sufficiently small billets, negative loading or unloading times could be predicted by the model. To amend this drawback and avoid crude mistakes in forecasting, the regression equations were re-written, and conditional parameters were added, according to the minimum observed values for both components on each category.

Even though the residuals plots confirmed the normality of the distribution (see normal probability residuals plots), the fitted values of residuals showed unequal variances. This fact suggests that non-linear models could be a better fit to the data, however the assumed linearity yields reasonably accurate results. Additionally, considering the Analysis of Variance tables shown in Figures 3-6, 3-8 and 3-10, the P-values for lack-of-fit are not significant. Therefore, there is not enough evidence at a 95% confidence level to conclude that there is a lack-of-fit on any of the multiple linear regression models.

Although 9-layer billets are also considered in the conventional CLT panel layup options (see Figure 3-3), no billets with these characteristics were observed during the data collection period. Henceforward, to grant the model its desired flexibility, it was stablished that, for 9-layer billets, loading and unloading intervals are going to be three times the estimated time of a 3-layer billet with the same width and length. The derived equations for press loading and unloading times are as follows:

$$p_{i,PLT} = \begin{cases} lay = 3 \rightarrow \max\{-7.08 + 0.00471wd + 0.00008l\,; 3\} \\ lay = 5 \rightarrow \max\{-3.28 + 0.00471wd + 0.00008l\,; 8\} \\ lay = 7 \rightarrow \max\{\exp(0.813 + 0.000595wd + 0.000024l)\,; 12\} \\ lay = 9 \rightarrow \max\{3(-7.08 + 0.00471wd + 0.00008l)\,; 15\} \end{cases} \qquad \textbf{Equation 7}$$

$$p_{i,PUT} = \begin{cases} lay = 3 \rightarrow \max\{-10.23 + 0.005wd + 0.000044l\,; 1\} \\ lay = 5 \rightarrow \max\{-3.27 + 0.005wd + 0.000044l\,; 3\} \\ lay = 7 \rightarrow \max\{-1.57 + 0.005wd + 0.000044l\,; 6\} \\ lay = 9 \rightarrow \max\{3(-10.23 + 0.005wd + 0.000044l\,); 9\} \end{cases} \qquad \textbf{Equation 8}$$

where, lay, wd, and l are the number of layers, rough width and length in millimeters (mm) of the ith billet.

3.3.2 Pressing time

The observed pressing times were relatively consistent to the premise of fixed pressing times, given by both plant management and literature. Nevertheless, according to section 3.2.2.1, the significant variation observed in the pressing times was attributed to the error component of uncontrollable labor-related factors. For example, sometimes, even though the prescribed pressing time was finished, the operator could be involved on a secondary activity, or on his resting or lunch time, leading to longer observed pressing times. Figure 3-12 and Figure 3-13 show the Boxplot and Histogram of the observed pressing times.

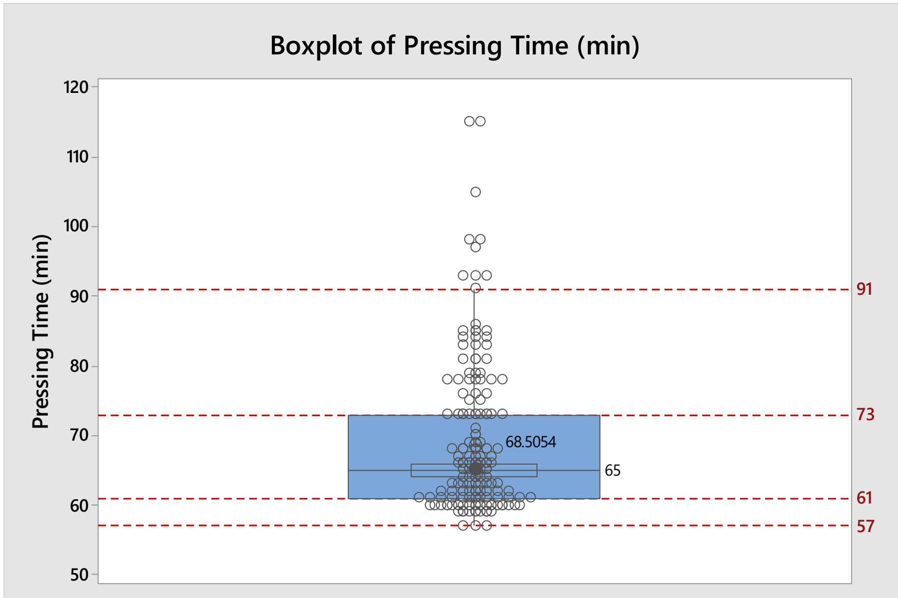


Figure 3-12 - Boxplot of pressing times

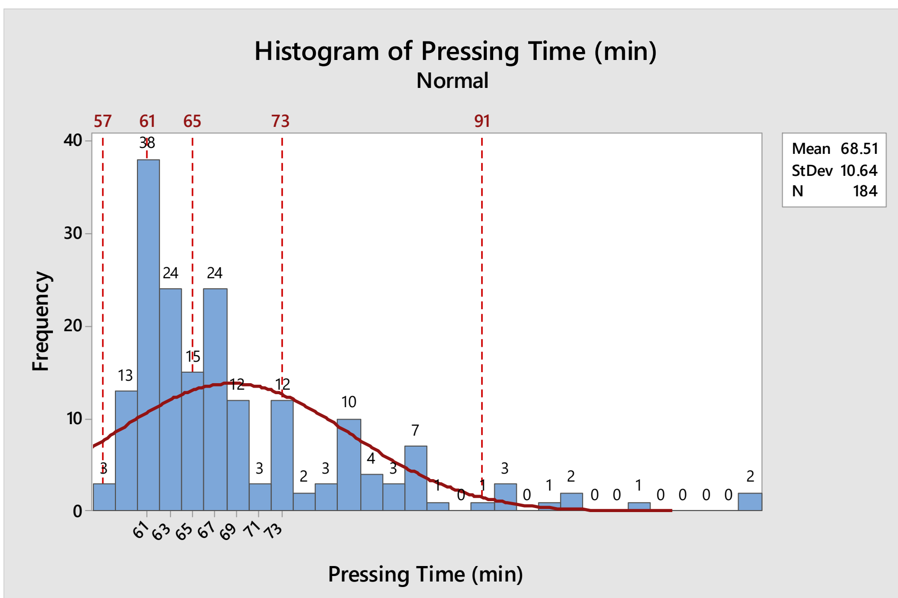


Figure 3-13 - Histogram of pressing times

Note that the observed pressing times are highly concentrated between 57 and 73 minutes. The mean is approximately 69 minutes, with first and third quartiles at 61 and 73 minutes, respectively. Therefore, as the pressing time cannot be precisely assigned and depend on the subjective judgment of an estimator, the following ordinary triangular fuzzy membership function was created to explain the expected pressing time for all billets. The defined lower and upper boundaries to the fuzzy number were the first and third quartiles of the distribution, respectively, with the middle term being expressed by the mean. Thus, the fuzzy pressing time can be represented with the triangular fuzzy number (61,69,73), as shown in Figure 3-14.

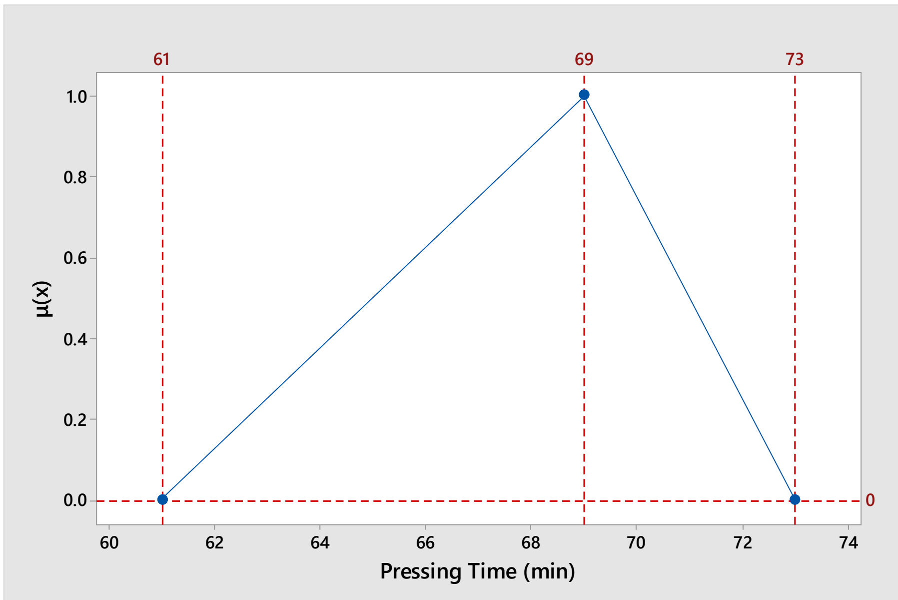


Figure 3-14 - Ordinary triangular fuzzy membership function for pressing time

Solving the centroid method described by Equation 4, for the proposed fuzzy set, the estimated pressing time component of the total pressing process time is approximately 68 minutes.

$$p_{i,PT} = 68$$

3.3.3 Press waiting time and setup time

The observed waiting and setup times distribution was analyzed with a similar approach to the pressing times. There was no available data or reasonable rationale/relationship to develop a prediction model for waiting and setup times. Figure 3-15 and Figure 3-16 show the Boxplot and Histogram of the observed waiting and setup times.

Analyzing the distribution, the first and third quartile are 4 and 13, respectively, and the mean, about 12 minutes.

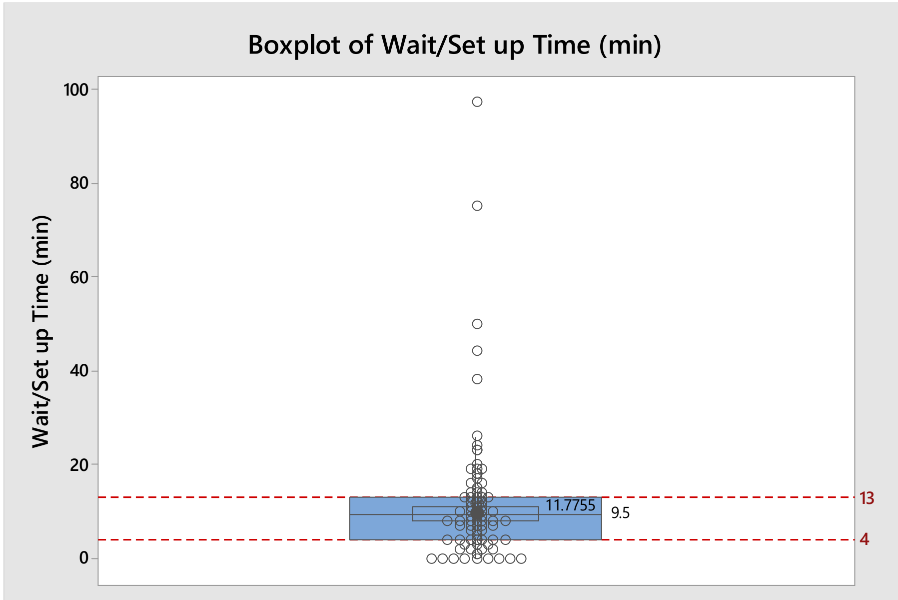


Figure 3-15 - Boxplot of press waiting and setup times

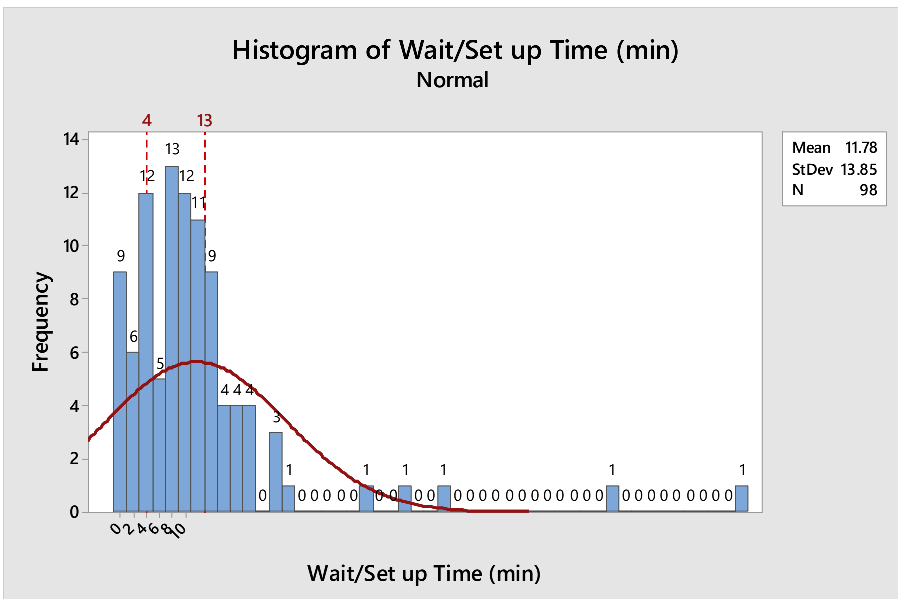


Figure 3-16 - Histogram of press waiting and setup times

Using the same criterion to the pressing time analysis, the resulting ordinary triangular fuzzy membership function for waiting and setup time in between cycles is shown in Figure 3-17, or by the triangular fuzzy number (4,12,13).

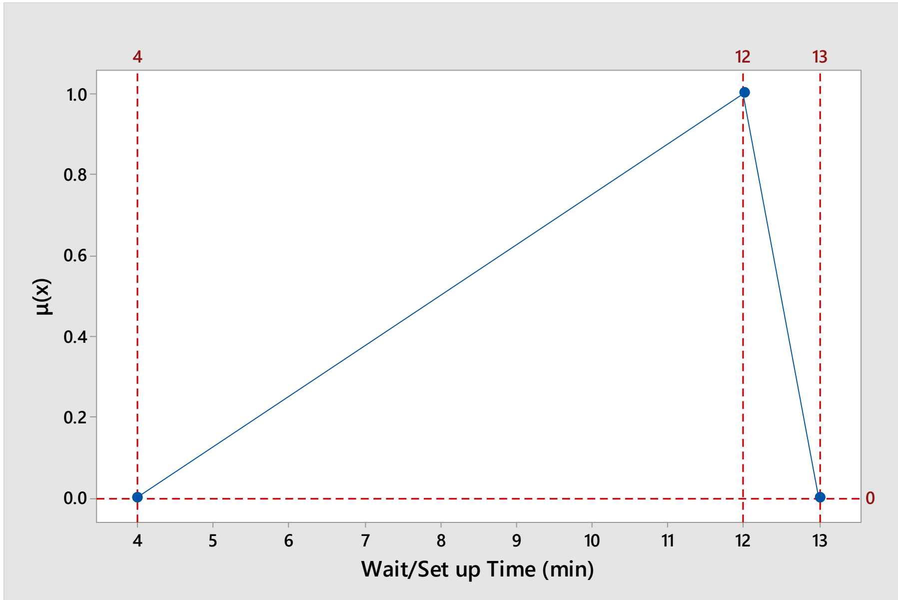


Figure 3-17 - Ordinary triangular fuzzy membership function for press waiting and setup time

Finally, the defuzzified crisp value to for the waiting and setup time component of the Pressing time model is approximately 10 min, also using the centroid method depicted by Equation 4.

$$p_{i,PWT} = 10$$

3.3.4 CNC router cutting time

As described in section 3.2.2.2, the CNC process time is estimated by a single component, encapsulating all substages of this process (i.e. loading, setup, cutting and unloading times). As explained, billet width and length were not included as independent variables. Figure 3-18 and Figure 3-19, show the analysis output, residuals plots, and regression equations for the total CNC process time of each billet.

Note that like in the pressing stage, the residuals plots confirm the normality of the distribution and that, in this case, the residuals also showed randomly distributed variances, confirming linearity. Likewise, the model showed reasonable lack-of-fit. Still considering the Analysis of Variance table shown in Figure 3-18, even though the P-value for the waste % parameter is the least significant in the model, it is important to keep it as it relates to how much time is spent removing waste during the cutting process.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	95338	19067.7	34.08	0.000
NUMBER OF PARTS	1	3435	3435.3	6.14	0.015
WASTE %	1	2648	2648.3	4.73	0.032
SOFTWARE ESTIMATED TIME	1	41589	41589.2	74.34	0.000
LAYERS	2	9882	4940.9	8.83	0.000
Error	104	58183	559.5		
Lack-of-Fit	69	40667	589.4	1.18	0.303
Pure Error	35	17516	500.5		
Total	109	153521			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
23.6527	62.10%	60.28%	57.13%

Regression Equation

LAYERS			
3	TOTAL PROCESS TIME	=	1.13 + 9.77 NUMBER OF PARTS + 52.5 WASTE % + 2.567 SOFTWARE ESTIMATED TIME
5	TOTAL PROCESS TIME	=	14.33 + 9.77 NUMBER OF PARTS + 52.5 WASTE % + 2.567 SOFTWARE ESTIMATED TIME
7	TOTAL PROCESS TIME	=	25.09 + 9.77 NUMBER OF PARTS + 52.5 WASTE % + 2.567 SOFTWARE ESTIMATED TIME

Figure 3-18 - Analysis outputs and regression equations for total CNC time of 3-, 5-, and 7-layers billets

Note from the analysis of variance that all elected independent variables are significant to the regression model. As expected, the closer relationship and significance level can be attributed to the CNC software estimated time.

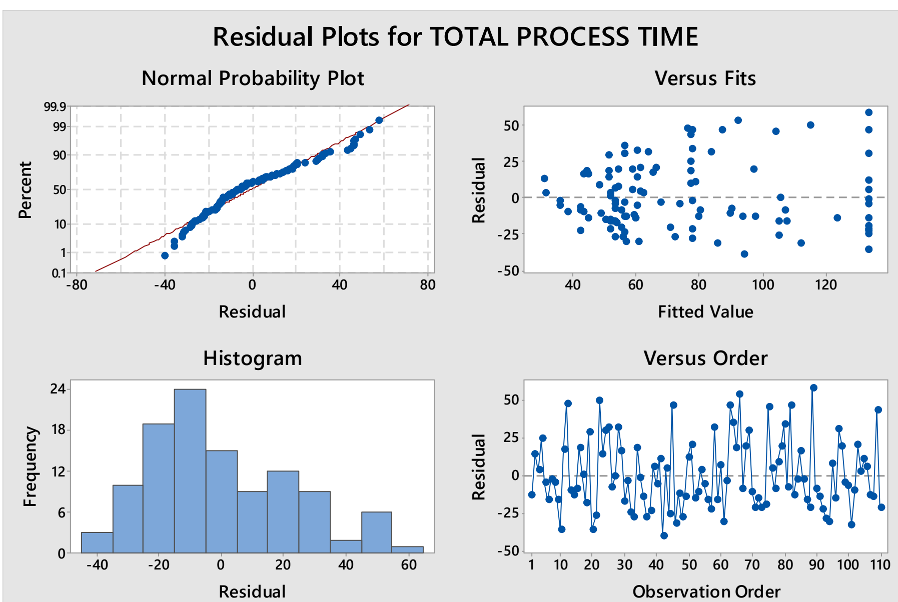


Figure 3-19 - Residuals plots for total CNC time of 3-, 5-, and 7-layers billets

It is important to mention that the CNC router cutting time estimation model assumes that every billet processed by the PBA is not going to be interrupted, i.e., once a billet enters the stage, all necessary processes are going to be executed until the job is completely done. The same premise (no preemptions) is considered in generic flow shop scheduling models (Haupt 1989).

Similar to the pressing stage, no 9-layers billets were observed during the data collection period. To maintain model flexibility, eventual 9-layer billets' CNC process time are going to be estimated by the 7-layers equation corrected by the average of ratios between the estimated time of 5-layers and 3-layers equations, and between the estimated time of 7-layers and 5-layers equations. The equations for total CNC process time are as follows:

$$\boldsymbol{p_{i,CNC}} = \begin{cases} \boldsymbol{lay = 3 \rightarrow 1.13 + 9.77np + 52.5wt\% + 2.567set} \\ \boldsymbol{lay = 5 \rightarrow 14.33 + 9.77np + 52.5wt\% + 2.567set} \\ \boldsymbol{lay = 7 \rightarrow 25.09 + 9.77np + 52.5wt\% + 2.567set} \\ \boldsymbol{lay = 9 \rightarrow p_{i,CNC}^{CNC(9\ lay)} = p_{i,CNC}^{CNC(7\ lay)} \frac{\left(\frac{p_{i,CNC}^{CNC(5\ lay)}}{p_{i,CNC}^{CNC(3\ lay)}} + \frac{p_{i,CNC}^{CNC(7\ lay)}}{p_{i,CNC}^{CNC(5\ lay)}}\right)}{2}} \end{cases} \qquad \textbf{Equation 9}$$

where, $p_{i,CNC}$ is the total CNC process time in minutes (min), np is the number of cut parts, lay is the billets' number of layers, $wt\%$ is the waste generation percentage, set is the coding software CNC estimated process time in minutes (min), and $p_{i,CNC}^{CNC(x\ lay)}$ is the process time for the ith billet in the CNC stage, using the x-layers equations above.

3.3.5 Finishing and quality control time

Like the CNC process, FQC time was also estimated in a single component. Therefore, a single global process time was collected for each job encapsulating all subprocesses in the stage (i.e. loading, flipping, protecting, rearranging, sanding and measuring). However, as explained in section 3.2.2.3, FQC and packaging times were separated. Figure 3-20 and Figure 3-21, show the analysis outputs, residuals plots, and regression equation for the total FQC process time of each panel.

Note that like in the pressing stage, the residuals plots confirm the normality of the distribution and that, in this case, the residuals also showed randomly distributed variances, confirming linearity. Likewise, the model showed reasonable lack-of-fit.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	42669	14223.0	58.50	0.000
Work Area (m^2)	1	19736	19736.4	81.18	0.000
Visual faces	2	25853	12926.4	53.17	0.000
Error	79	19207	243.1		
Lack-of-Fit	55	15077	274.1	1.59	0.106
Pure Error	24	4130	172.1		
Total	82	61876			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
15.5924	68.96%	67.78%	63.57%

Regression Equation

Visual faces			
0	Finsihing time (man x min)	=	-2.35 + 1.176 Work Area (m^2)
1	Finsihing time (man x min)	=	29.10 + 1.176 Work Area (m^2)
2	Finsihing time (man x min)	=	53.02 + 1.176 Work Area (m^2)

Figure 3-20 - Analysis outputs and regression equations for total FQC time of panels with 0, 1 and 2 visual faces

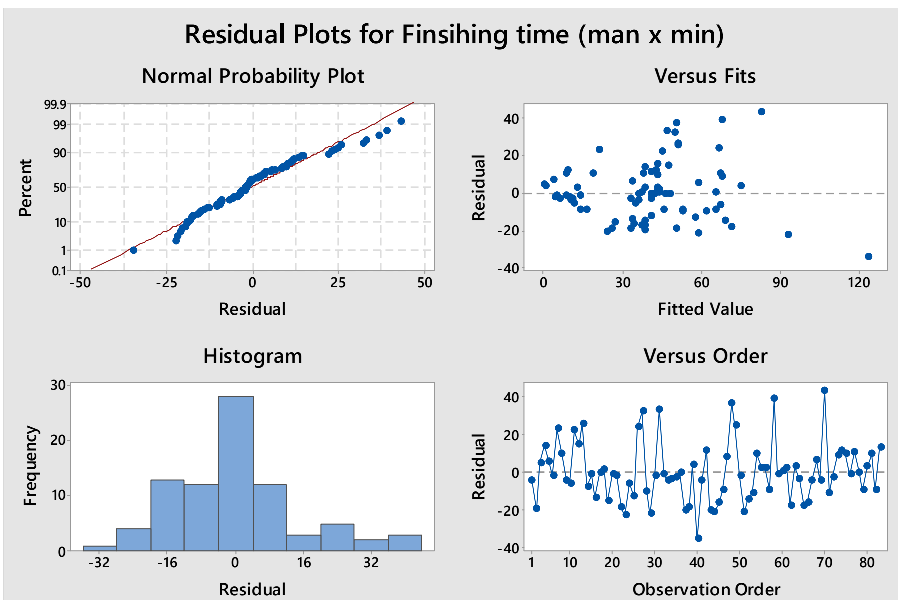


Figure 3-21 - Residuals plots for total FQC time of panels with 0, 1 and 2 visual faces

Note that like in the pressing stage, the residuals plots confirm the normality of the distribution and that, in this case, the residuals also showed randomly distributed variances, confirming linearity. Likewise, the model showed reasonable lack-of-fit.

Furthermore, when the number of visual faces is zero, the derived regression equation has a negative intercept parameter. This means that, for sufficiently small panel, negative FQC process times could be predicted by the model. To amend this drawback and avoid crude mistakes in forecasting, the regression equation was re-written, and a conditional parameter was added, according to the minimum observed value for the zero visual faces category.

$$p_{i,FQC} = \begin{cases} vf = 0 \rightarrow \max\{-2.35 + 1.176 \cdot rwd \cdot rl\,;\ 2\} \\ vf = 1 \rightarrow 29.10 + 1.176 rwd \cdot rl \\ vf = 2 \rightarrow 53.02 + 1.176 rwd \cdot rl \end{cases} \qquad \textbf{Equation 10}$$

where, $p_{i,FQC}$ is the total FQC nominal process time in man x minutes (man x min), vf is the number of visual faces, rwd and rl are the rough width and length in meters (m) for panel i.

3.3.6 Packaging time

The results of the regression analysis for packaging time are shown in Figure 3-22 and Figure 3-23. Note that the number visual faces was not a significant parameter in the regression equation.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	9166.9	3055.63	18.42	0.000
Rough area (m²)	1	1299.5	1299.53	7.83	0.007
Bundle Size	1	8114.5	8114.47	48.91	0.000
Visual Faces	1	5.0	5.02	0.03	0.863
Error	46	7631.1	165.89		
Lack-of-Fit	35	6353.4	181.53	1.56	0.218
Pure Error	11	1277.7	116.15		
Total	49	16798.0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
12.8800	54.57%	51.61%	46.77%

Regression Equation

Packaging time (man x min) = -5.87 + 0.667 Rough area (m^2) + 23.92 Bundle Size + 0.70 Visual Faces

Figure 3-22 - Analysis outputs and regression equations for total packaging time

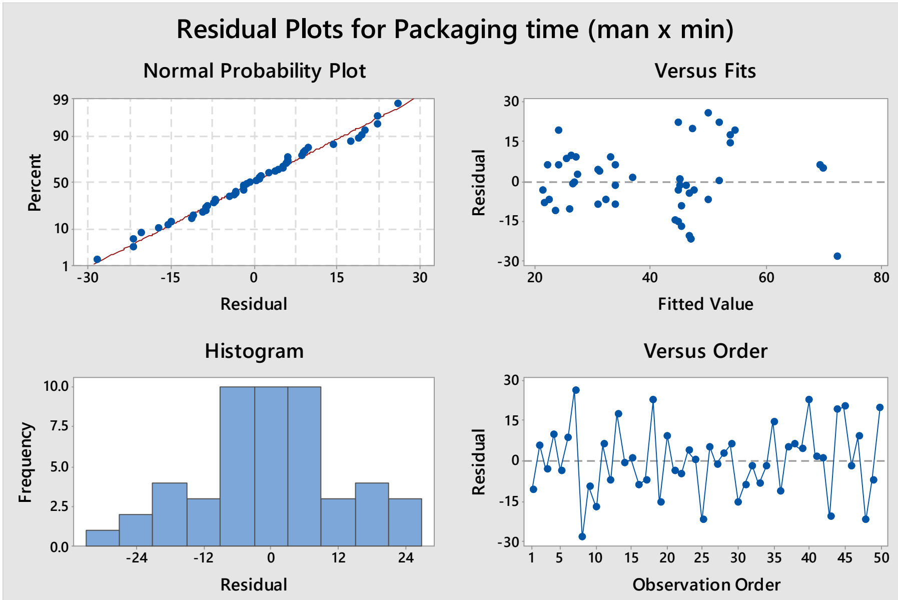


Figure 3-23 - Residuals plots for total packaging time

However, even though the number of visual faces was not significant, it was kept in the equation as it can be used for future model calibration, when more data is available. Furthermore, the model needed to be corrected due to the data limitation regarding the number of panels in each bundle wrapping observation. As only bundles up to three panels were observed, the regression equation was providing too unrealistically high estimations to bundles composed of four or more panels. Therefore, the bundle size component in the equation was converted to a logarithmic scale, providing more reasonable estimations for larger bundle sizes.

The equation below shows the developed and corrected model for panel packaging time.

$$p_{i,PACK} = -5.87 + 0.667(rwd \cdot rl) + 23.92(1 + \log(bs)) + 0.7vf \quad \textbf{Equation 11}$$

where, $p_{i,PACK}$ is the total packaging nominal process time in man x minutes (man x min), vf is the number of visual faces, bs is the bundle size in number of panels, rwd and rl are the rough width and length in meters (m) for panel i.

3.4 Model validation

The findings of the production process map exposed drawbacks and constraints inherent to customizable CLT panel manufacturing process. The production process map development was crucial in identifying the requirements and particularities of customizable CLT panel.

3.4.1 Case-specific production process map

The specific production process observed at the Okanagan Falls CLT plant laid the foundations to defining the time estimation models. However, by analyzing the developed process flowchart and process map, it is possible to draw a few comments, in addition to the diagnosis of each production stage, already described in section 3.2.1.

As can be observed in Figure 3-2, the second and third production stages are not sequentially placed in the plant. The disposition of the buffer areas is also not ideal. The convolutedness in material, equipment and labor flow displayed in Figure 3-2, shows how important the plant layout is in a manufacturing system. This situation is potentialized when panel rearranging must be constantly executed in the plant due to sequenced load requirements. Were the warehouse a little longer, intermediate buffer areas could be placed among each production stage, as well alongside the service corridor, reducing material handling time. Another measure that could simplify material flow and reduce material movement and interrelated machine distance is switching CNC and FQC stations placement.

Additionally, plant layout re-organization could potentially allow for more intermediate buffer storage areas, especially for the finishing stage. In projects with smaller jobs, several unfinished panels are completed and leave the CNC stage in a short time span, overflowing the FQC stage and causing several panel shuffles. In this regard, having extra buffer capacity after the CNC stage is beneficial in reducing the number of panel shuffles.

Due to the production bottleneck in the CNC stage, production management should focus in maximizing the CNC stage output, even if this means shutting down the pressing stage from time to time.

3.4.2 Data splitting validation

Using the remaining randomly selected 30% of the database, all developed time models were validated. Predicted values were plotted against the real observed values in the validation sample for each process time component. The coefficient of determination R^2 calculated for each component is shown in Figure 3-24 and Figure 3-25 for the press loading and unloading models, Figure 3-26 for the CNC total process time model and Figure 3-27 and Figure 3-28 for the FQC and packaging models, respectively.

Regarding pressing time and the press waiting and setup time components, as it was not possible to perform regression analysis to estimate them and based on the inputs from plant management and field personnel, these two components were considered validated, according to the fuzzy numbers generated on section 3.3.2 and 3.3.3.

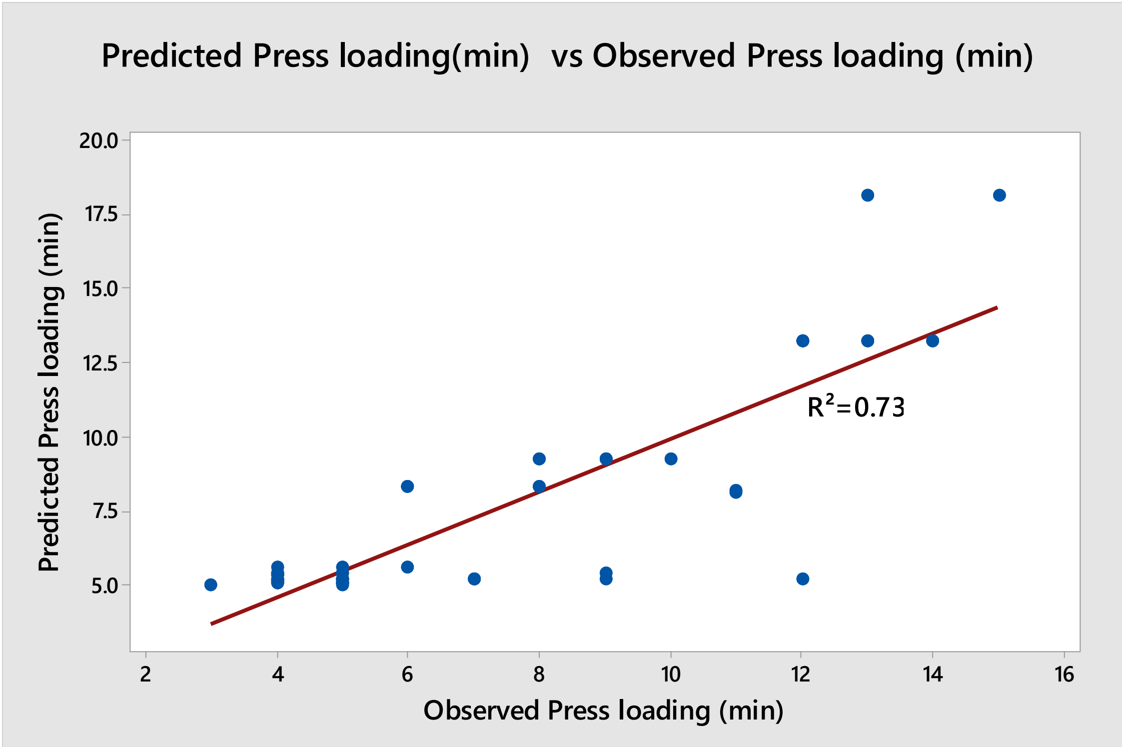


Figure 3-24 - Data-splitting validation of the press loading time model

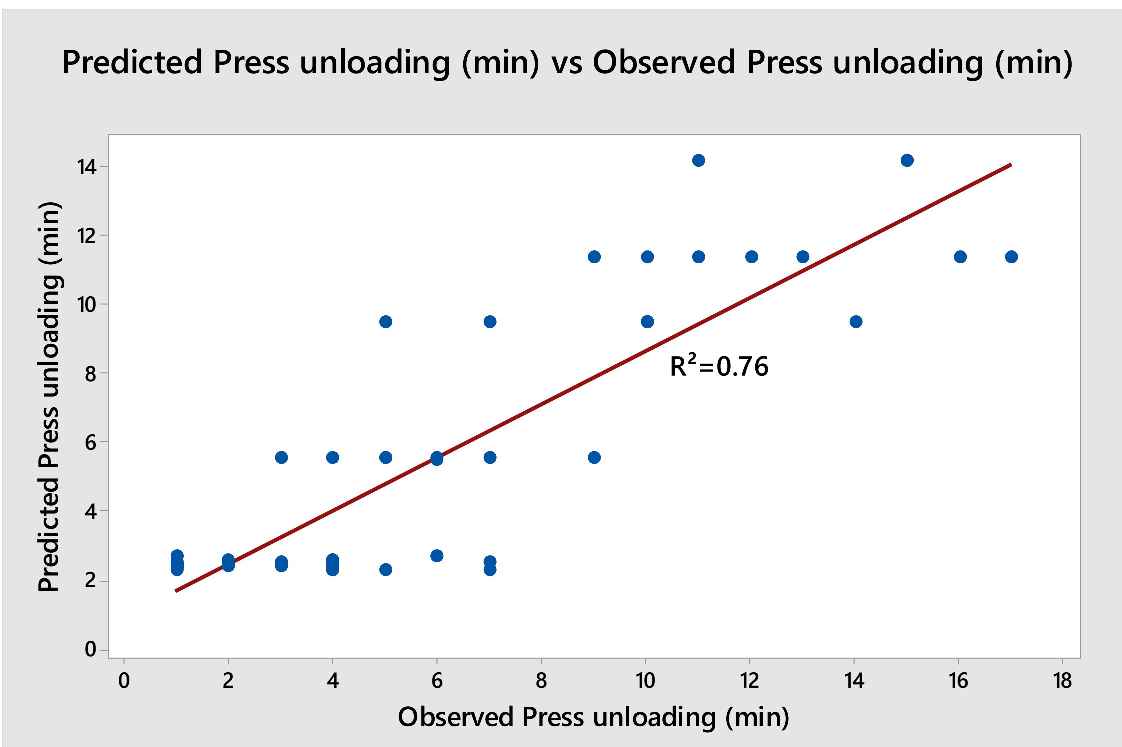


Figure 3-25 - Data-splitting validation of the press unloading time model

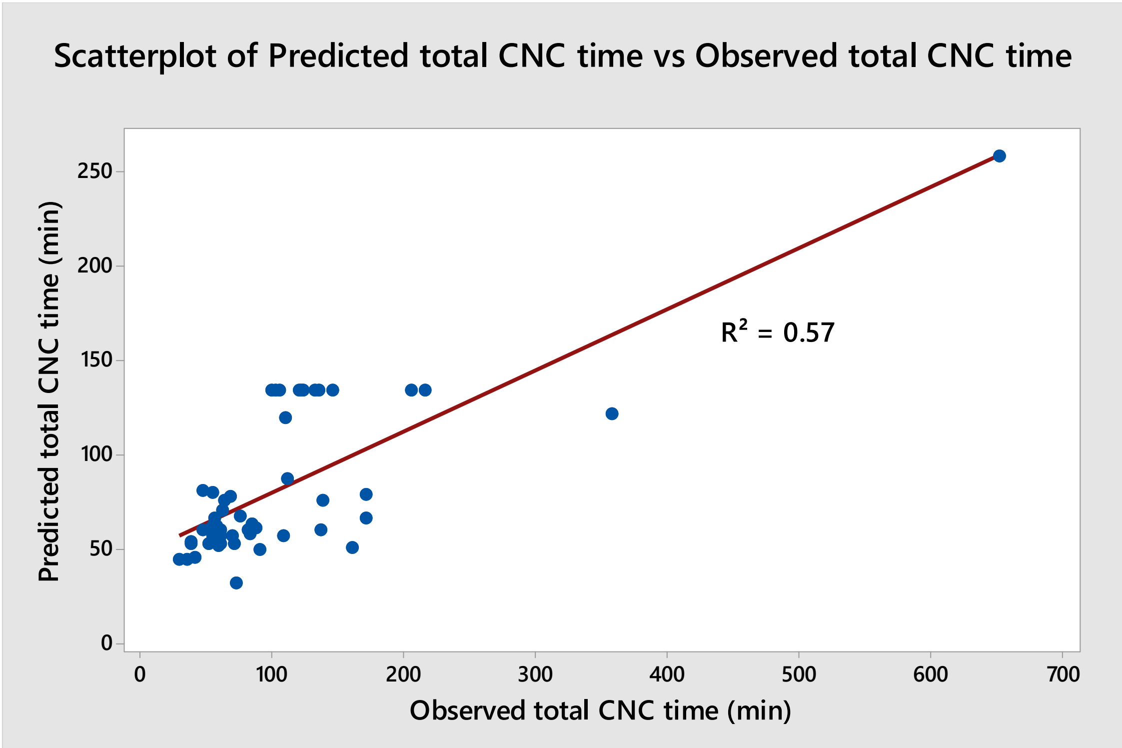


Figure 3-26 - Data-splitting validation of the total CNC process time model

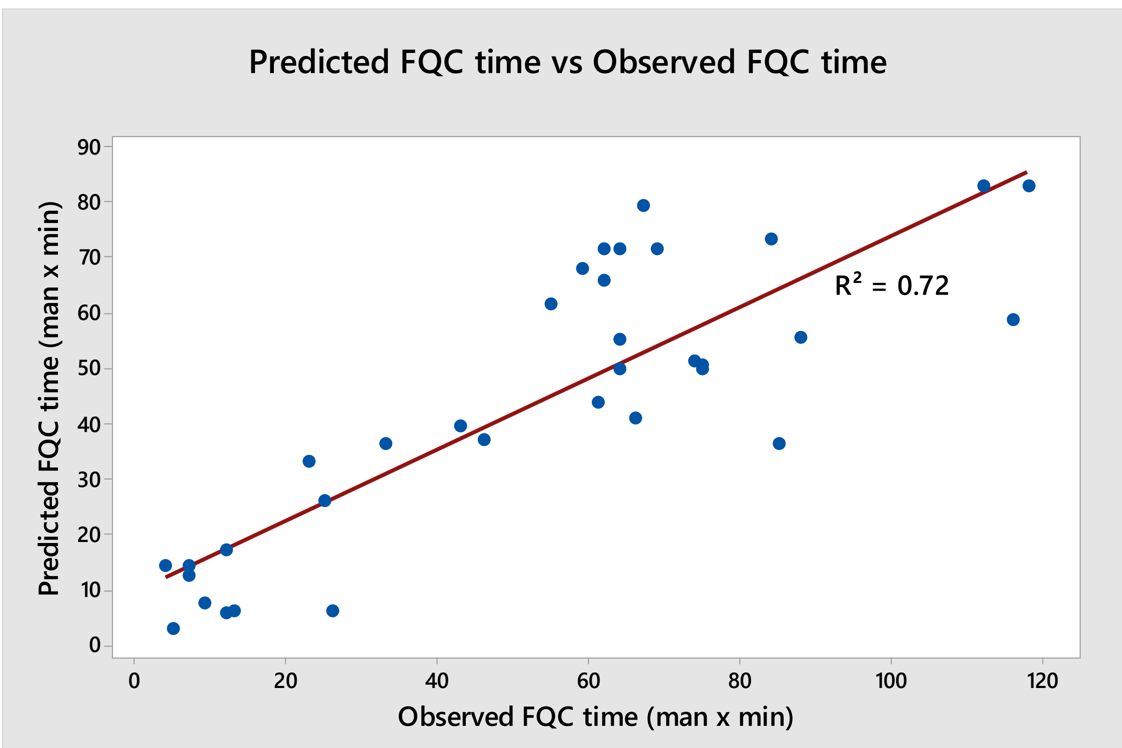


Figure 3-27 - Data-splitting validation of nominal FQC process time model

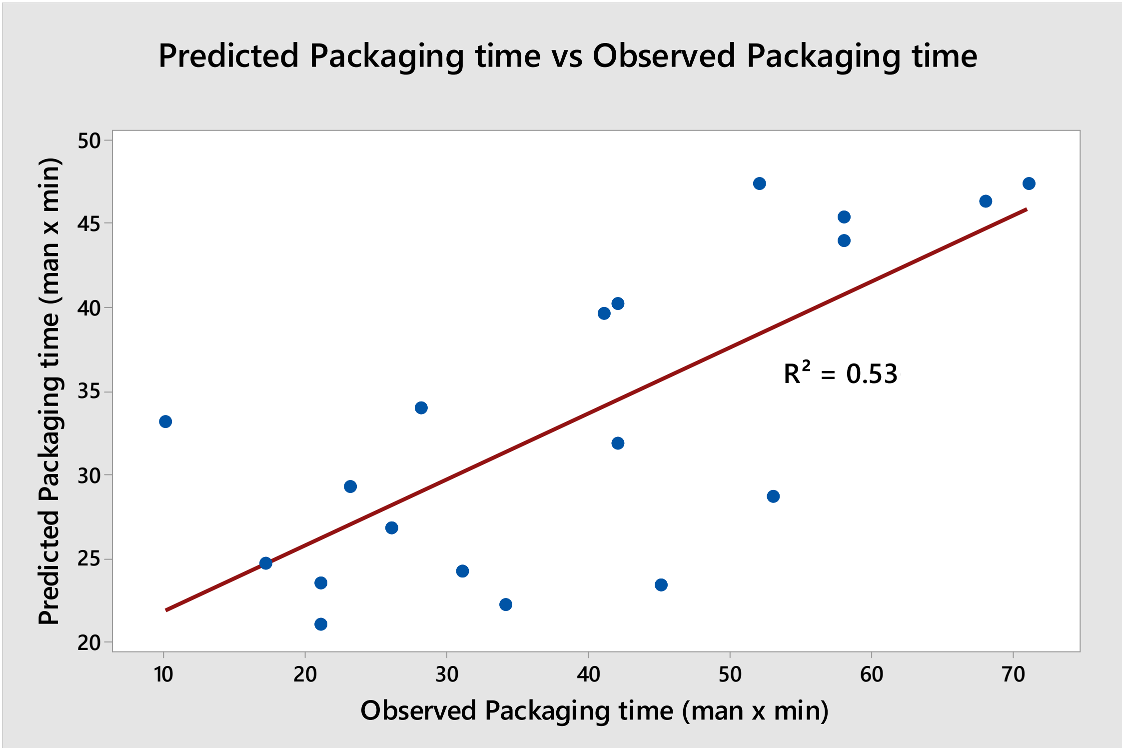


Figure 3-28 - Data-splitting validation of nominal packaging process time model

From each figure above, note that R^2 values range from 0.76 to 0.53 for the proposed models. Although the goodness-of-fit is not ideal, the range of behavioral variance explained by the models is enough for its purpose. The validation graphics shown in the figures above present a few outliers and not-so-well-fitted values. However, although the percental errors might be significant, the absolute errors in minutes are not significant, especially considering human-aided manufacturing processes, dealing with uncertainty. The tables presented in Appendices A to E show the validation data for each model, the predicted and observed process times for each billet or panel and the percentage error for each prediction.

3.4.3 Discussion

Whereas the developed models are going to be applied in uncontrolled, highly susceptible-to-human-interference environments, they are capable of capturing process dynamics, providing feasible and practical approximations for the process times, with limited and easy-to-acquire input data.

Each model has different predicting capacity and limitations. The pressing stage model, for instance, is heavily dependent on the estimated pressing time, which in turn, should be defined by an expert, adding more uncertainty to the estimation. For the CNC and FQC stages models, as the total fitted process time increases, the error and uncertainty level also increase, as more human interference is expected to happen during the cutting and finishing process. Likewise, for the packaging stage, data limitations lead to models that are good approximations for bundles up to three panels. Less precise approximations are expected when this model is used for forecasting packaging times of bundles composed of four or more panels. Additionally, although rare in real situations, the production of 9-layers panels is still a possibility. However, due to inexistent data, the proposed models for 9-layer panels have not been verified and could result in unrealistic approximations.

Plant management and CLT experts corroborated the achieved results and estimated process times. Experts further added that, as uncertainty factors are still a significant component in the customizable CLT panel manufacturing process, efforts should be directed to develop stochastic models that consider uncontrollable confounding factors in the analysis. The linear regression approach developed in this section provided a simple, efficient and easy way to predict manufacturing process times of future projects. Nevertheless, different modelling approaches, more fitting to uncertainty-ruled scenarios could also be explored, such as fuzzy set theory or Monte-Carlo simulation.

It is important to emphasize that the developed process time estimation models are specific to the plant conditions, employed equipment and production process to which they were developed. It is expected to be a good estimation for the process at hand, according to validation and test results. However, much higher scrutiny should be used when applying the proposed models to different CLT manufacturing systems. Re-calibrating, adapting and re-validating results is highly recommended. In fact, plant management careful scrutiny is advised when using any of the proposed models.

3.5 Summary

Manufacturing process times are one of the most important inputs necessary to production scheduling. To properly understand the customized CLT panel manufacturing process, production constraints, capacities and limitations, a production process map of a CLT manufacturing plant was developed. The process map also laid conditions to develop a thorough process observation study.

The field observations provided the necessary empirical data to develop process time estimation models of each production activity in customized CLT panel manufacturing. The developed process time estimation models were validated using data splitting technique and provide reasonably accurate predictions, with simple and easy-to-acquire input data.
According to the study methodology, the developed process time estimation models will be used to feed the production scheduling algorithm described in the next chapter.

Chapter 4: Scheduling model

Based on the inputs provided by the process map and the process time estimation models, a scheduling algorithm was developed. This chapter describes in detail how the scheduling algorithm works, the necessary inputs and the provided outputs. A scheduling tool dubbed as the Scheduling Heuristic Rule-Based Simulation Model for CLT Products (SCHER-CLT) was developed to integrate the process time estimation models, scheduling input importing procedures, scheduling algorithm and outputs printing. Following, the scheduling model is put to test under a case study for a real commercial project with a demonstration of SCHER-CLT. The results of the case study and scheduling simulation scenarios are analyzed.

4.1 Background

Manufacturing production scheduling have the potential to greatly increase process efficiency, reduce production time, minimize costs and enhance productivity (Sun and Yu 2015). Manufacturing scheduling applied research has focused on several specific production processes and optimization objectives. The results and perceived benefits of scheduling optimization are directly related with how the scheduling model is built, as well as what are the optimization objectives.

The first objective of this scheduling algorithm is to minimize the average finishing and wrapping time of a single package bundle (i.e., whenever a panel belonging to a certain package bundle is completed, the schedule should prioritize their mates, to minimize to total finishing and wrapping time of that bundle). At the same time, it is a second objective to minimize the number of panel shuffles in the buffer areas (i.e., when the priority panel is not placed in the top position of a stack pile causing panel shuffles) before each stage. Lastly, it is desirable that the bundle finishing order follows an intuitive increasing order according to the assembly sequence of the customizable panels on the construction field. As bundles are labeled in an ascending manner following the panels' assembly order on field, lower package bundle and truck load IDs should be finished earlier.

These objectives themselves are a novelty as most optimization research studies focuses on simplified flow shop problems with makespan or other time-related objective (e.g. earliness, tardiness, total slack), and error bound analysis (Emmons and Vairaktarakis 2013). In real-life flow shop applications the most common pursued objectives also relate to time metrics such as minimum flow time (Lin and Chen 2015), mean flow time, mean tardiness, and the number of tardy jobs (Choi et al. 2011), total tardiness (Jun and Park 2015; Yalaoui et al. 2013), combined total makespan and total tardiness (Yang and Xiaobing 2008), shortest processing time, earliest dues date and longest processing time (Azami et al. 2018), weighted mean completion time (Gholami-Zanjani et al. 2017), total weighted completion time (Sun and Yu 2015), and weighted tardiness (Voß and Witt 2007). Needless to say, this concise list is non-exhaustive.

The CLT production management experts who contributed to this research were adamant in emphasizing the importance of finalizing CLT package bundles as soon as possible. This measure is effective in preventing finishing stage blocking and, therefore, avoiding additional panel shuffling.

Field personnel opinions and field observations proved how costly and time-demanding are unnecessary panel shuffles in the sequenced CLT production line. It was possible to observe long periods of unproductive activities on field, when the workers were basically shifting panels around and organizing the buffer areas. However, the real damage in productivity happens on the routine loading and unloading procedures that frequently take almost double the expected time due to panel shuffles.

Another important issue relates to the additional exposure to work accidents. Shuffling panels involve higher risk than regular production processes, as heavy machinery and moving components are used to lift and move heavy panels around. Therefore, by minimizing panel shuffles, it is expected to reduce workers' exposure level to work accidents.

However, it is not easy to consider such constraints in a manufacturing scheduling problem. The complexity of flow shop problems is greatly increased when real-life applications with operational constraints must be accounted for (Lin and Chen 2015). Depending on the size of the presented project, an optimal solution might not be achievable due to computational limitation (Paolucci and Sacile 2005). Even the formulation of a single objective function to achieve the objectives described above is extremely complex, since they are conflicting parameters under buffer capacity limitations. Empirical evidence from previous studies show that analytical approaches are usually not applied to address real-case industrial problems with unconventional constraints and objectives (Emmons and Vairaktarakis 2013; Jeong and Kim 1998; Kang and Choi 2013; Lin and Chen 2015; Min Hee Kim and Kim 1994; Parthanadee and Buddhakulsomsiri 2010; Pinedo 2008; Vaidyanathan and Park 1998).

Due to the intricate interrelationships among job parameters, plant limitations and production process constraints, the real-life customizable CLT panel manufacturing process is virtually unsolvable through analytical means. Therefore, an empirical, deterministic, simulation-based, and dynamic rule-based heuristic solution to the scheduling problem was proposed, attempting to minimize single bundle makespan and job shuffles in the buffer areas.

4.1.1 Problem formulation

This real-life application problem consists of a complex 3-stage (pressing, CNC router cutting, and finishing, quality control and packaging) flexible flow shop CLT production. The problem presents increased buffer constraints (CLT panels with different bundle or truck load IDs stacked on top of each other), job nesting (more than one job is processed at a time on select stages), and batch (package bundle or truck loads) completion implications. The scheduling problem is formulated according to the following characteristics:

1. In flow shop systems, each job (in this case, panels) must visit each work station (production stages, i.e. pressing, cutting, finishing and quality control and packaging) in this same specific order. For example, no panels can go through cutting before they are pressed in billets. The task sequence is fixed and previously specified. In this application, a non-permutation flow shop is proposed, as the sequence of jobs that visit a workstation may be different for each station;
2. Different customers may require different product specifications, i.e. panels dimensions, geometry, incorporated features, visual faces, etc. Therefore, each job may demand different process times on each stage. Moreover, each job has a predefined truck load and package bundle ID. Both numbers indicate, on distinct levels, the preferred job completion order. Each bundle is composed of CLT panels grouped depending on their geometry, weight and size. Each truck load is composed of several bundles, depending on each bundle geometry, weight and size, as well as logistic constraints (e.g. truck bed, road width, field limitations). All those definitions are inputs to the scheduling problem and are assumed to be provided along with the project dataset;
3. Buffer constraints are enhanced in this problem, as improper stacking of panels in the buffer areas may cause unnecessary panel shuffling, i.e. the order in which each panel is stacked matters in the overall scheduling problem. Additionally, buffer conditions are variable depending on the project and plant characteristics. As the plant space is fixed and the buffer

areas after each stage is limited, the buffer capacity depends on how large the job components (billets or panels) are and how much space the plant has available. In projects with large panels, buffer capacity is further diminished. Projects with smaller panels, allow for more buffer capacity;

4. Regarding workstation dynamics, the pressing stage operates with batching, since it allows for more than one job to be processed at a time. Furthermore, the problem was simplified since it was considered that no stages would have parallel machines (i.e. plant configurations with more than one press, more than one cutting machine or more than one finishing team). Buffer capacity parameters are user-defined inputs to the model;
5. Finally, the scheduling algorithm is highly impacted with bundle completion constraints. Finished panels can only be packed up and sent out for storage or loading if the full package bundle is complete. In the meantime, the finished panels must wait for their mates in the finishing area, which might end up blocking this stage, or be sent to a temporary buffer area (which will increase the number of panel shuffles).

4.2 Methodology

The simulation scheduling model was developed according to the objectives diagram in Figure 1-2, Section 1.3. All preliminary objectives and activities were discussed in detail in the previous chapters of this thesis.

After scrutinizing the CLT production process, based on the field observations, production process map, and experts' inputs, brainstorming sections were performed to abstract the CLT manufacturing process into a solvable analytical problem. The formulation should consider the objectives pursued in the scheduling model (minimizing bundle production time and panel shuffles). Due to the extremely complex network of production constraints, sub-objectives and control variables as described in the problem formulation section above, an analytical formulation was not reached.

The proposed DES-based solution was achieved after several manual simulation sections over a small, simplified scheduling problem, but keeping all constraints, objectives and control variables in mind. Although this algorithm was developed to address customizable CLT panel manufacturing flow shop problems with sequenced loads and increased buffer constraints, the solution described in Figure 4-1 is generalizable and might be applicable to any flow shop manufacturing set up dealing with sequenced production parameters and complex buffer limitations, with the necessary adaptations.

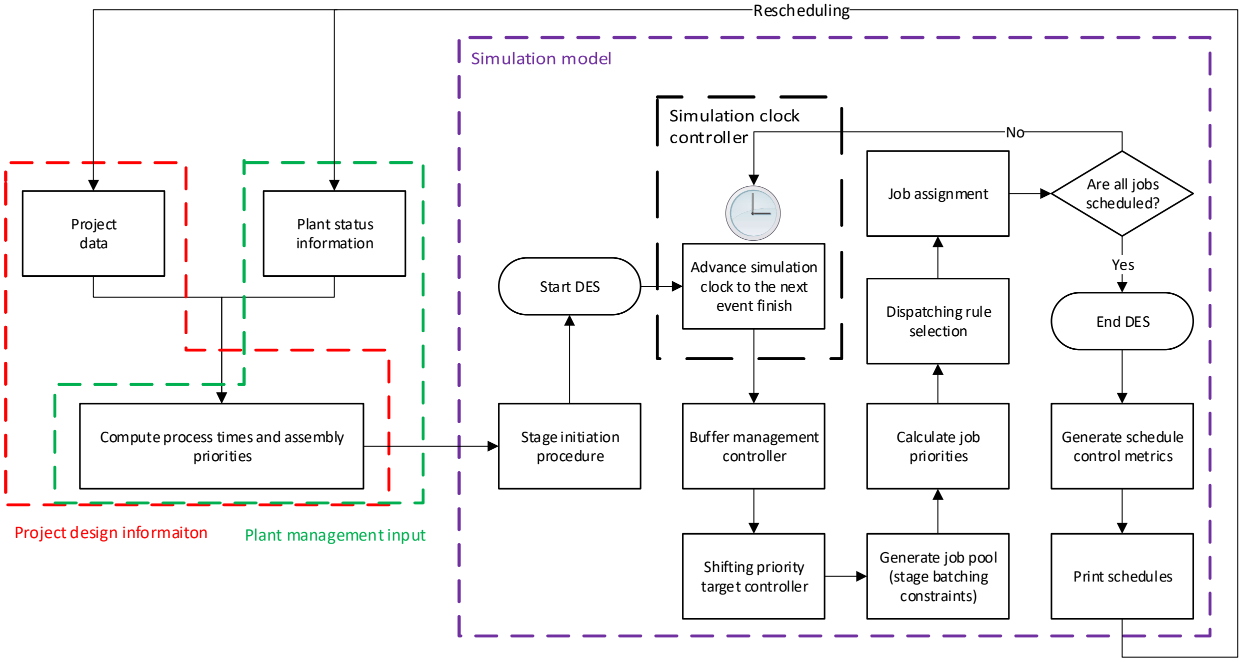


Figure 4-1 - Architecture of a DES-rule-based algorithm for manufacturing scheduling with sequenced loads and increased buffer constraints

In the first part of the scheduling algorithm, project and plant parameters are initialized. The total set of jobs to be scheduled are formatted into a job database containing the job attributes necessary to calculate the process times on each stage and each job's desired priority in a sequenced load scheme. The same procedures are made for the jobs currently under process or intermediately stored in the plant. A relative priority index should be specified to arrange the priorities for the jobs in the project information, and the jobs in the plant status.

After both, project and plant databases are assembled, the DES is commenced. The shifting priority target controller will evaluate buffer and production stage conditions and determine which job's relative priority parameter should have preference.

Next, all stages are initialized considering current production stages and buffer allocation, according to the plant parameters previously specified. The simulation clock controller will forward the simulation time step to the end of the next queued event.

The algorithm generates a pool of available jobs for scheduling. Hard physical limitations and process management batching constraints are accounted for in the pool generation component, applying a first filter to whatever jobs might be available for scheduling. At this point, the simulation will determine each jobs' priority value according to buffer and production stage conditions, using priority functions. After that, the algorithm will select the appropriate dispatch rule and schedule the next job.

After each event ending, the finished job is allocated in the buffer areas. The increased buffer management constraints incorporated to the problem, as the stacking order of jobs in intermediate buffers directly impact one of the scheduling objectives, demanded a dedicated component in the solution architecture. This sub-algorithm sweeps the buffers and determines the best buffer area and stacking position for each job coming out of a production stage. Each stage in the production line have a similar DES structure as shown in Figure 4-1.

Once all jobs are scheduled and the control metrics calculated, the user can either accept the schedule output or change it at any point, by re-feeding unprocessed jobs and current plant conditions information in the model and re-running the scheduling algorithm.

In the next sections, the algorithm is described in a customizable CLT panel manufacturing application for projects up to 10,000 jobs. For larger projects, some scaling coefficients in the priority functions described below would have to be changed.

All necessary inputs and provided outputs of the model are described on Table 4-1 and Table 4-3, respectively.

4.2.1 Data compilation

The first module in SCHER-CLT will import and treat the project and plant data into the model. As shown in Figure 3-1, CLT parts are nested together and optimized into billets to minimize material waste. This nesting process implicates in one more complexity factor to the model as the job unit changes during the production process. The job unit for the first stage (pressing) is CLT billet. In the next stage, (CNC cutting) the jobs are loaded as billets and unloaded into parts or panels. In the final stage, although the job unit is CLT panel, one or more panels are grouped together into bundles for packaging, loading and shipping.

Each job unit will have a priority parameter assigned to it. The priority parameter refers to the desired assembly order of a job and, in this CLT manufacturing problem, relates to the truck load and package bundle ID numbers.

Both project information and current plant state generation modules are responsible in indexing billets nests and parts according to unique billets and parts ID numbers. The algorithm sweeps the billets in the job list splitting each billet into unique parts ID. This procedure is necessary because even though there might be more than one element of the same part in a billet, these elements might belong to different truck loads or package bundles. Therefore, parts with the same features might have to be treated as different elements, and for this reason, are given unique identification numbers within the project. After the separation and indexing procedure, the data compilation module attaches the construction assembly sequence of panels, bundles and truck loads to each job entity (unique parts IDs) in the database. Each part will inherit the unchanged physical parameters from its mother billet such as material type and number of layers. All in all, this module organizes job and plant databases comprised of job physical characteristics (e.g. panel length, width, thickness, material type) and metadata (such as buffer area, stacking position, truck load and bundle ID). Jobs parameters are fed into the estimation models to calculate static, non-sequence dependent process times for every job and production stage in the dataset. As described in Sections 3.2 and 3.3, manufacturing process times are calculated for each job and each production stage.

A list with all the necessary inputs for the customizable CLT panel schedule simulation model is shown in Table 4-1. Some of the inputs listed in Table 4-1 belong to later stages in the simulation model and are going to be properly addressed in the following sections.

Table 4-1 - List of necessary inputs for SCHER-CLT

Input (Notation)	Module / Source	Description
Project and Plant job list	**Data compilation**	**-**
Billets ID	Project data	Billet unique identification
Parts ID in each billet	Project data	List of parts contained in each billet and their identification (might not be unique at this point)
Material type (mt)	Project data	A code that will identify the composition of each billet in terms of lumber type, width and thickness for each layer
Raw billet width (wd)	Project data	Raw width of each unfinished billet
Raw billet length (l)	Project data	Raw length of each unfinished billet
Rough part width (rwd)	Project data	Rough width of each part ID (the parts IDs might not be unique at this point)

Input (Notation)	Module / Source	Description
Rough part length (rl)	Project data	Rough length of each part ID (the parts IDs might not be unique at this point)
Number of sanded visual faces (vf)	Project data	Number of sanded faces or each part ID
Number of layers in the billet (lay)	Project data	Number of layers of each billet
Truck load ID (tl)	Project data	Truck load identification number for each part in each billet – It is a sequential number starting from 1 to the total number of truck loads in the project.
Package bundle ID (z)	Project data	Package bundle identification number for each part in each billet – It is a sequential number starting from 1 to the total number of package bundles in the project. It is important to note that it is logical to have different bundle numbers present in different truck loads. However, it is impossible to have the same bundle in different truck loads.
Process time estimation	**Data compilation**	**-**
Software estimated process times for each billet	Design team	Cutting process time for each billet ID estimated by the CNC software
Estimated pressing time (p_{PT})	Plant management	The pressing component of the total process time of the pressing stage, in minutes. See Section 3.3.2 for a detailed description.
Estimated pressing waiting and setup time (p_{PWT})	Plant management	The waiting/setup component of the total process time of the pressing stage, in minutes. See Section 3.3.3 for a detailed description.
Number of workers in the FQC stage (ts)	Plant management	Number of workers simultaneously deployed to the FQC stage (team size). See Section 3.2.2 for a detailed description.
Current plant stats	**Data compilation**	**-**
Buffer areas storing conditions	Plant management	List of billets or parts temporarily stored in the buffer areas for all stages and their specific stacking position s. If $s = 1$, the panel is the first one in the buffer area (touching the ground). Parameter s increases as new panels are stacked on top of each other. Capital S would be the total number of stacked jobs on each buffer area.
Current production stage conditions	Plant management	Which billets, or parts IDs are currently under production on each stage.

Input (Notation)	Module / Source	Description
Priority relation between Jobs in the Project list vs Jobs in the Plant status list	Plant management	The plant is either occupied by jobs with higher or lower priority than the jobs in the scheduling project list, or by jobs with concurring priorities.
Plant parameters	**Simulation**	**-**
Number of buffer areas after the pressing stage (Pb)	Plant management	-
Number of buffer areas after the CNC stage (Cb)	Plant management	-
Number of buffer areas after the FQC stage (Fb)	Plant management	-
Number of simultaneous FQC job slots (Js)	Plant management	The total number of job slots for FQC and packaging processes. The total number of workers in the finishing team that will be divided and considered to be working in the job slots simultaneously.
Maximum stack pile (Ms)	Plant management	The maximum number of stacked panels on top of each other – This number is going to be assumed to be the same to all buffer areas for all stages.
Project scheduling parameters	**Simulation**	**-**
Material type grouping for billet batching on press	Plant management	A list of possible material types codes (mt) indicating which types of panel might be grouped and pressed together.
Truck load ID depth for billet batching on press (tld)	Plant management	A number that will indicate the maximum truck load difference to allow billets to be grouped and pressed together.
Just-in-time (JIT) scheduling mode switch	Plant management	Indicates that, whenever "improper stacking conditions" are met in an intermediate buffer area, the upstream production stage will be halted. Once the buffer area is released and "proper stacking conditions" are met, production in the upstream stage will resume. Please see Sections 4.2.2.6 and 4.2.2.7 for a detailed description of "proper / improper stacking conditions".
Full buffer area scheduling behavior	Plant management	When an intermediate buffer area is full, indicates whether upstream stage production should be halted or not. If not, the scheduling model will assume that any jobs released by the upstream stage will be stored in unmanaged buffer areas.

Input (Notation)	Module / Source	Description
Output parameters	**Results reporting**	**-**
Production shift duration	Plant management	How many productive hours in a shift (discounting lunch and break hours)
Number of shifts per day	Plant management	-

Finally, SCHER-CLT, through the data compilation module, allows project rescheduling. Results from a previous simulation, along with changed plant status and unfinished job parameters might be re-fed in the data compilation module, reformulating the whole database. This new database is then processed to generate a new schedule. Rescheduling is an important feature which allows for manufacturing systems to keep operating productively and efficiently (Vieira et al. 2003), creating an adapted agenda after the occurrence of unpredicted random events (machine breakdowns, quality-related issues, labor-related problems, etc.) that may have disrupted the original schedule.

4.2.2 Scheduling simulation algorithm

Essentially, the DES algorithm in SCHER-CLT abridges the complex CLT scheduling problem into several single-decision job selection problems, at each step in the simulation clock. This approach was also applied by (Gupta and Sivakumar 2005).

To clarify how the DES is applied in SCHER-CLT, an example of a possible order of discrete events mimicking a real production scenario is shown below. Intermediate components in the algorithm such as shifting priority target controller, job pool generation, priority calculation and dispatching rule selection are background procedures to determine which job should be schedule next that do not translate in any physical real-world action. Therefore, such components were veiled from the event list in Figure 4-2.

Empirical knowledge, experience from field personnel, design team and plant management, as well as the developed production process map were the main source of information to identify each decision point in the DES, and the applicable dispatching rules for each job assignment event.

In the following sections, each component of SCHER-CLT simulation algorithm is explained, and simplified algorithm decision trees are outlined and described, for each stage.

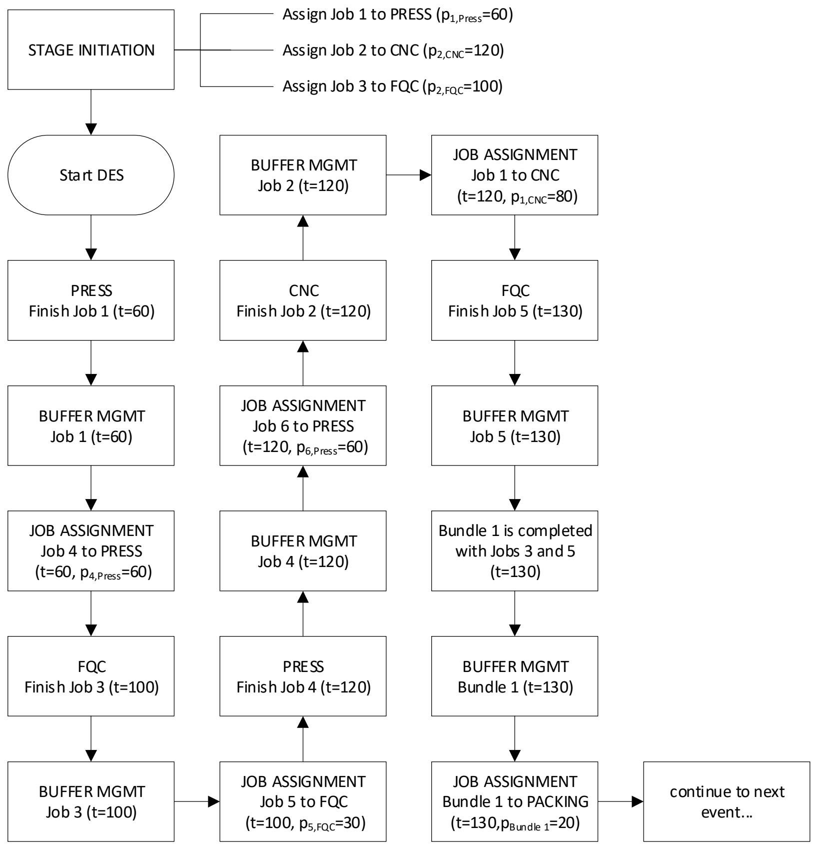


Figure 4-2 - Example list of possible discrete events in SCHER-CLT

4.2.2.1 Stage initiation

In the stage initiation component, all stations in the production line are initiated, and the first jobs on each stage are defined. The simplified stage initiation algorithm is shown in Figure 4-3, below.

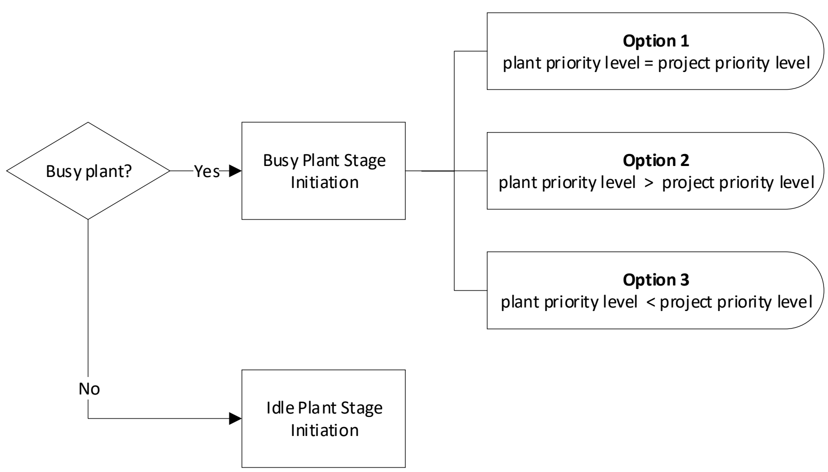


Figure 4-3 - SCHER-CLT stage initiation simplified decision tree

Whereas the scope of this study is limited to the production process of customized CLT panels, the plant consistently works continuously, attaching new projects as previous jobs are being finished, and often intercalating industrial mats with customized panels production. Except from rare hiatuses, the production stages are never idle. When the plant is busy (most likely situation on a real scenario), three possibilities were considered:

1. The plant is busy with jobs that have concurring priority levels when compared to the jobs in the project database. In this case, all jobs from plant and project databases are treated as equals in terms of assembly priority (truck load or bundle ID). For example: a billet pertaining to truck load 3 currently stored in the after-press buffer area, will have the same priority level as a truck load 3-billet which has not been pressed yet, currently in the project database. Their final priority is not calculated yet, and this scenario is not conclusive in defining which billet will have the final preference, however, it means that both billets are competing with the same level of precedence;
2. The plant is busy with jobs that have higher priority when compared to the jobs in the project database. In this case, the jobs in the plant database will have higher preference when compared to jobs with the same truck load or bundle IDs in the project database;
3. The plant is busy with jobs that have lower priority when compared to the jobs in the project database. In this case, the jobs in the plant database will not even be considered for scheduling. Any panels in the buffer areas are going to stay put until all jobs in the project database are scheduled. In case any job from the plant database is currently under production at any stage, it is just going to be stored in the buffer area once the work is finished at that station and is not going to be considered for scheduling after that.

The implications of each busy plant scenario will impact the job priority calculation results for every job assignment decision made in the simulation. Every job in the plant database will have their priority parameter multiplied by a correction factor to either scale up or down their precedence level in comparison with the jobs from the project database, according to the following coefficients:

1. Concurring priority levels → $\frac{z_{i_{plant}}}{z_{k_{project}}} = 1$ and $\frac{tl_{i_{plant}}}{tl_{k_{project}}} = 1$
2. Plant priority level > project priority level → $\frac{z_{i_{plant}}}{z_{k_{project}}} = 0.00001$ and $\frac{tl_{i_{plant}}}{tl_{k_{project}}} = 0.00001$

3. Plant priority level < project priority level → $\frac{z_{i_{plant}}}{z_{k_{project}}} = 10000$ and $\frac{tl_{i_{plant}}}{tl_{k_{project}}} = 10000$

where $z_i = z_k$ and $tl_i = tl_k$ are the priority parameter (bundle ID and truck load ID numbers, respectively) for job i in the plant database and job k in the project database. Higher truck load or bundle ID numbers have lower preference in the scheduling algorithm.

If the plant is considered idle, i.e. there are no jobs currently stored at the buffer areas or under production in any station, the very first jobs to be scheduled to each stage will follow the starting priorities calculated during the data compilation process. The priority calculation, scheduling rule selection, and job assignment procedures for the first job follow the same method described for each stage in the following sections.

4.2.2.2 Shifting priority target

Before every discrete event in the simulation, the shifting priority target controller sweeps all buffer areas and production stages checking for the production and storage patterns described on Table 4-2, below. The identified patterns will point to jobs that will be defined as priority target candidates.

Table 4-2 - Shifting priority candidates production and storage patterns

Shifting priority candidate	Description	Location
Pattern 1 → z^1	Improper* stacking conditions in the buffer areas after the pressing stage, i.e. a billet of higher priority parameter z_i stacked on top of a billet with lower priority parameter z_g.	Raw billet buffer area
Pattern 2 → z^2	Improper* stacking conditions in the buffer areas after the CNC cutting stage, i.e. a part of higher priority parameter z_i stacked on top of a part with lower priority parameter z_g.	Unfinished panels buffer area
Pattern 3 → z^3	Occurrence of finished panels waiting for their bundle mates in one of the finishing area job slots.	FQC stage
Pattern 4 → z^4	Occurrence of finished panels waiting for their bundle mates in one of the buffer areas after the FQC stage.	Finished panels buffer area
Pattern 5 → z^5	Improper* stacking conditions in the buffer areas after the FQC stage, i.e. a part of higher priority parameter z_i stacked on top of a part with lower priority parameter z_g.	Finished panels buffer area

* Please see Sections 4.2.2.6 and 4.2.2.7 for a detailed description of "proper / improper stacking conditions".

The shifting priority target controller will find panels with the smallest priority parameter z_i (bundle ID), matching any of the listed patterns above. In any given event in the simulation, up to five different panel priority parameters $\{z^1, z^2, z^3, z^4, z^5\}$ might be found and held as priority target candidates, where z^1 is the priority parameter given by Pattern 1, z^2 by Pattern 2, and so on. The priority target candidates will be considered for shifting priority target parameter tz in the dispatch rule selection algorithm described in Section 4.2.2.5.

4.2.2.3 Job pool generation

First, a pool of available jobs is generated at each assignment event's time step. The job pool accounts for the batching constraints on each stage, i.e. equipment constraints as well as buffer management implications and limitations derived from management input parameters. The principles to defining whether a job is available and, therefore, able to join the stage's pool, are different for each stage. An available job consists in any panel already processed by the upstream stage, which was not yet processed by the current stage, and meet all requirements stablished by the following guidelines:

- Pressing stage (for every billet to join the press cycle):

An internal parameter is calculated to determine the maximum assignment depth in terms of the priority parameter tl. The assignment depth (ad) is given by the maximum tl able to be stored in the buffer areas in an interrupted decreasing order.

$$\boldsymbol{ad = Current(tl) + x} \qquad \textbf{Equation 12}$$

where, $Current(tl)$ is the smallest incomplete (not yet fully scheduled for the pressing stage) truck load ID in the project database, and x is how many different complete truck loads IDs might be stored in the raw billets buffer area, in an interrupted decreasing order.

For example: consider that for a particular plant there are three buffer areas for raw billets. Each area is able of accommodating 10 panels. Also consider that, for this project, every truck load ID is composed of 5 billets and that one of the areas is already occupied by a billet with a truck load ID 1, and that the smallest, incomplete truck load ID for the pressing stage is $Current(tl) = 2$. The other two areas are free. In this case, the pile which is already occupied is not able to accommodate any panels in a decreasing order, since it is already occupied by a truck load 1-billet, and all truck load-1 billets have already been pressed. However, as the two other piles are free, the buffer area is capable of accommodating up to 4 sequential truck load IDs, in an interrupted decreasing order (five billets from truck load 5, five from truck load 4, five from 3, and five from 2). Therefore, for this situation, $ad = 2 + 4 = 6$. This means that every billet up to truck load 6 is eligible to join the press pool.

In case all buffer piles are occupied or when no truck load IDs might be stored in an interrupted decreasing order, the algorithm determines that:

$$\boldsymbol{ad = Current(tl) + 1} \quad \textbf{Equation 13}$$

Finally, whenever the shifting priority target tz belongs to a truck load tl that is higher than the $Current(tl)$, the assignment depth is given by the relationship below:

$$\boldsymbol{\{tz \in tl > Current(tl) \rightarrow ad = (tl' \ni tz) + 1} \quad \textbf{Equation 14}$$

For example: consider that the priority target $tz = 25$ and that the bundle ID 25 belongs to truck load ID 4. Also consider that the smallest incomplete truck load ID in the pressing stage is $Current(tl) = 2$. In this case, $tl' = 4$, since the bundle ID 25 is contained in truck load ID 4. The assignment depth will be $ad = 4 + 1 = 5$. This means that every billet up to truck load 5 are eligible to join the press pool.

The assignment depth is recalculated at every press job pool generation event. Only billets within the calculated assignment depth may join the pool.

- Pressing stage (for the following billets after the first one is chosen in each press cycle):

a. Only billets within the same press nesting group material type mt may join the pool;

$$\boldsymbol{mt_i = mt_{first}} \quad \textbf{Equation 15}$$

b. Only billets with the same raw width wd may be grouped together in a press cycle;

$$\boldsymbol{wd_i = wd_{first}} \quad \textbf{Equation 16}$$

c. Only billets with truck load ID numbers tl within the allowed truck load depth user-input parameter (tld) may be grouped together in a press cycle;

$$\boldsymbol{tl_i \in [tl_{first} - tld, tl_{first} + tld]} \quad \textbf{Equation 17}$$

d. The maximum thickness of all billets combined in the press, at each cycle, must be equal or smaller to 10 layers:

$$\boldsymbol{\sum_i^{batch\ size} lay_i \leq 10} \quad \textbf{Equation 18}$$

where, mt_{first}, wd_{first} and tl_{first} are the material type, raw width and truck load ID of the first billet that was already chosen to join the press batch, and lay_i is the number of layers of billet i chosen to join the press batch.

- CNC router cutting stage

All available jobs join the pool.

- FQC stage

All available jobs join the pool.

4.2.2.4 Priority functions

Once the job pools are created, SCHER-CLT relies on six priority functions to determine jobs priorities. Each function is applicable to a different stage in the production line, under certain specific conditions. Rules belonging to the same production stage are dynamically chosen depending on the origin of the concurring jobs, i.e. whether the jobs are coming directly from the upstream stage or from the upstream buffer area.

The priority functions in SCHER-CLT are modified version of the SPT (shortest process time) rule, weighted with the priority parameter of each job. To guarantee scaling consistency, the SPT is normalized with the subset of available jobs in the job pool at each event. In the pressing stage, as batching is considered, a job similarity parameter (billet length) was also applied. Although set up times were not directly considered in the process time estimation models described in Chapter 3, accounting for job similarity is an indirect way of minimizing intermediate set up times.

The priority functions are applied to every job entity in the stage pool. The job priority calculation functions, and the rules defining when each function is applicable are as follows:

- Pressing stage (to choose the first billet to enter the press, i.e. first batch component):

$$\boldsymbol{Z_{i,Press} = 0.8z_i - 0.15\frac{[\max(p_{i,j+1}) - p_{i,j+1}]}{(\max p_{i,j+1})} - 0.05\frac{\left[\max(\sum_j^m p_{i,j}) - \sum_j^m p_{i,j}\right]}{\left(\max \sum_j^m p_{i,j}\right)}} \quad \textbf{Equation 19}$$

- Pressing stage (to choose the following billets to enter the press, i.e. later batch components):

$$\boldsymbol{Z_{i,Press} = 0.8z_i + 0.1\frac{abs(l_{first} - l_i)}{l_i} - 0.075\frac{(\max p_{i,j+1} - p_{i,j+1})}{(\max p_{i,j+1})} - 0.025\frac{\left[\max(\sum_j^m p_{i,j}) - \sum_j^m p_{i,j}\right]}{\left(\max \sum_j^m p_{i,j}\right)}} \quad \textbf{Equation 20}$$

where, z_i is the priority parameter (bundle ID) , $p_{i,j+1}$ is the process time for in the next stage in the production line, $\sum_j^m p_{i,j}$ is the total process time for job i in all production stages j, and l_{first} is the raw billet length for the first billet chosen to enter the press on each cycle.

- CNC cutting stage (when the billet is coming straight from the pressing stage, i.e. it has not been stored in any buffer area yet):

$$\boldsymbol{Z_{i,CNC} = 0.9z_i - 0.075\frac{[\max(p_{i,j}) - p_{i,j}]}{(\max p_{i,j})} - 0.025\frac{[\max(p_{i,j+1}) - p_{i,j+1}]}{(\max p_{i,j+1})}} \qquad \textbf{Equation 21}$$

- CNC cutting stage (when the billet is coming from an upstream buffer area):

$$\boldsymbol{Z_{i,CNC} = 0.8z_i - 0.1s_i - 0.075\frac{(\max p_{i,j} - p_{i,j})}{(\max p_{i,j})} - 0.025\frac{(\max p_{i,j+1} - p_{i,j+1})}{(\max p_{i,j+1})}} \qquad \textbf{Equation 22}$$

where, s_i is the stacking position in the buffer pile, and $p_{i,j}$ is the process time for job i in the current production stage j.

- FQC stage (when the part is coming straight from the CNC cutting stage, i.e. it has not been stored in any buffer area yet):

$$\boldsymbol{Z_{i,FQC} = 0.9z_i - 0.1\frac{[\max(p_{i,j}) - p_{i,j}]}{(\max p_{i,j})}} \qquad \textbf{Equation 23}$$

- FQC stage (when the part is coming from an upstream buffer area):

$$\boldsymbol{Z_{i,FQC} = 0.8z_i - 0.15s_i - 0.05\frac{(\max p_{i,j} - p_{i,j})}{(\max p_{i,j})}} \qquad \textbf{Equation 24}$$

where, s_i is the stacking position in the buffer pile, and $p_{i,j}$ is the process time for job i in the current production stage j.

It is important to emphasize that higher priority values Z_{ij} have lower precedence in the scheduling algorithm.

4.2.2.5 Dispatch rule selection algorithm

The dispatch rule selection algorithm in SCHER-CLT relies on the processed information in the previous stages to select the most fitting dispatching rule for each job assignment event. Three different dispatch rules may be applicable:

- Rule 1 → Package bundle completion:

  Select the panel with the smallest priority value, and with the same bundle ID as the shifting priority target parameter.

  $$\boldsymbol{\min(Z_{ij}) \mid z_i = tz} \qquad \textbf{Equation 25}$$

- Rule 2 → Bottom to top assignment:

  Select the panel with the highest priority value.

  $$\boldsymbol{\max(Z_{ij})} \qquad \textbf{Equation 26}$$

- Rule 3 → Top to bottom assignment:
  Select the panel with the lowest priority value.
  $$\min(Z_{ij})$$ **Equation 27**

The rules above are dynamically selected depending on the buffer area conditions and available job pool generated after each discrete event. The algorithm to select which rule to use is different for each stage, as the level of influence of a stage is different on each surrounding buffer conditions. *For example:* a job assignment event on stage 3 of a manufacturing line would have no direct influence over the current stacking conditions of the buffer area immediately after stage 1. The concept of the influence level of the job assignment at any given stage over surrounding buffer areas' stacking conditions will determine which shifting priority target candidate $\{z^1 \ to \ z^5\}$ will be selected as the shifting priority target (tz) at any event in the simulation. The following simplified decision trees describe the shifting priority target election for each stage in SCHER-CLT:

- Pressing stage:

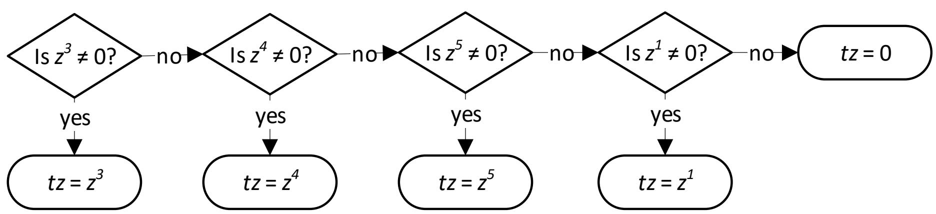


Figure 4-4 - Pressing stage shifting priority target election mechanism

- CNC router cutting stage:

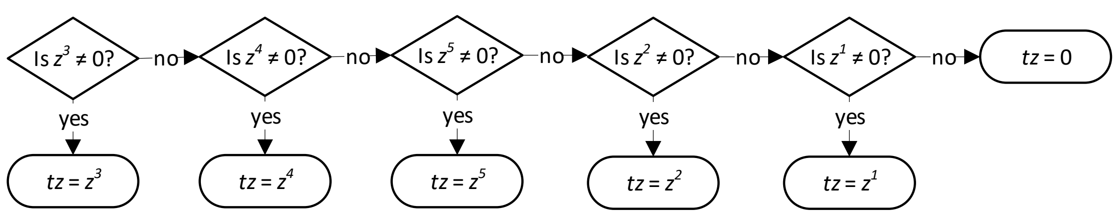


Figure 4-5 - CNC cutting stage shifting priority target election mechanism

- Finishing, quality control and packaging stage:

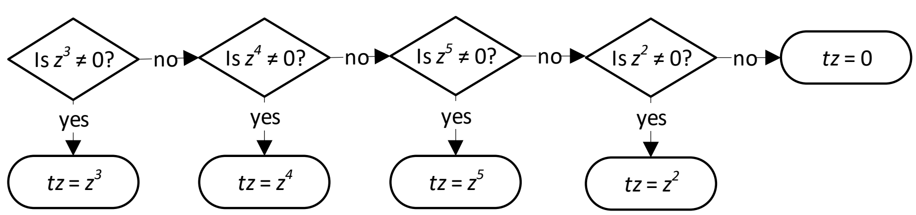


Figure 4-6 - FQC stage shifting priority target election mechanism

4.2.2.6 Job assignment algorithm

The job assignment algorithm is responsible to defining which dispatch rule and ultimately, which job, is going to be selected to enter production next. The algorithm runs each time a job assignment discrete event happens in the simulation.

Once the shifting priority target is defined, one of the dispatch rules is selected. As for the shifting priority target selection decision trees, in SCHER-CLT, there are three different decision trees for the job assignment algorithm, one for each stage:

- Pressing stage:

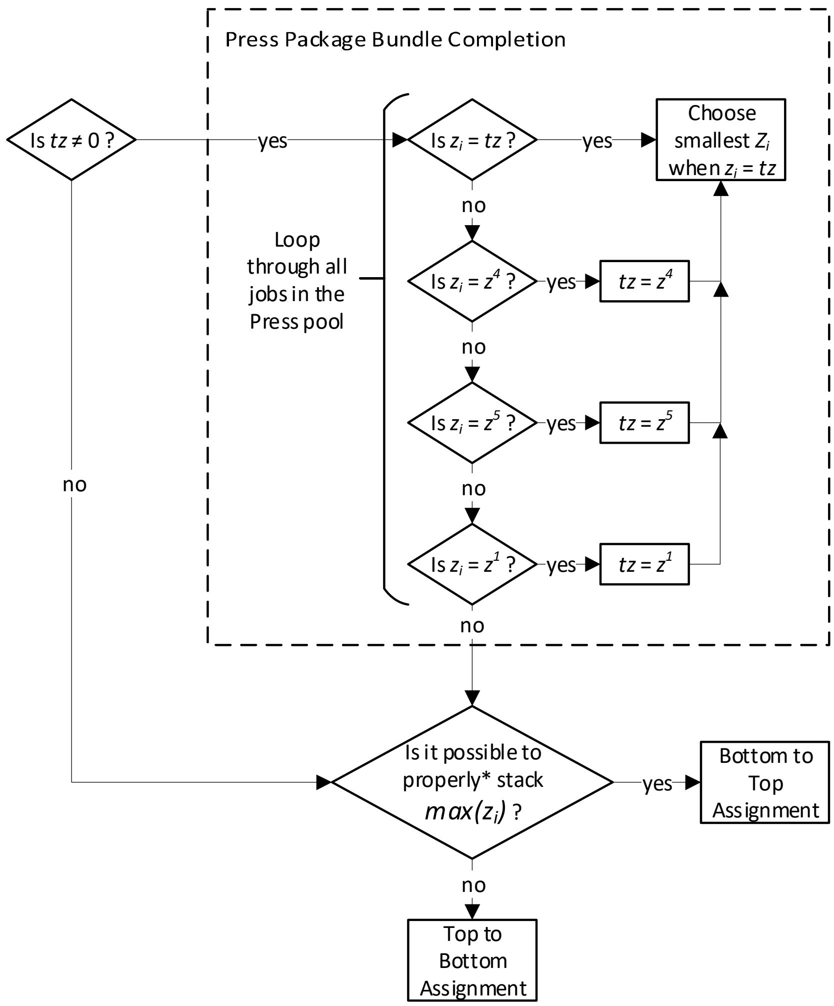


Figure 4-7 - Press job assignment algorithm

On the pressing stage, after the shifting priority target is determined (either assuming one of the candidates or equals zero), the algorithm first select which job assignment routine will be used. If $tz \neq 0$, then the package bundle completion algorithm will be enabled, otherwise, either the bottom to top or top to bottom assignment algorithm shall be selected, depending on current stacking conditions in the downstream buffer area. Both bottom to top and top to bottom algorithms just follow the rules described on Equations 26 and 27, respectively. Regarding the package bundle completion routine, the algorithm will sweep through all available jobs in the press pool. Rule 01 (Equation 25) will then be applied. Whenever no jobs in the press pool have the same priority parameter (z_i) as the shifting priority target (tz), the algorithm will change tz to the next candidate and perform the search on the press pool again. This procedure goes on until a match is found or, if there are no matching jobs on the pool, for any of the candidates, either the bottom to top or top to bottom assignment is going to be selected.

- CNC router cutting stage:

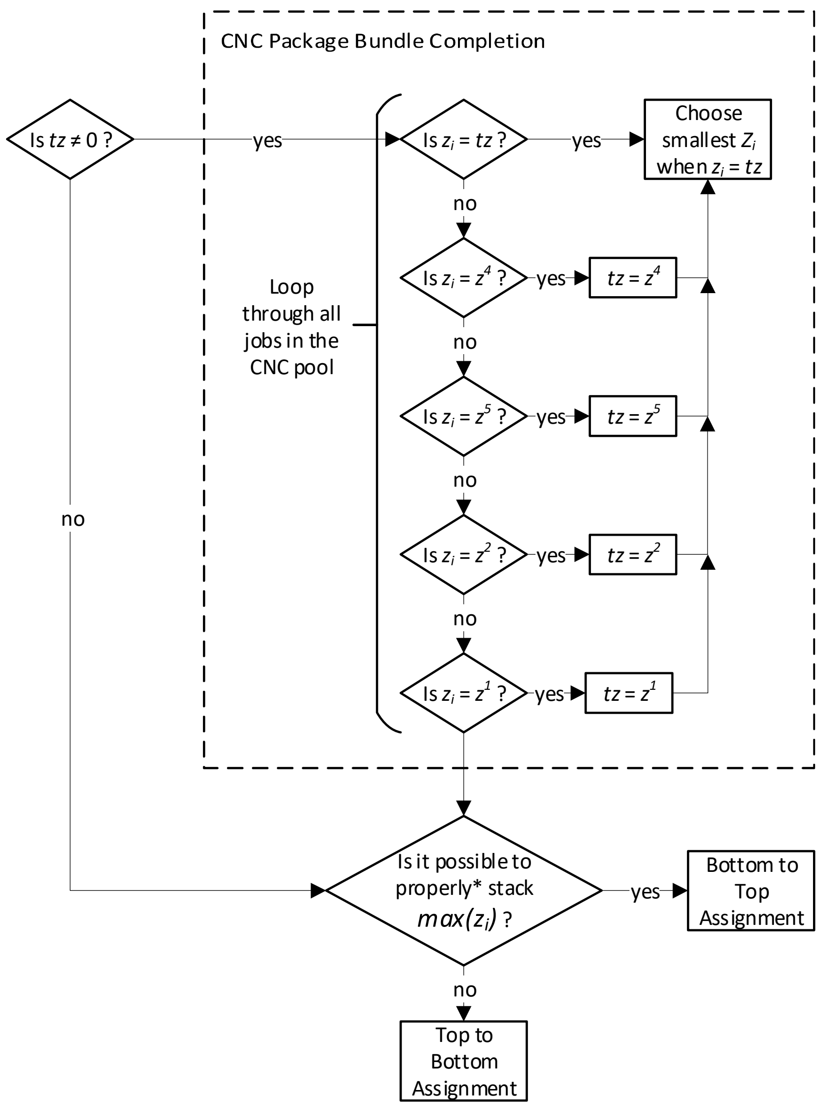


Figure 4-8 - CNC cutting job assignment algorithm

The CNC job assignment routine follows the same procedures described for the Press job assignment algorithm, but obviously considering jobs and priority parameters (Z_i) for the CNC stage.

- Finishing, quality control and packaging stage:

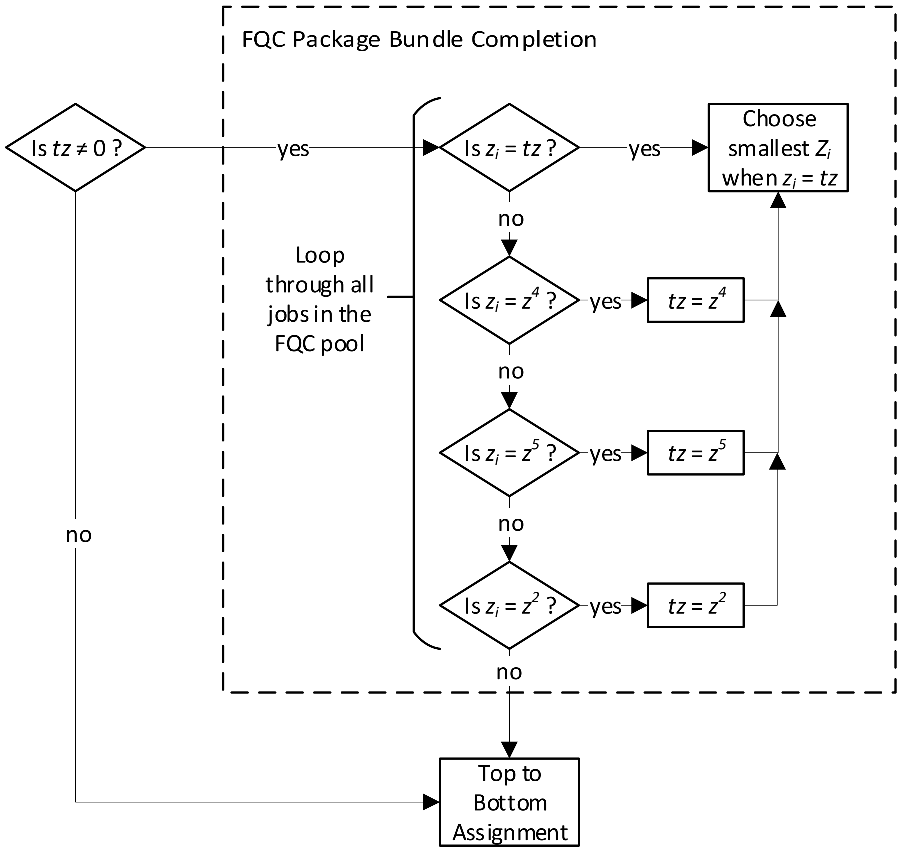


Figure 4-9 - FQC job assignment algorithm

The FQC job assignment routine follows the same procedures described for the Press job assignment algorithm, but obviously considering jobs and priority parameters (Z_i) for the FQC stage. However, in the FQC job assignment algorithm, when $tz = 0$ or when no jobs in the FQC pool match any of the priority target candidates, only the top to bottom rule is selected (Equation 27).

(*) In Figure 4-7 and Figure 4-8 depicted above, consider that properly stacked panels are panels stored in an interrupted decreasing order on top of each other, in terms of their priority parameter z_i. See section 4.2.2.7 for more details.

Note that, depending on the job pool, buffer and production stage conditions, the shifting priority target tz and the job dispatching rules dynamically change according to the algorithms above.

Just in time option

In case the "Just in Time" (JIT) scheduling mode switch is "on", the CNC and FQC job assignment algorithms described above incorporate an additional constraint: only panels placed in the last position of their respective buffer area stack piles (when no panel shuffles are needed), may be picked as the next job to join production.

This constraint implicates on shutting down the upstream stage until proper stacking conditions are verified. Meanwhile, downstream job assignments focus only on the jobs positioned at the top of their respective upstream buffer areas, avoiding panel shuffles.

The way the algorithm is built, what the JIT switch essentially does is: whenever no panels placed in the last position of the buffer area stack piles match the $z_i = tz$ rule, it will automatically change the job assignment to a $\max(Z_{ij})$ or $\min(Z_{ij})$ rule, depending on the buffer area conditions, not allowing a bundle completion panel to be chosen if that implies on extra panel shuffles at that decision event.

The JIT option pragmatically switches the job assignment preference from one of the simulation objectives to the other, i.e. from package bundle finishing time (or minimizing average bundle finishing and wrapping time) to panel shuffles (or minimizing the number of panel shuffles) at the intermediate stages. However, one of downsizes of the JIT option is that, longing for minimizing panel shuffles at the intermediate buffer areas, depending on the process times and panel composition, it might postpone panel shuffle events to happen at the FQC stage, as several panels of different bundle IDs might be finished before a single panel bundle is completed. Nevertheless, the JIT option has the capacity to highly improve the efficiency of the calculated schedule, reducing overall panel shuffle quantity on the expense of equipment downtime.

4.2.2.7 Buffer management controller

One of the discrete events simulated in the model is the buffer area management and job stacking algorithm. This model component manages buffer area stacking piles and defines the best pile to stack the jobs coming out of a production stage.

The first step in the buffer management algorithm consists in defining the stacking order of multiple billets coming out of the pressing stage, or multiple parts processed in the CNC cutting stage. As explained in Chapter 3, panels are finished in the FQC stage, one at a time, considering multiple job slot areas. Therefore, after each FQC finishing discrete event, only one part is going to be addressed individually, even if multiple parts are finished at the same time step.

For pressing and CNC cutting stages, lower preference panels shall be stored first, therefore, being placed in the "bottom" of a stack pile. This basic rule is only broken in case the coming panels' priority parameter is equal to one of the shifting priority target candidates. If that is the case, then the first panel to be stored shall be the second lowest preference panel, and so on. The formulation of the basic stacking order rule is as follows:

$$\begin{cases} \boldsymbol{z_i \neq \{z^1, z^2, z^3, z^4, z^5\} \rightarrow \max(Z_{i,j+1})} \\ \boldsymbol{z_i = \{z^1, z^2, z^3, z^4, z^5\} \rightarrow \max_{+1}(Z_{i,j+1})} \end{cases} \quad \textbf{Equation 28}$$

where $\max_{+1}(Z_{i,j+1})$ is the second highest priority function value (second smallest preference) for the next stage in the panels coming out any given stage.

Next, the algorithm sweeps all stacking areas to find the smallest positive difference between the priority parameters of the panel being stored and the panel placed on top of a buffer area pile. The formulation for this rule is as follows.

- Basic job stacking rule:

$$\boldsymbol{\min(z_b^{top} - z_i) \mid z_b^{top} \geq z_i \qquad b = 1, 2, \dots, (Pb, Cb, Fb)} \quad \textbf{Equation 29}$$

where, z_b^{top} is the priority parameter of the job stacked at the top of buffer area b. Pb, Cb and Fb are the total number of buffer areas for the pressing stage, CNC cutting stage and FQC stage, respectively.

If no buffer areas offer proper stacking conditions, the managing part of the algorithm kicks in. All buffer areas are searched to find possible single panel shuffle rearrangements that would allow for more panels to be properly stacked. If such conditions are found, the algorithm addresses panel rearranging instructions to the work order and considers the new buffer conditions for the following events in the simulation. Figure 4-10 shows an example of a possible job rearranging and stacking instance in the buffer management algorithm.

When no buffer piles are able to properly accommodate a coming part even after the buffer rearranging algorithm, an intermediate buffer priority parameter (B_b) is calculated to find the maximum buffer priority parameter, according to the following equations.

$$\begin{cases} \boldsymbol{z_b^{top} \neq \{z^1, z^2, z^3, z^4, z^5\} \rightarrow d = 10000} \\ \boldsymbol{z_b^{top} = \{z^1, z^2, z^3, z^4, z^5\} \rightarrow d = 0} \end{cases} \quad \textbf{Equation 30}$$

$$\boldsymbol{B_b = 0.9d + 0.075z_b^{top} + 0.02z_b^{bottom} + 0.005S_b} \quad \textbf{Equation 31}$$

where d is a dummy variable to determine whether the buffer area b has a panel on top with priority parameter z_b^{top} equal to one of the shifting priority target candidates, and S_b is the total number of panels stacked on area b.

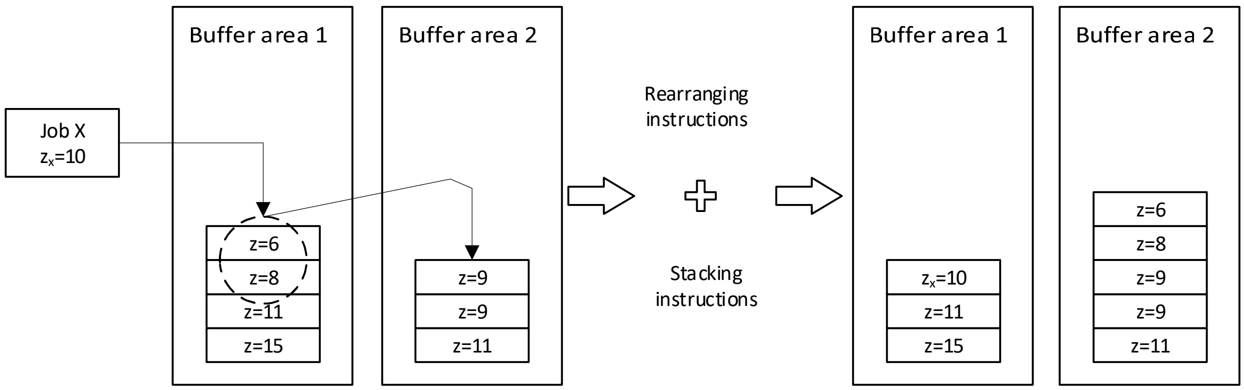


Figure 4-10 - Example of job rearranging and stacking in buffer areas

Figure 4-11 is a simplified flowchart of the buffer management controller in SCHER-CLT.

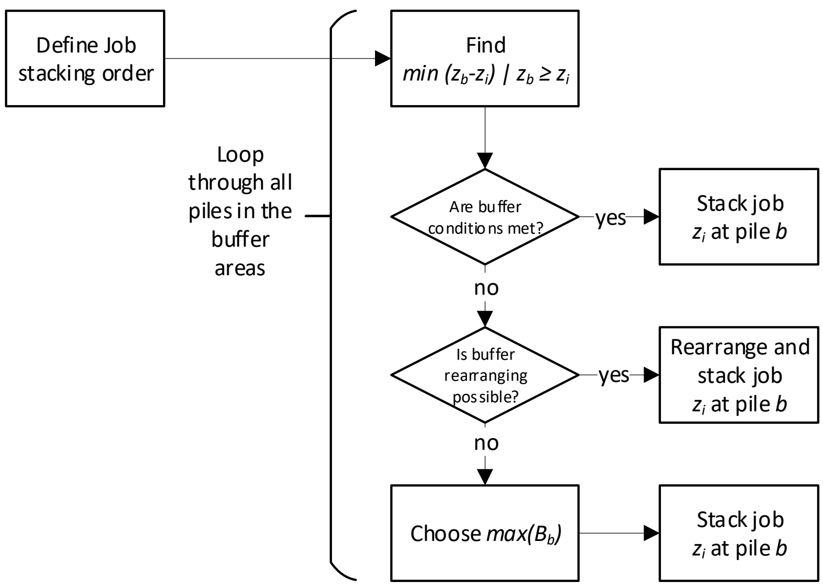


Figure 4-11 - Buffer management controller algorithm in SCHER-CLT

4.2.2.8 Package bundle wrapping

The process of waiting for the bundle mates implies that finished panels stay around the FQC work area, disrupting production and causing many unnecessary panel shuffles. Therefore, is reasonable to consider that the longer finished panels need to wait at the work area, the more panel shuffles are going to happen.

When a panel is finished, the package bundle wrapping algorithm will check if the bundle it belongs to is completed or not. If the bundle is not completed, the finished panel may either wait for its mates in any of the FQC work areas or, be placed at a FQC buffer area. If the bundle is completed, the algorithm will search for every bundle mate in the buffer areas, and FQC work areas. Once all mates are found and quantified, the algorithm determines at which FQC work area the bundle is going to be packed. The simplified package bundle wrapping algorithm is represented in Figure 4-12.

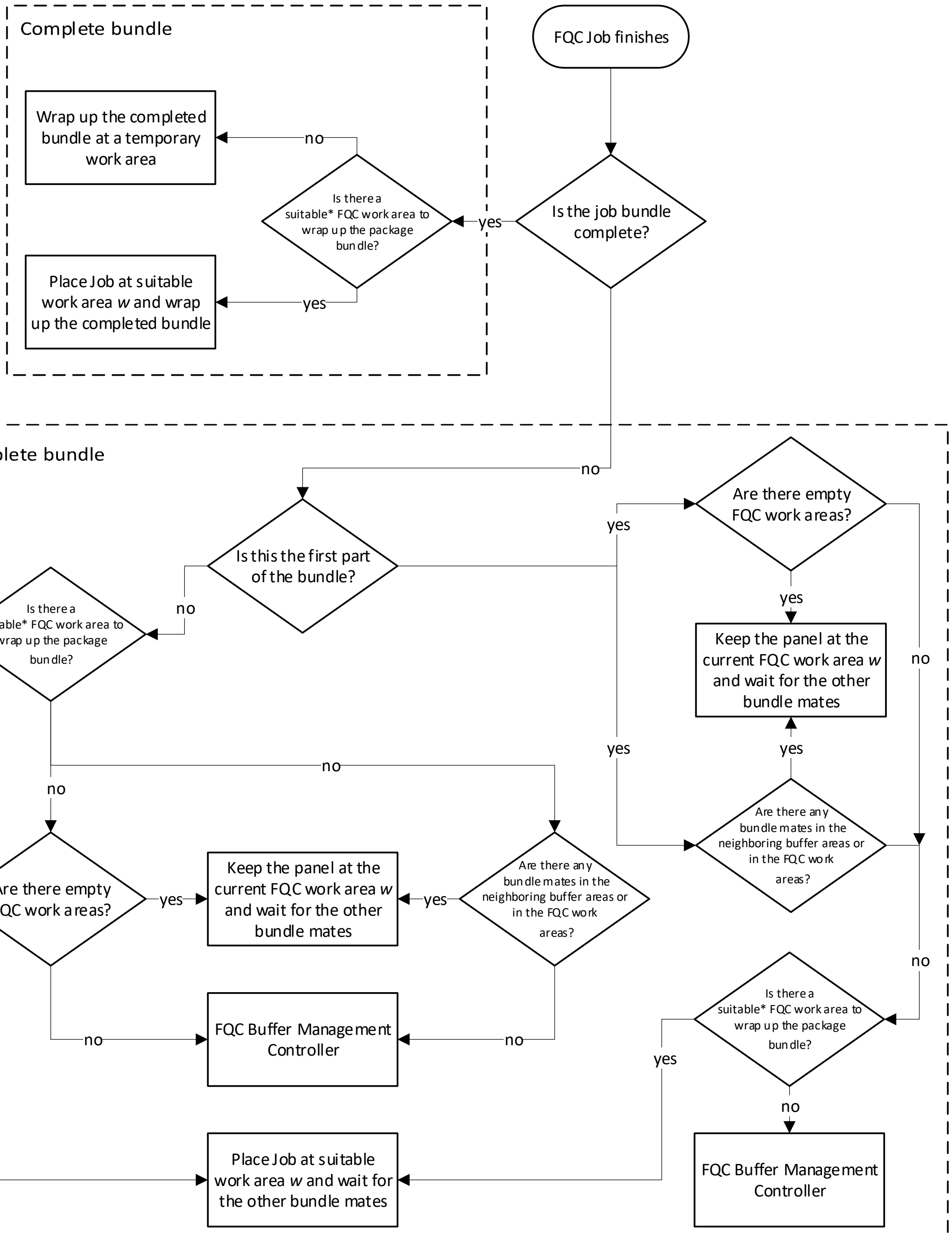


Figure 4-12 - Package bundle wrapping algorithm in SCHER-CLT

(*) In the decision tree shown in Figure 4-12, consider that the term suitable work area means either an empty work area, or a work area with a panel with the same priority parameter as the current job, on top. The most suitable work area will either be empty or be the work area with the most number of panels of the same priority parameter as the current job, according to the following.

$$\mathbf{max}(\boldsymbol{z_w^s} = \boldsymbol{z_i})\ \{\boldsymbol{S_w} = \mathbf{0}\,, \boldsymbol{z_w^{top}} = \boldsymbol{z_i} \qquad \begin{matrix} \boldsymbol{w} = \mathbf{1}, \mathbf{2}, \dots, \boldsymbol{Js} \\ \boldsymbol{s} = \mathbf{1}, \mathbf{2}, \dots, \boldsymbol{Ms} \end{matrix}$$ **Equation 32**

where S_w is the total number of jobs temporarily placed at FQC work area w, and z_w^s is the priority parameter number of the panel placed at position s of FQC work area w. As previously explained, in Section 4.3, z_i is the priority parameter of job i, Js is the total number of simultaneous work areas for the FQC stage, and Ms is the maximum buffer area pile size. Completed bundles are then wrapped up at the selected work area in accordance with the estimated bundle wrapping process time. After the packing process is finished, the simulation assumes that the bundle is taken out of the plant for permanent storing or loading, and the simulation scope has ended.

A simplified flowchart of the sub-steps described in the sections above, encompassing the whole DES algorithm applied for a customizable CLT panel manufacturing line is shown in Figure 4-13.

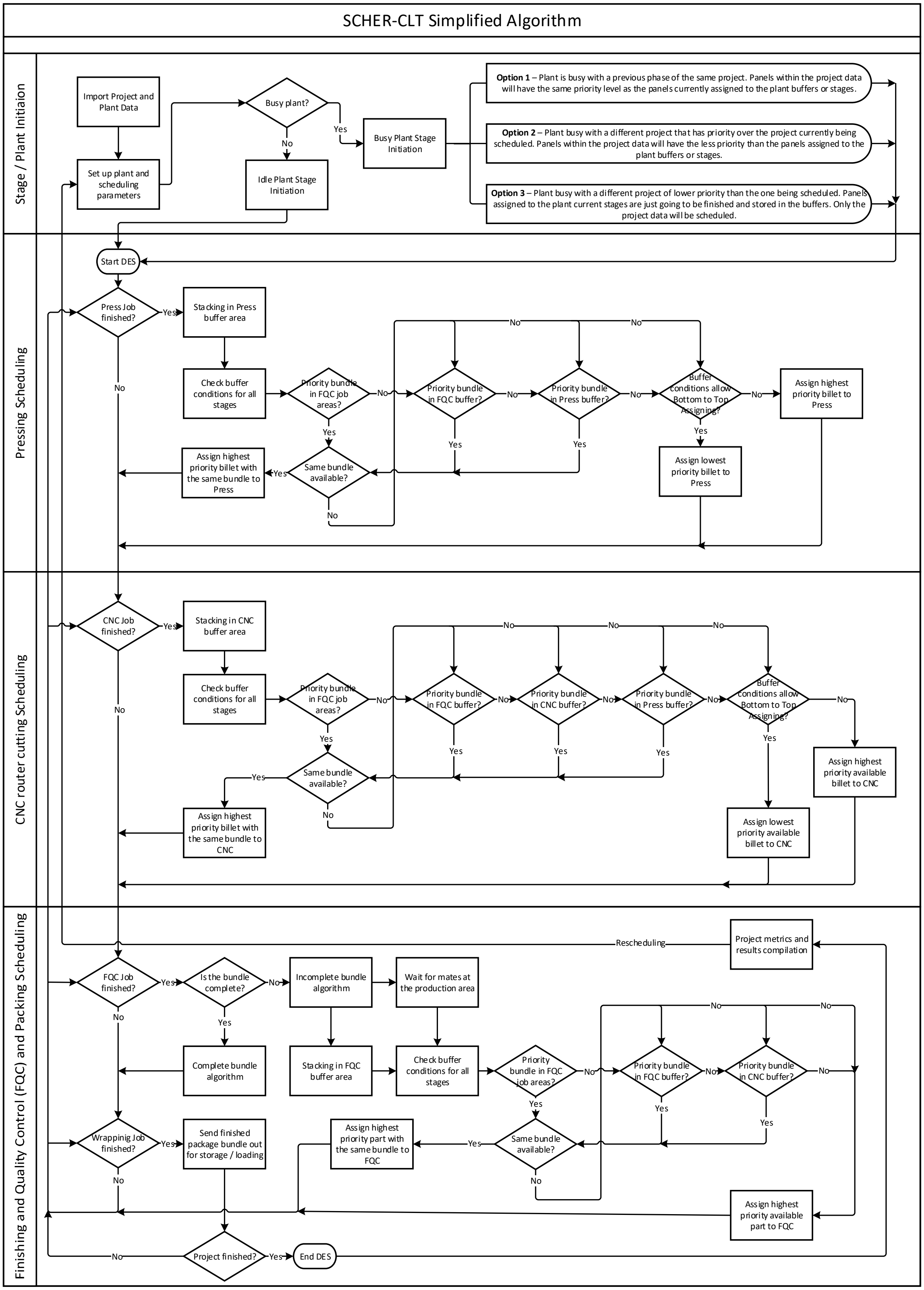


Figure 4-13 - SCHER-CLT simplified algorithm

4.2.3 Results

The last component of SCHER-CLT is the results compilation and report generation module. As the simulation algorithm advanced, project metrics were calculated after each discrete event. Once the DES is ended, results are compiled and, after the output parameters are given, final project metrics and objective control variables are reported. The simulation scheduling model outputs are listed in Table 4-3.

Table 4-3 - Outputs from SCHER-CLT

Output	Description
Total production elapsed time	Total flow time in minutes. Also shown in productive business days, hours and minutes.
Stage downtime	Total downtime for each stage in the production line.
Total number of panel shuffles	Total panel shuffle instances on each production stage.
Specific truck load production time	Production start and finish time step and elapsed production time for each truck load ID in the project database.
Specific bundle production time	Production start and finish time step and elapsed production time for each package bundle ID in the project database.
Production stage work orders	Work orders showing job assignment instances, stacking procedures, and job rearranging operations in the production flow for all jobs in the project database.

The rule-based attribute of the scheduling model allows for new, improved rules to be incorporated in the algorithm at a later date. At the same time, the DES algorithm allows for different events sequences to be modeled. The model can be adapted to generate schedules for different projects, plant layouts, buffer constraints or even manufacturing systems.

4.3 Case study

To better understand the behavior and sensitivity of the configurable parameters in the developed scheduling algorithm, a manufacturing scheduling case study was performed. The simulated plant environment replicates a customized CLT panel manufacturing plant in Okanagan Falls, BC. Several production scenarios were simulated with the same database to evaluate the scheduling outputs.

Two real project databases were used to simulate the real plant environment, where a current project is underway (plant database) and, before completely finished, a new project (project database) joins the production line and must be scheduled accordingly. All necessary inputs for the case study were provided by the Okanagan Falls CLT Plant’s management, and design teams and are shown at Appendices F and G for the project and plant database, respectively.

4.3.1 SCHER-CLT tool demonstration

As mentioned earlier, the scheduling algorithm described on Section 4.2 was embedded in a user-friendly Excel tool. Due to the algorithm complexity, and to allow large and complex projects to be easily scheduled, is was necessary to develop a software tool.

The SCHER-CLT tool combines the process time estimation models with the scheduling model facilitating their utilization and guiding the user from the data input procedures, all the way to scheduling results reporting. It is important though, that the user carefully follows all the instructions given by the software, especially during the project and plant data import procedures.

4.3.1.1 Project data input

The very first step in the SCHER-CLT tool is to import the project database. For this simulation, a 187-billet and 337-part project database was imported. The project counts with 86 bundles divided in 9 different truck loads. The import procedure is divided in four main steps:

- 1st step: import billets’ information from the billets list;
- 2nd step: import parts’ parameters from the production list;
- 3rd step: import CNC coding software estimated cutting times for each billet, and;
- 4th step: calculate the process times for each billet, parts in every stage in the production line.

Figure 4-14 shows the first tab of the tool interface, where the 1st and 2nd steps are taken. The 1st and 2nd steps are very similar, and after selecting the files where the information for billets and parts are, the user will be asked to provide the intervals, in the desired file, where each input is.

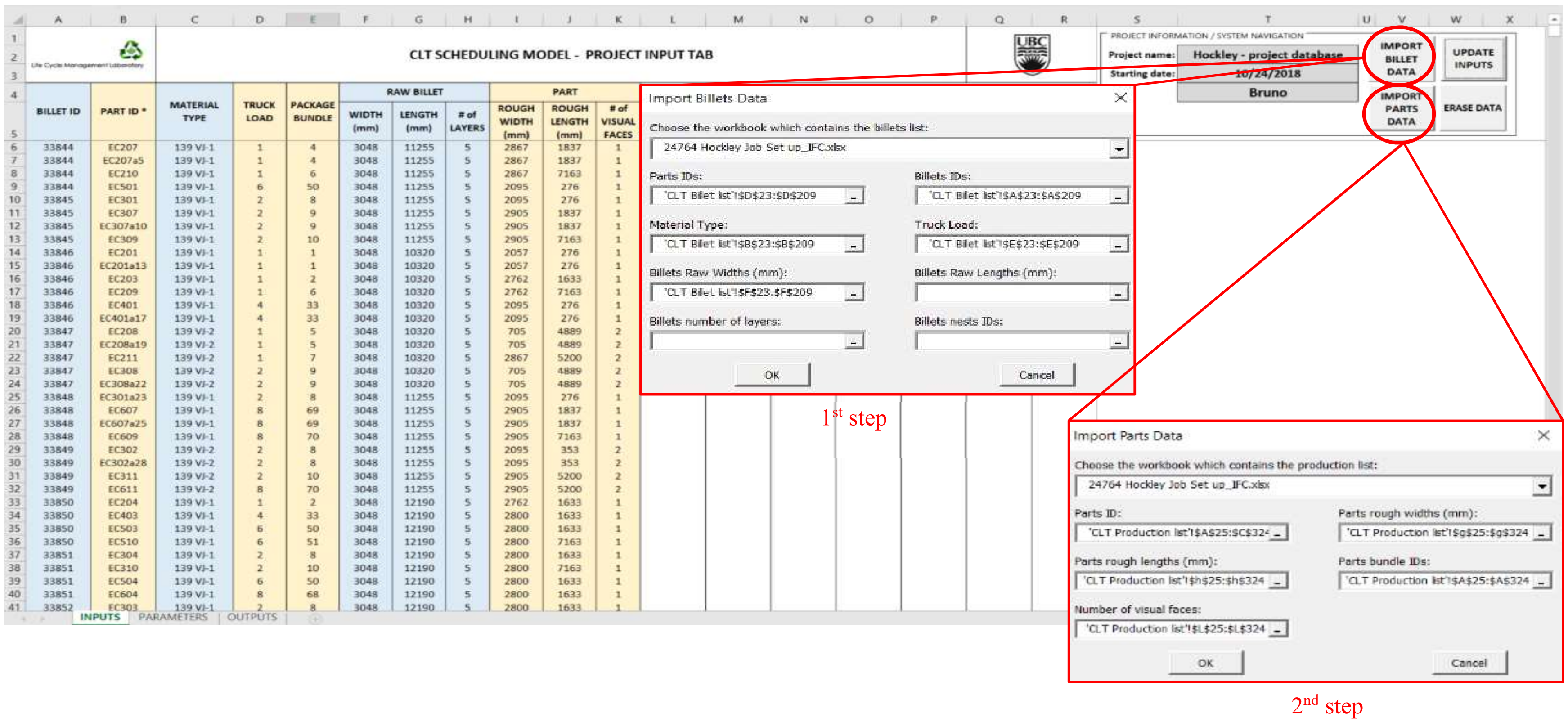


Figure 4-14 - SCHER-CLT INPUTS tab (first and second steps on the project data import procedure

After importing parts data for the project database, the user needs to move to the second tab in the tool to perform the 3rd and 4th steps in the import procedure, according to Figure 4-15. First, the user needs to provide the estimated fixed pressing time and the estimated fixed press waiting/setup time, in minutes, and the number of workers in the FQC team. Next, by clicking on the "CALCULATE PROCESS TIMES" button, the tool will check the consistency of the imported data, i.e. whether truck load and bundle IDs are valid numbers and if there are parts with the same bundle ID in different truck load IDs.

Once process times are estimated, the project inputs tab is finished according to Figure 4-16. If preferred, the user can also manually type all necessary inputs at the project or plant input tabs and use the "UPDATE INPUTS" button to save the manually provided inputs to the database.

Upon completion of the data import and process time estimation procedures for the project database, the user may choose whether the plant is currently busy or idle, before scheduling the project.

As shown in Figure 4-15, if the plant is idle, the user only needs to provide the project scheduling parameters, plant parameters, and the material type grouping for the press stage to proceed with the scheduling. If the checkbox that indicates whether the plant is busy or idle is not checked, the used will be allowed to schedule the project without providing the plant current stats inputs, and the algorithm will work with an idle plant from the start. On the other hand, if the checkbox is checked, the "PLANT CURRENT STATS" button will be enabled, and the user must provide all necessary plant information to proceed with the scheduling.

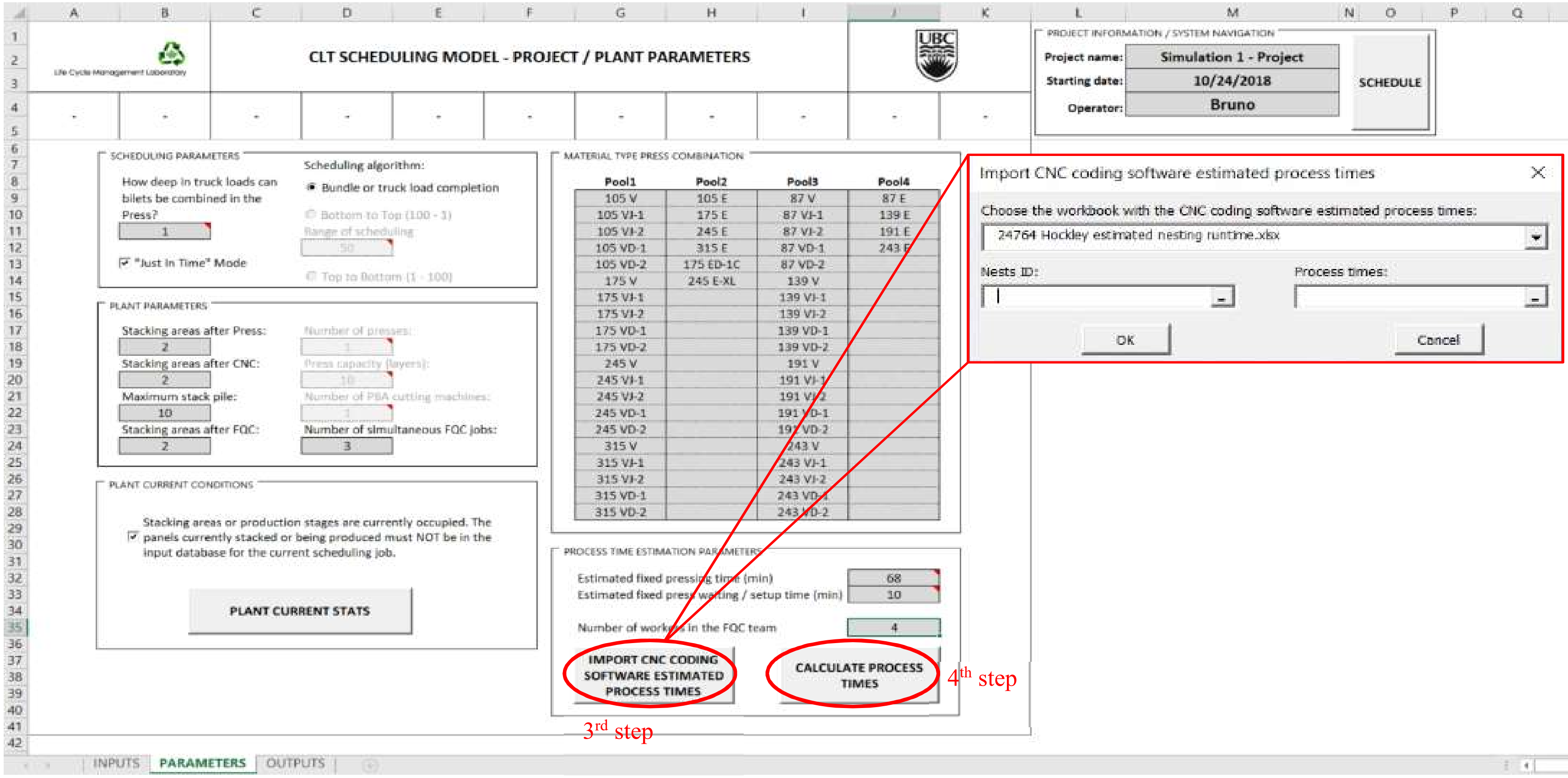
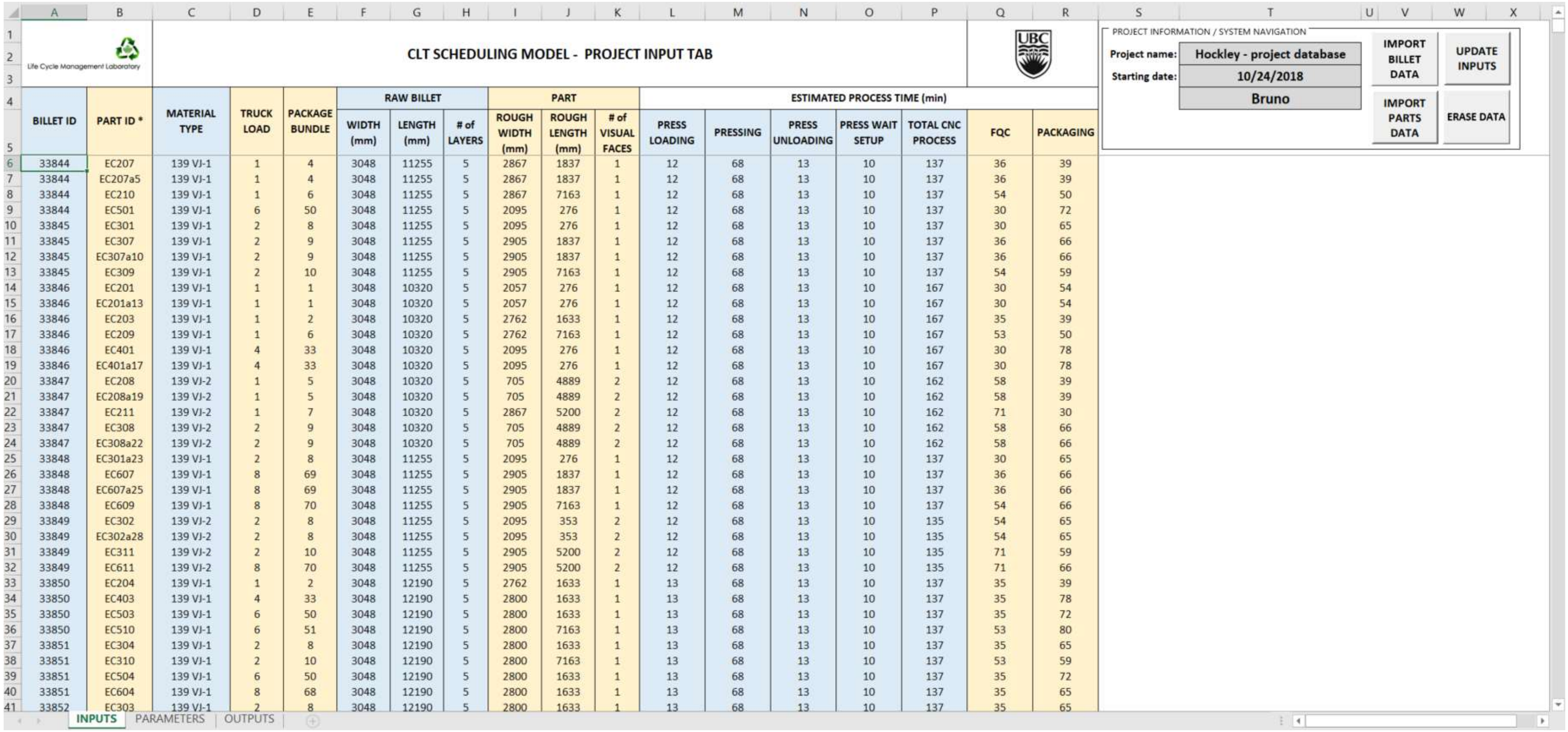


Figure 4-15 - SCHER-CLT PARAMETERS tab (third and fourth steps on the project data import procedure)



CLT SCHEDULING MODEL - PROJECT INPUT TAB

Life Cycle Management Laboratory

UBC

PROJECT INFORMATION / SYSTEM NAVIGATION

Project name: Hockley - project database

Starting date: 10/24/2018

Bruno

IMPORT BILLET DATA | UPDATE INPUTS | IMPORT PARTS DATA | ERASE DATA

					RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33844	EC207	139 VJ-1	1	4	3048	11255	5	2867	1837	1	12	68	13	10	137	36	39
33844	EC207a5	139 VJ-1	1	4	3048	11255	5	2867	1837	1	12	68	13	10	137	36	39
33844	EC210	139 VJ-1	1	6	3048	11255	5	2867	7163	1	12	68	13	10	137	54	50
33844	EC501	139 VJ-1	6	50	3048	11255	5	2095	276	1	12	68	13	10	137	30	72
33845	EC301	139 VJ-1	2	8	3048	11255	5	2095	276	1	12	68	13	10	137	30	65
33845	EC307	139 VJ-1	2	9	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33845	EC307a10	139 VJ-1	2	9	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33845	EC309	139 VJ-1	2	10	3048	11255	5	2905	7163	1	12	68	13	10	137	54	59
33846	EC201	139 VJ-1	1	1	3048	10320	5	2057	276	1	12	68	13	10	167	30	54
33846	EC201a13	139 VJ-1	1	1	3048	10320	5	2057	276	1	12	68	13	10	167	30	54
33846	EC203	139 VJ-1	1	2	3048	10320	5	2762	1633	1	12	68	13	10	167	35	39
33846	EC209	139 VJ-1	1	6	3048	10320	5	2762	7163	1	12	68	13	10	167	53	50
33846	EC401	139 VJ-1	4	33	3048	10320	5	2095	276	1	12	68	13	10	167	30	78
33846	EC401a17	139 VJ-1	4	33	3048	10320	5	2095	276	1	12	68	13	10	167	30	78
33847	EC208	139 VJ-2	1	5	3048	10320	5	705	4889	2	12	68	13	10	162	58	39
33847	EC208a19	139 VJ-2	1	5	3048	10320	5	705	4889	2	12	68	13	10	162	58	39
33847	EC211	139 VJ-2	1	7	3048	10320	5	2867	5200	2	12	68	13	10	162	71	30
33847	EC308	139 VJ-2	2	9	3048	10320	5	705	4889	2	12	68	13	10	162	58	66
33847	EC308a22	139 VJ-2	2	9	3048	10320	5	705	4889	2	12	68	13	10	162	58	66
33848	EC301a23	139 VJ-1	2	8	3048	11255	5	2095	276	1	12	68	13	10	137	30	65
33848	EC607	139 VJ-1	8	69	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33848	EC607a25	139 VJ-1	8	69	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33848	EC609	139 VJ-1	8	70	3048	11255	5	2905	7163	1	12	68	13	10	137	54	66
33849	EC302	139 VJ-2	2	8	3048	11255	5	2095	353	2	12	68	13	10	135	54	65
33849	EC302a28	139 VJ-2	2	8	3048	11255	5	2095	353	2	12	68	13	10	135	54	65
33849	EC311	139 VJ-2	2	10	3048	11255	5	2905	5200	2	12	68	13	10	135	71	59
33849	EC611	139 VJ-2	8	70	3048	11255	5	2905	5200	2	12	68	13	10	135	71	66
33850	EC204	139 VJ-1	1	2	3048	12190	5	2762	1633	1	13	68	13	10	137	35	39
33850	EC403	139 VJ-1	4	33	3048	12190	5	2800	1633	1	13	68	13	10	137	35	78
33850	EC503	139 VJ-1	6	50	3048	12190	5	2800	1633	1	13	68	13	10	137	35	72
33850	EC510	139 VJ-1	6	51	3048	12190	5	2800	7163	1	13	68	13	10	137	53	80
33851	EC304	139 VJ-1	2	8	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65
33851	EC310	139 VJ-1	2	10	3048	12190	5	2800	7163	1	13	68	13	10	137	53	59
33851	EC504	139 VJ-1	6	50	3048	12190	5	2800	1633	1	13	68	13	10	137	35	72
33851	EC604	139 VJ-1	8	68	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65
33852	EC303	139 VJ-1	2	8	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65

INPUTS | PARAMETERS | OUTPUTS

Figure 4-16 - SCHER-CLT INPUTS tab completely filled after the project database import procedure

4.3.1.2 Plant data input

Upon clicking the button "PLANT CURRENT STATS", another tab will be available to input the current plant data. Initially, the user must specify the priority level of the current jobs in the plant. According to the description on Section 4.2.2.1, one of the three busy plant initiation options must be selected. Upon this choice, the user shall start the plant database import procedure. The plant database import procedure is the same as the project database import procedure and is also divided in four steps. Figure 4-17 shows the PLANT CURRENT STATS tab. The fields shown on the left side of the PLANT CURRENT STATS tab are automatically configured according to the plant parameters specified in the PARAMETERS tab (number and capacity of the buffer areas after each stage - see Figure 4-15). The buffer areas are enabled, and billets or parts shall be assigned to their respective areas and positions in the plant. Similarly, the production stages current conditions might be populated with undergoing jobs being processed.

It is important to mention that the plant current stats may only be populated with billets or parts from the plant database. The tool will also consider that, jobs not assigned to any buffer area or production stage are finished, packed up and taken out of the plant production area for storage (i.e. the package bundle is complete, and all parts contained in it are automatically out of the scheduling algorithm).

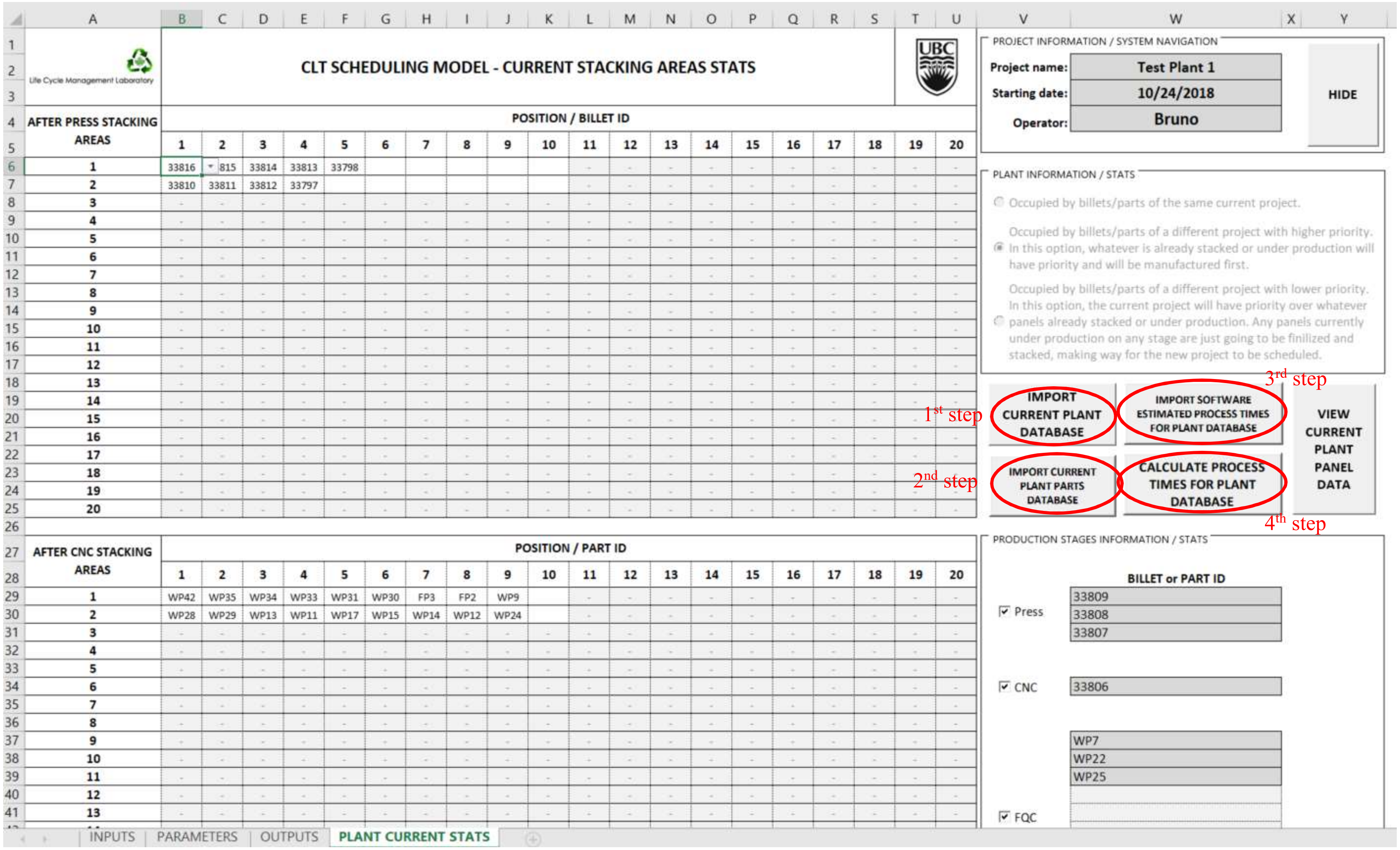


Figure 4-17 - SCHER-CLT PLANT CURRENT STATS tab - first to fourth steps on the plant data import routine

Upon clicking on the "HIDE" button in the PLANT CURRENT STATS tab, a consis
tency check is performed to guarantee that:

- No jobs have been mentioned in more than one assignment position (either a buffer area or a production stage);
- Every production stage assigned as busy has at least one job assigned to them;
- Batching constraints like billet width, material type and combined thickness at the pressing stage are obeyed;
- Parts vs billets consistency is maintained, i.e. a billet cannot have parts assigned to downstream buffer areas or production stage if itself is assigned either to the press buffer area or to the pressing stage;
- Package bundle consistency is maintained, i.e. single bundles cannot be broken in finished panels and panels still assigned to any point in the production line. Bundles that are considered finished cannot have any of their components assigned to any buffer area or production stage.

A smaller dataset was imported to compose the plant database on this simulation, a project comprised of 35 billets and 52 parts. The project counts with 24 bundles divided in 3 different truck loads. Once the PLANT CURRENT STATS tab is hidden, the user may proceed with the scheduling.

4.3.1.3 Scheduling module

Before proceeding with the scheduling, the user may configure two schedule parameters that will guide how the algorithm will select the next jobs after each discrete event in the simulation, the truck load assignment depth parameter and the "Just-in-time" (JIT) mode switch. Both parameters are explained in Section 4.2.2.3 and Section 4.2.2.6, respectively. Once all parameters are properly inputted, the "SCHEDULE" button is enabled, and the use may initiate the simulation. The software will interactively progress through the algorithm described in Figure 4-13 until all available jobs on the project database are scheduled. In case the jobs contained in the plant database have concurring or superior priorities than the jobs in the project database (see Section 4.2.2.1 for more details), the algorithm will sweep the plant database and schedule the existing unfinished jobs as well.

Figure 4-18 shows the scheduling progress on SCHER-CLT when the "SCHEDULE" button is clicked.

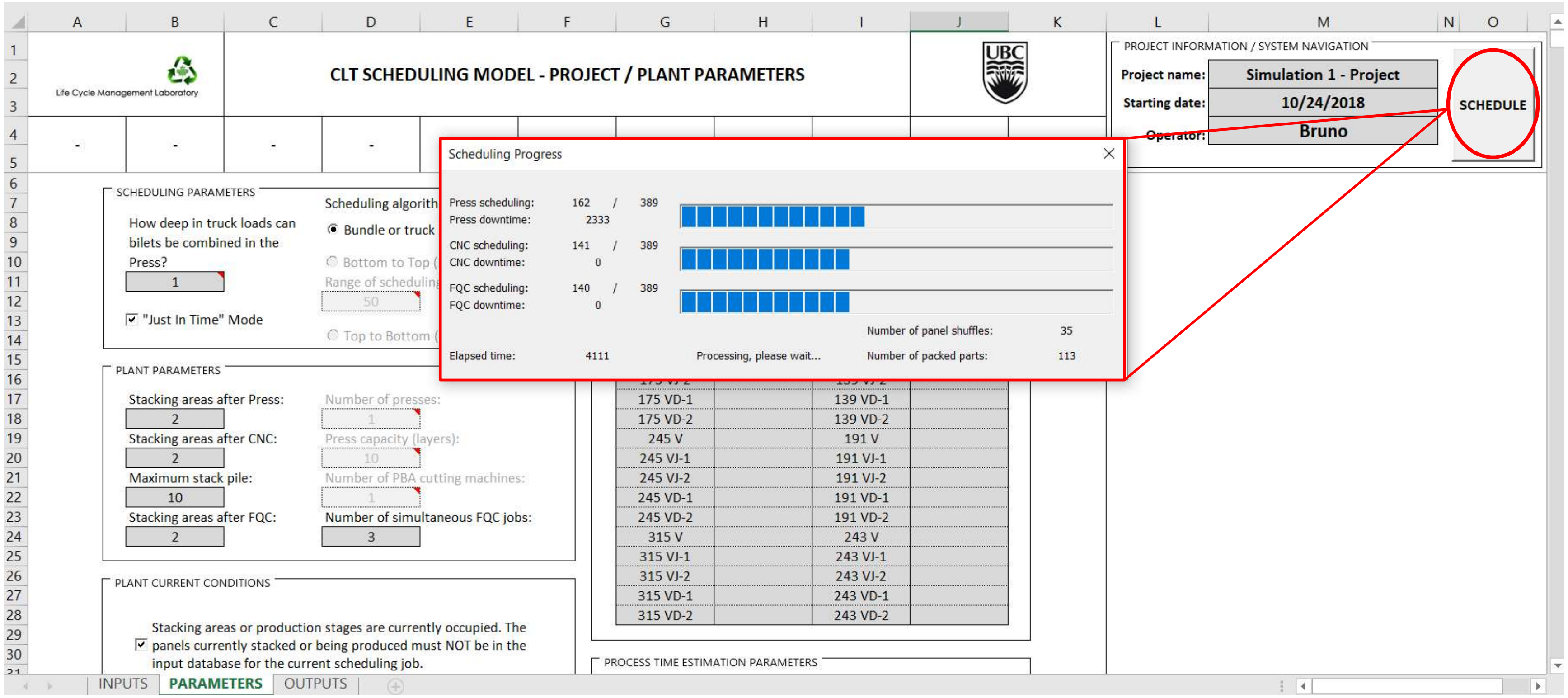


Figure 4-18 - Scheduling simulation progress in SCHER-CLT

4.3.1.4 Scheduling outputs and results printing module

As the DES is finalized, the OUTPUTS tab is enabled, and the project outputs are displayed. Project schedule metrics and work orders for each stage are provided. The user may select specific truck loads or bundle IDs to check their total makespan on each stage. The work order schedules are generated based on two user-inputted production parameters: shift duration (in productive hours) and the number of shifts per day. Figure 4-19 shows the OUTPUTS tab.

The generated work orders are divided in shifts and productive days as per the output parameters specified in the OUTPUTS tab (see Figure 4-19). For the FQC and wrapping work orders, the job schedule is further divided in work areas. On each work order, the tool provides jobs IDs, start and end time steps in minutes, and logistic parameters indicating, according to the specified plant parameters, from where the job is coming, and where it should be going to after each production stage or shuffling event.

Note that, although the priority parameter (bundle ID) is the indicator of how urgent a job might be, depending on the buffer areas and stages schedules, jobs with higher bundle IDs or "lower priority" might be finished, packed and sent out for storage, before jobs with lower bundle IDs, or "higher priority". This is reasonable since as soon as any bundle component reaches the FQC stage, its bundle ID should become the shifting priority target, giving the priority to their bundle mates over all the other parts, to minimize the single bundle makespan.

Bundle and truck load ID numbers that appear either divided or multiplied by 10,000, belong to panels currently in the plant database, i.e. when the current job has more (when it its divided by 10,000), or less priority (multiplied by 10,000) than the jobs in the project database (see Section 4.2.2.1).

Figure 4-20 to Figure 4-23, presented below, show the printable work order schedules for the pressing, CNC, FQC and wrapping procedures, respectively. The complete work order generated for the pressing stage, according to the inputted project and plant database, current plant conditions (in terms of buffer areas and stages occupation), and scheduling parameters shown in the tool demonstration (see Figure 4-14 to Figure 4-19, above), is displayed in Appendix H. The other stages' work orders are similar but were not included in the appendices for the sake of brevity.

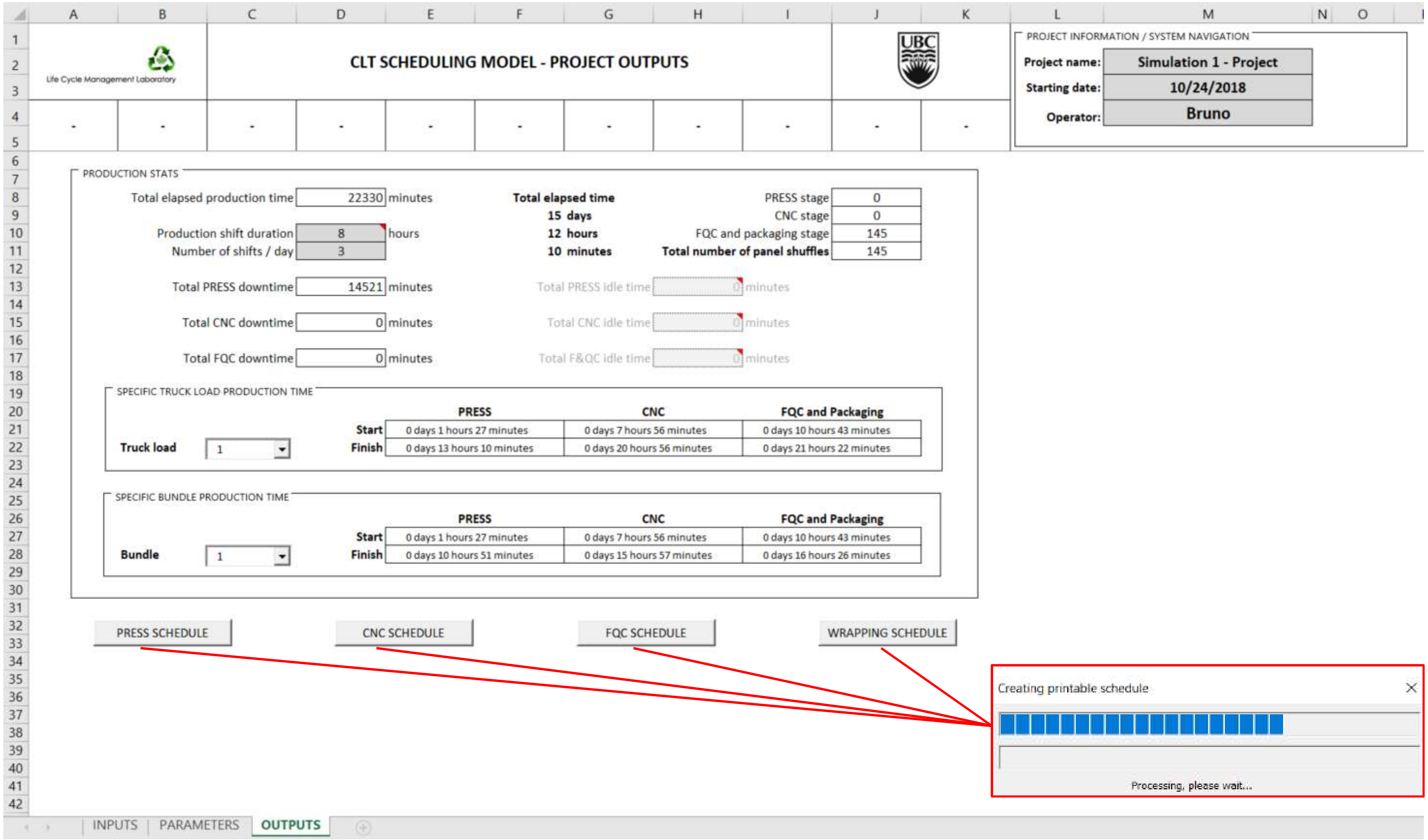


Figure 4-19 - SCHER-CLT OUTPUTS tab

Life Cycle Management Laboratory

CLT SCHEDULING MODEL
PRESS SCHEDULE

Project name:	Simulation 1 - Project
Starting date:	10/24/2018
Operator:	Bruno

PROJECT INFORMATION / SYSTEM NAVIGATION

Project name:	Simulation 1 - Project	HIDE
Starting date:	10/24/2018	
Operator:	Bruno	

	BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
72				SHIFT 2, DAY 1				
73	Downtime	51	163	-			-	-
74	33844	171	309	3	1	4	Raw material	Press Stacking Area 2 Position 3
75	33844	171	309	3	1	6	Raw material	Press Stacking Area 2 Position 3
76	33844	171	309	3	6	50	Raw material	Press Stacking Area 2 Position 3
77	33847	171	309	3	1	5	Raw material	Press Stacking Area 2 Position 2
78	33847	171	309	3	1	7	Raw material	Press Stacking Area 2 Position 2
79	33847	171	309	3	2	9	Raw material	Press Stacking Area 2 Position 2
80	Downtime	274	300	-			-	-
81	33845	309	623	4	2	8	Raw material	Press Stacking Area 2 Position 3
82	33845	309	623	4	2	9	Raw material	Press Stacking Area 2 Position 3
83	33845	309	623	4	2	10	Raw material	Press Stacking Area 2 Position 3
84	33848	309	623	4	2	8	Raw material	Press Stacking Area 2 Position 2
85	33848	309	623	4	8	69	Raw material	Press Stacking Area 2 Position 2
86	33848	309	623	4	8	70	Raw material	Press Stacking Area 2 Position 2
87	Downtime	412	477	-			-	-
88								
89				SHIFT 3, DAY 1				
90	Downtime	11	134	-			-	-
91	33852	143	578	5	2	8	Raw material	Press Stacking Area 2 Position 2
92	33852	143	578	5	4	33	Raw material	Press Stacking Area 2 Position 2
93	33852	143	578	5	8	68	Raw material	Press Stacking Area 2 Position 2
94	33852	143	578	5	8	70	Raw material	Press Stacking Area 2 Position 2
95	33907	143	578	5	4	33	Raw material	Press Stacking Area 2 Position 1
96	33907	143	578	5	4	34	Raw material	Press Stacking Area 2 Position 1
97	33907	143	578	5	8	68	Raw material	Press Stacking Area 2 Position 1
98	Downtime	247	296	-			-	-
99	Downtime	311	433	-			-	-
100	Downtime	441	570	-			-	-
101								
102				SHIFT 1, DAY 2				
103	33849	98	202	6	2	8	Raw material	Press Stacking Area 2 Position 3
104	33849	98	202	6	2	10	Raw material	Press Stacking Area 2 Position 3
105	33849	98	202	6	8	70	Raw material	Press Stacking Area 2 Position 3
106	33851	98	202	6	2	8	Raw material	Press Stacking Area 2 Position 4

INPUTS | PARAMETERS | OUTPUTS | PRESS SCHEDULE | CNC SCHEDULE | FQC SCHEDULE | WRAPPING SCHEDULE

Figure 4-20 - Printable Press schedule work order from SCHER-CLT

Life Cycle Management Laboratory

CLT SCHEDULING MODEL
CNC SCHEDULE

Project name: Simulation 1 - Project
Starting date: 10/24/2018
Operator: Bruno

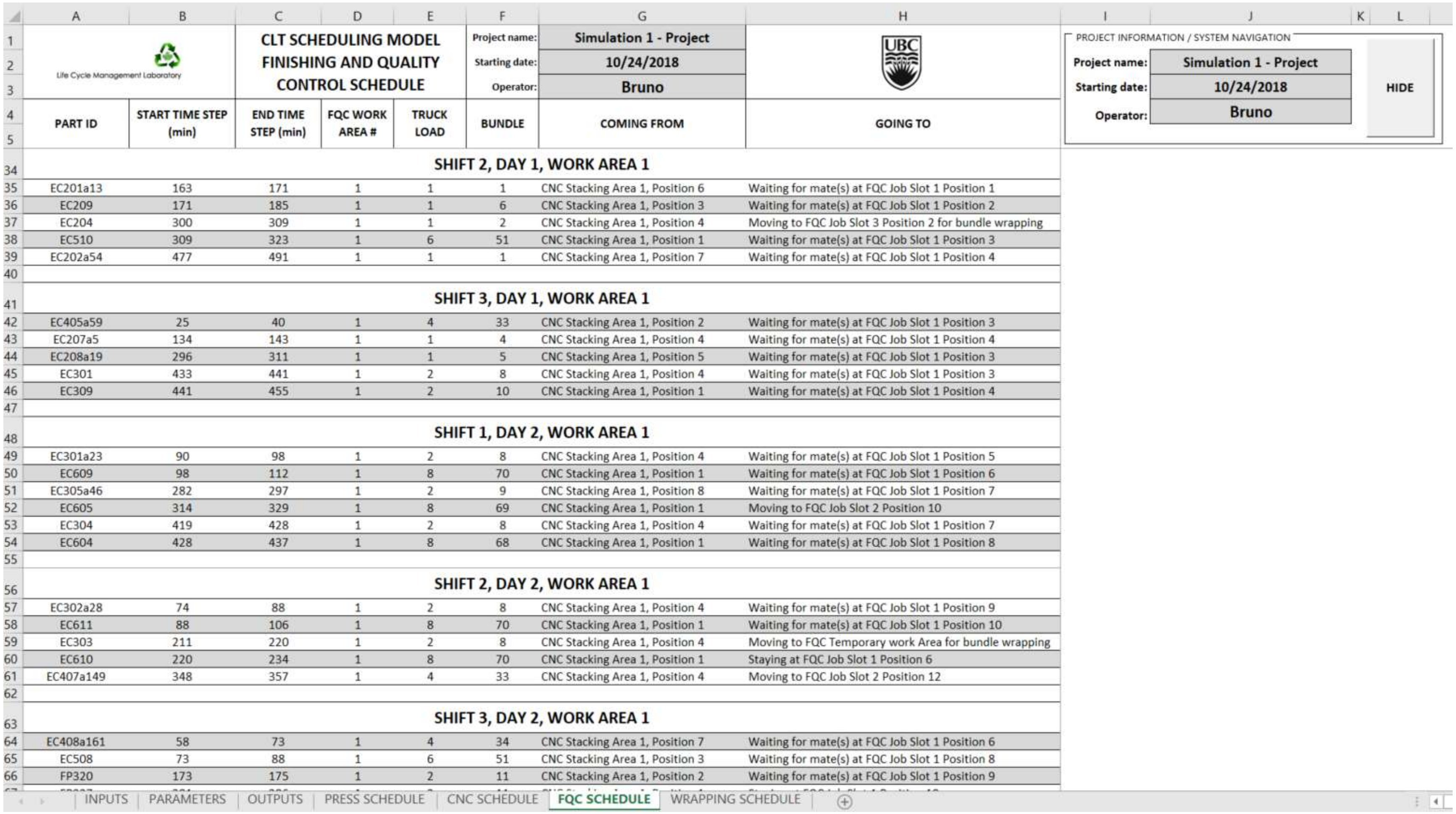
UBC

PROJECT INFORMATION / SYSTEM NAVIGATION
Project name: Simulation 1 - Project
Starting date: 10/24/2018
Operator: Bruno
HIDE

BILLET ID	PART ID	START TIME STEP (min)	END TIME STEP (min)	CNC CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
SHIFT 2, DAY 1								
33850	EC204	163	300	11	1	2	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 4
33850	EC403	163	300	11	4	33	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 3
33850	EC503	163	300	11	6	50	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 2
33850	EC510	163	300	11	6	51	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 1
33855	EC202	300	477	12	1	1	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 6
33855	EC205	300	477	12	1	3	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 4
33855	EC402a57	300	477	12	4	33	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 3
33844	EC207	477	614	13	1	4	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 2
33844	EC210	477	614	13	1	6	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 3
33844	EC501	477	614	13	6	50	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 1
SHIFT 3, DAY 1								
33847	EC208	134	296	14	1	5	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 4
33847	EC211	134	296	14	1	7	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 3
33847	EC308	134	296	14	2	9	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 1
33845	EC301	296	433	15	2	8	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 4
33845	EC307	296	433	15	2	9	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 2
33845	EC309	296	433	15	2	10	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 1
33848	EC301a23	433	570	16	2	8	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 4
33848	EC607	433	570	16	8	69	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 2
33848	EC609	433	570	16	8	70	Press Stacking Area 2, Position 2	CNC Stacking Area 1 Position 1
SHIFT 1, DAY 2								
33854	EC305	90	282	17	2	9	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 7
33854	EC402	90	282	17	4	33	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 6
33854	EC502	90	282	17	6	50	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 5
33854	EC605	90	282	17	8	69	Press Stacking Area 2, Position 1	CNC Stacking Area 1 Position 1
33851	EC304	282	419	18	2	8	Press Stacking Area 2, Position 4	CNC Stacking Area 1 Position 4
33851	EC310	282	419	18	2	10	Press Stacking Area 2, Position 4	CNC Stacking Area 1 Position 3
33851	EC504	282	419	18	6	50	Press Stacking Area 2, Position 4	CNC Stacking Area 1 Position 2
33851	EC604	282	419	18	8	68	Press Stacking Area 2, Position 4	CNC Stacking Area 1 Position 1
33849	EC302	419	554	19	2	8	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 3
33849	EC311	419	554	19	2	10	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 2
33849	EC611	419	554	19	8	70	Press Stacking Area 2, Position 3	CNC Stacking Area 1 Position 1

INPUTS | PARAMETERS | OUTPUTS | PRESS SCHEDULE | CNC SCHEDULE | FQC SCHEDULE | WRAPPING SCHEDULE

Figure 4-21 - Printable CNC schedule work order from SCHER-CLT



CLT SCHEDULING MODEL FINISHING AND QUALITY CONTROL SCHEDULE

Life Cycle Management Laboratory

Project name: Simulation 1 - Project
Starting date: 10/24/2018
Operator: Bruno

PROJECT INFORMATION / SYSTEM NAVIGATION
Project name: Simulation 1 - Project
Starting date: 10/24/2018
Operator: Bruno
HIDE

PART ID	START TIME STEP (min)	END TIME STEP (min)	FQC WORK AREA #	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
SHIFT 2, DAY 1, WORK AREA 1							
EC201a13	163	171	1	1	1	CNC Stacking Area 1, Position 6	Waiting for mate(s) at FQC Job Slot 1 Position 1
EC209	171	185	1	1	6	CNC Stacking Area 1, Position 3	Waiting for mate(s) at FQC Job Slot 1 Position 2
EC204	300	309	1	1	2	CNC Stacking Area 1, Position 4	Moving to FQC Job Slot 3 Position 2 for bundle wrapping
EC510	309	323	1	6	51	CNC Stacking Area 1, Position 1	Waiting for mate(s) at FQC Job Slot 1 Position 3
EC202a54	477	491	1	1	1	CNC Stacking Area 1, Position 7	Waiting for mate(s) at FQC Job Slot 1 Position 4
SHIFT 3, DAY 1, WORK AREA 1							
EC405a59	25	40	1	4	33	CNC Stacking Area 1, Position 2	Waiting for mate(s) at FQC Job Slot 1 Position 3
EC207a5	134	143	1	1	4	CNC Stacking Area 1, Position 4	Waiting for mate(s) at FQC Job Slot 1 Position 4
EC208a19	296	311	1	1	5	CNC Stacking Area 1, Position 5	Waiting for mate(s) at FQC Job Slot 1 Position 3
EC301	433	441	1	2	8	CNC Stacking Area 1, Position 4	Waiting for mate(s) at FQC Job Slot 1 Position 3
EC309	441	455	1	2	10	CNC Stacking Area 1, Position 1	Waiting for mate(s) at FQC Job Slot 1 Position 4
SHIFT 1, DAY 2, WORK AREA 1							
EC301a23	90	98	1	2	8	CNC Stacking Area 1, Position 4	Waiting for mate(s) at FQC Job Slot 1 Position 5
EC609	98	112	1	8	70	CNC Stacking Area 1, Position 1	Waiting for mate(s) at FQC Job Slot 1 Position 6
EC305a46	282	297	1	2	9	CNC Stacking Area 1, Position 8	Waiting for mate(s) at FQC Job Slot 1 Position 7
EC605	314	329	1	8	69	CNC Stacking Area 1, Position 1	Moving to FQC Job Slot 2 Position 10
EC304	419	428	1	2	8	CNC Stacking Area 1, Position 4	Waiting for mate(s) at FQC Job Slot 1 Position 7
EC604	428	437	1	8	68	CNC Stacking Area 1, Position 1	Waiting for mate(s) at FQC Job Slot 1 Position 8
SHIFT 2, DAY 2, WORK AREA 1							
EC302a28	74	88	1	2	8	CNC Stacking Area 1, Position 4	Waiting for mate(s) at FQC Job Slot 1 Position 9
EC611	88	106	1	8	70	CNC Stacking Area 1, Position 1	Waiting for mate(s) at FQC Job Slot 1 Position 10
EC303	211	220	1	2	8	CNC Stacking Area 1, Position 4	Moving to FQC Temporary work Area for bundle wrapping
EC610	220	234	1	8	70	CNC Stacking Area 1, Position 1	Staying at FQC Job Slot 1 Position 6
EC407a149	348	357	1	4	33	CNC Stacking Area 1, Position 4	Moving to FQC Job Slot 2 Position 12
SHIFT 3, DAY 2, WORK AREA 1							
EC408a161	58	73	1	4	34	CNC Stacking Area 1, Position 7	Waiting for mate(s) at FQC Job Slot 1 Position 6
EC508	73	88	1	6	51	CNC Stacking Area 1, Position 3	Waiting for mate(s) at FQC Job Slot 1 Position 8
FP320	173	175	1	2	11	CNC Stacking Area 1, Position 2	Waiting for mate(s) at FQC Job Slot 1 Position 9

INPUTS | PARAMETERS | OUTPUTS | PRESS SCHEDULE | CNC SCHEDULE | FQC SCHEDULE | WRAPPING SCHEDULE

Figure 4-22 - Printable FQC schedule work order from SCHER-CLT

Life Cycle Management Laboratory

CLT SCHEDULING MODEL WRAPPING SCHEDULE

Project name: Simulation 1 - Project
Starting date: 10/24/2018
Operator: Bruno

UBC

PROJECT INFORMATION / SYSTEM NAVIGATION
Project name: Simulation 1 - Project
Starting date: 10/24/2018
Operator: Bruno
HIDE

PART ID	START TIME STEP (min)	END TIME STEP (min)	FQC WORK AREA #	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
SHIFT 2, DAY 1, WORK AREA 1							
RP5	5	13	1	0.00003	0.00019	FQC Job Slot 1	Out for storage and/or loading
SHIFT 3, DAY 1, WORK AREA 1							
EC201	11	16	1			FQC Job Slot 2 Position 1	FQC Job Slot 1 for bundle wrapping
EC202	11	25	1	1	1	FQC Job Slot 2	Out for storage and/or loading
EC202a54	11	25	1	1	1	FQC Job Slot 1 Position 4	Out for storage and/or loading
EC201a13	11	25	1	1	1	FQC Job Slot 1 Position 1	Out for storage and/or loading
EC201	11	25	1	1	1	FQC Job Slot 2 Position 1	Out for storage and/or loading
EC207	143	153	1	1	4	FQC Job Slot 3	Out for storage and/or loading
EC207a5	143	153	1	1	4	FQC Job Slot 1 Position 4	Out for storage and/or loading
EC208	311	321	1	1	5	FQC Job Slot 2	Out for storage and/or loading
EC208a19	311	321	1	1	5	FQC Job Slot 1 Position 3	Out for storage and/or loading
SHIFT 1, DAY 2, WORK AREA 1							
EC307	297	302	1			FQC Job Slot 2 Position 9	FQC Job Slot 1 for bundle wrapping
EC307a10	297	302	1			FQC Job Slot 2 Position 8	FQC Job Slot 1 for bundle wrapping
EC308	297	302	1			FQC Job Slot 2 Position 7	FQC Job Slot 1 for bundle wrapping
EC308a22	297	302	1			FQC Job Slot 2 Position 6	FQC Job Slot 1 for bundle wrapping
EC305	297	314	1	2	9	FQC Job Slot 2	Out for storage and/or loading
EC305a46	297	314	1	2	9	FQC Job Slot 1 Position 7	Out for storage and/or loading
EC307	297	314	1	2	9	FQC Job Slot 2 Position 9	Out for storage and/or loading
EC307a10	297	314	1	2	9	FQC Job Slot 2 Position 8	Out for storage and/or loading
EC308	297	314	1	2	9	FQC Job Slot 2 Position 7	Out for storage and/or loading
EC308a22	297	314	1	2	9	FQC Job Slot 2 Position 6	Out for storage and/or loading
SHIFT 1, DAY 3, WORK AREA 1							
FP321	297	302	1			FQC Job Slot 2 Position 2	FQC Job Slot 1 for bundle wrapping
FP322	297	314	1	3	18	FQC Job Slot 2	Out for storage and/or loading
FP325	297	314	1	3	18	FQC Job Slot 1 Position 10	Out for storage and/or loading
FP326	297	314	1	3	18	FQC Job Slot 1 Position 9	Out for storage and/or loading
FP321	297	314	1	3	18	FQC Job Slot 2 Position 2	Out for storage and/or loading
SHIFT 2, DAY 3, WORK AREA 1							

INPUTS | PARAMETERS | OUTPUTS | PRESS SCHEDULE | CNC SCHEDULE | FQC SCHEDULE | WRAPPING SCHEDULE

Figure 4-23 - Printable Packaging schedule work order from SCHER-CLT

4.3.2 Simulation analysis

To better understand the influence of the several scheduling, plant and projects inputs for the SCHER-CLT model, different simulations were performed for the same scheduling problem, i.e. fixed project database, plant database, and current plant stats. The production scenarios were simulated on the same case study described in the previous sections. Table 4-4 shows the scheduling iterations and how the scheduling and plant parameters were configured for each simulation. Next. the same experimental design was repeated to schedule the same project database but now considering the plant as idle. This way, the influence and interaction of a different project in the plant is removed.

Table 4-4 - Experimental design for scheduling simulations

Simulation	Truck load assignment depth (tld)	Number of buffer areas After Press (Pb)	After CNC (Cb)	After FQC (Fb)	Buffer area capacity (Ms)	Number of FQC work areas (Js)
1 to 5 / 21 to 25 41 to 45 / 61 to 65	1,2,3,4,5	2	2	2	10	3
6 to 8 / 26 to 28 46 to 48 / 66 to 68	3	3,4,5	2	2	10	3
9 to 11 / 29 to 31 49 to 51 / 69 to 71	3	4	3,4,5	2	10	3
12 to 14 / 32 to 34 52 to 54 / 72 to 74	3	4	4	3,4,5	10	3
15 to 17 / 35 to 37 55 to 57 / 75 to 77	3	4	4	4	10	4,5,6
18 to 20 / 38 to 40 58 to 60 / 78 to 80	3	4	4	4	5,15,20	4

An overall total of 80 simulations were run and the compiled outputs from SCHER-CLT, as described in Section 4.3.1.4, are shown in its entirety in Appendix I. All simulations were processed with the JIT switch “on”, and “off”, and with a busy and idle plant. On simulations 1 to 20 and 41 to 60, the JIT mode was “on”, and on simulations 21 to 40 and 61 to 80, the JIT mode was “off”. On simulations 1 to 40 the plant was busy, and on simulations 41 to 80 the plant was idle. The observed influence of each configurable parameter and output behavior is described and discussed in the next section.

4.4 Results and discussion

Under this section the outputs provided by SCHER-CLT of the various scenarios simulated for the case study are presented and discussed. The sensitivity of several configurable parameters was evaluated, and general conclusions about the scheduling model are posted.

4.4.1 Total project makespan

Initially, it is clear to see from the dataset that the total project makespan is much more dependent on the total production resource at the plant and to the project itself than to the configurable parameters in the scheduling algorithm. Should the plant have parallel CNC machining or FQC stages, the makespan would be severely impacted.

There was essentially no change in the total project makespan regardless of the changes in the scheduling and plant parameters (in terms of buffer areas). Table 4-5 shows the condensed results for total project makespan. These results corroborate the plant management diagnosis regarding the bottleneck in the CNC stage of the production line. Therefore, as long as the CNC stage is constantly busy (assuming no machine breakdowns or maintenance breaks), the total project makespan is fixed, depending on the scheduling configuration (JIT mode "on" or "off").

Table 4-5 - Total project makespan from scheduling simulations

Simulation	Plant status before scheduling	JIT mode switch	Total jobs scheduled	Total project makespan (min)
1 to 20	Busy	On	389 (project + plant databases)	22330
21 to 40	Busy	Off	389 (project + plant databases)	22325
41 to 60	Idle	On	337 (project database)	21766
61 to 80	Idle	Off	337 (project database)	21785

4.4.2 Buffer storage capacity

Regarding the buffer storage capacity, as described in the experimental design outlined on Table 4-4, the number of buffer area and their capacity were systematically altered to capture their influence over the scheduling outputs.

4.4.2.1 Stage downtime

Regarding stage downtime, the only stage forcefully stopped during the simulation was the pressing stage. As the fastest and most productive stage in the process, the press needs to be shut down most likely in two different occasions: when the buffer areas are full or, when the JIT mode switch is “on”, the buffer areas cannot accommodate more billets stored in a proper manner. The larger the press buffer capacity is, the lesser time the pressing stage will need to be shut down waiting for appropriate stacking conditions. Figure 4-24 shows that there is a clear relationship between the total storage capacity of the press buffer area and the total pressing stage downtime.

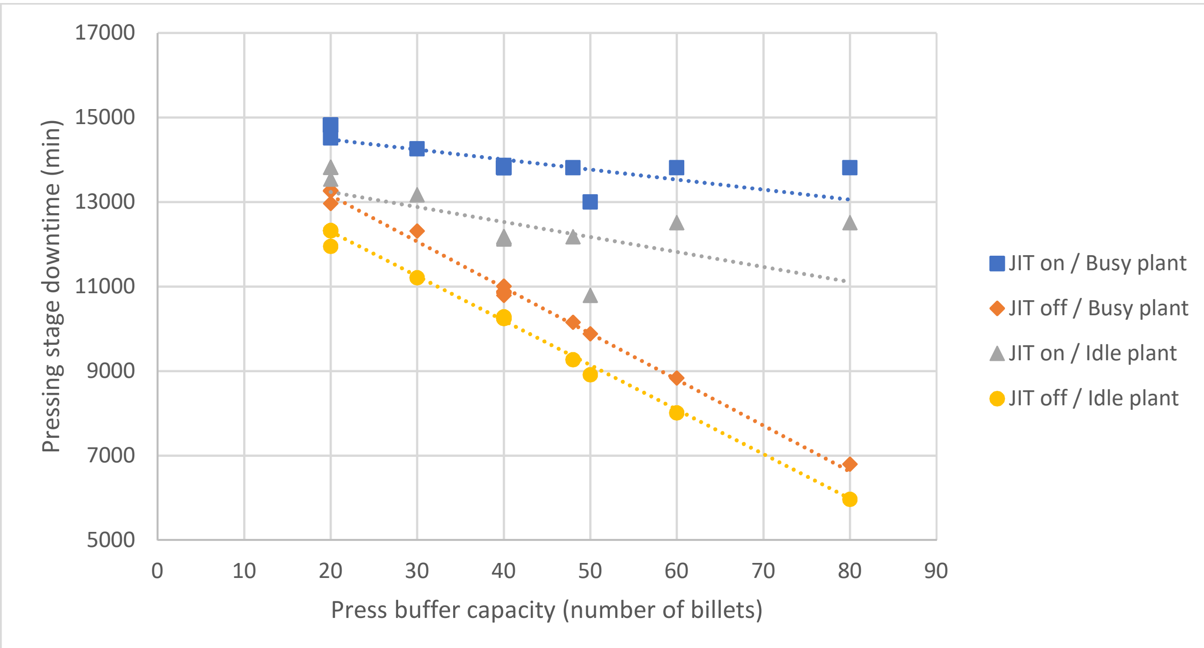


Figure 4-24 - Pressing stage downtime x Press buffer capacity

Considering the JIT option, to avoid panel shuffles in the intermediate buffer areas, the press stage downtime clearly increases, as it reduces the press throughput. It is also clear that, with the JIT switch off, the stage downtime decreases on a much higher rate as the press buffer capacity increases.

Table 4-6 shows the schedule output behavior due to variations in CNC and FQC storage capacity (Cb) and (Fb). Both CNC and FQC stages showed ZERO downtime, but for distinct reasons.

Table 4-6 - Schedule output behavior due to variations in CNC and FQC storage capacity

#	JIT mode / Plant Status	*tld*	*Pb*	*Cb*	*Fb*	*Ms*	*Js*	Project Makespan (min)	Panel shuffles: Press	CNC	FQC	Total	Press down time (min)	Max. bundle finish (min)	Avg. bundle finish (min)
9	On			3									13826		
10	/	3	4	4	2	10	3	22330	0	0	140	140		21237	3448
11	Busy			5											

#	JIT mode / Plant Status	*tld*	*Pb*	*Cb*	*Fb*	*Ms*	*Js*	Project Makespan (min)	Panel shuffles				Press down time (min)	Max. bundle finish (min)	Avg. bundle finish (min)
									Press	CNC	FQC	Total			
29	Off			3									10876		
30	/	3	4	4	2	10	3	23325	176	27	222	425		21259	4898
31	Busy			5											
49	On			3									12178		
50	/	3	4	4	2	10	3	21766	0	0	156	156		21523	5229
51	Busy			5											
69	Off			3									10251		
70	/	3	4	4	2	10	3	21785	164	20	151	335		21346	4112
71	Busy			5											
12	On				3								13822		
13	/	3	4	4	4	10	3	22330	0	0	139	139		21237	3407
14	Idle				5										
32	Off				3				178	31	217	426	10872		4819
33	/	3	4	4	4	10	3	23325	175	29	228	432	10893	21259	4824
34	Idle				5				177	29	223	429	10848		4817
52	On				3								12178		
53	/	3	4	4	4	10	3	21766	0	0	155	155		21523	5229
54	Idle				5										
72	Off				3				164	19	152	335	10273		4126
73	/	3	4	4	4	10	3	21785	165	18	146	329	10254	21346	4124
74	Idle				5				165	18	146	329	10254		4124

As explained before in Chapter 3, the CNC stage is the bottleneck in the production line and it was confirmed by the scheduling simulations. For this reason, the CNC stage operates flooded with waiting jobs in the upstream buffer area, showing no forced downtime.

For the FQC stage, after analyzing the complete stage work orders it was possible to detect that although the forced stage downtime is ZERO, there is idle time on the stage. The way the tool was developed, it sums up the stage forced downtime (i.e. when the downstream buffer area is either full or do not accommodate more jobs in a proper stacking manner), but it does not compute the stage idle time (i.e. when the stage is idle because there are no jobs waiting to be processed). Nevertheless, this information is available when analyzing the complete printable work orders for each stage.

From this analysis it is possible to affirm that, for this example, the workforce allocated in the FQC could be downsized to achieve better resource use. These behaviors in the CNC and FQC stages are easily detected when the variations in the CNC and FQC buffer capacities are analyzed against the outputs given by the tool, as shown in Table 4-6.

4.4.2.2 Average bundle finishing time

Absolute values of the average bundle finishing time are much more related to jobs characteristics in the project and plant databases (e.g. quantity, process times, priority parameters - truck load and bundle IDs, and bundle composition) and how these jobs are scheduled, than to the actual plant buffer capacity.

However, it is possible to observe slightly different behaviors (as seen by the trendlines in Figure 4-25) in the average bundle finishing time between simulations when the JIT mode is "on" and "off". Note that the average bundle finishing time variation rate due to changes in the press buffer capacity is more intense when the JIT mode is off, for both databases (busy and idle plant).

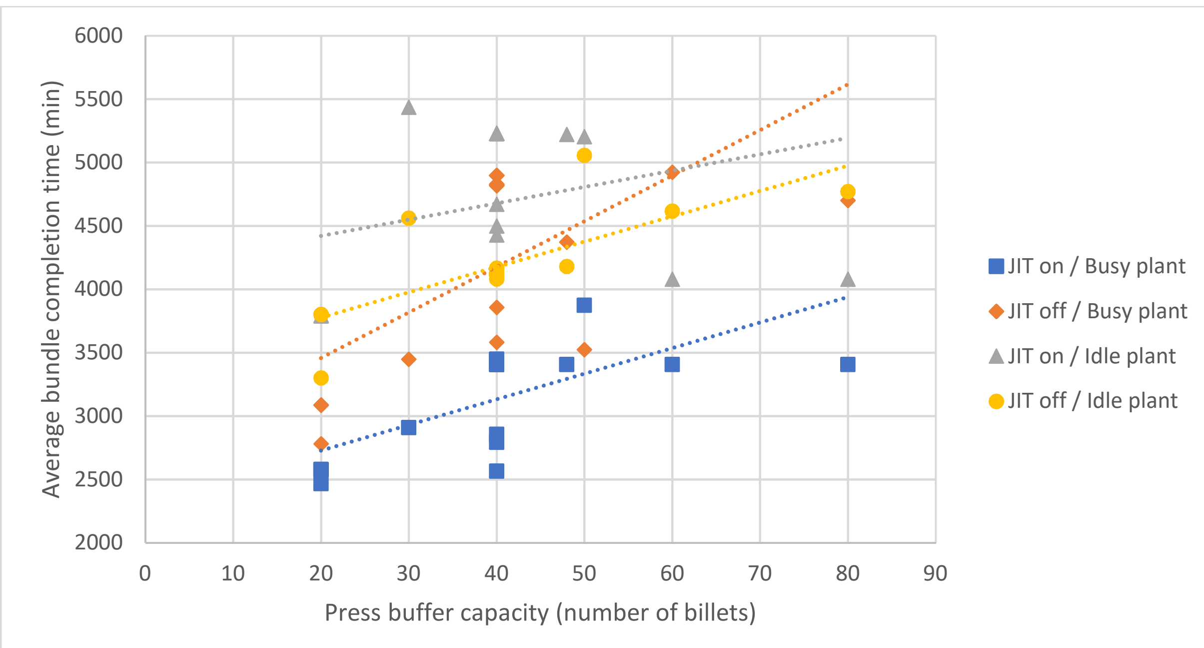


Figure 4-25 - Average bundle finishing time and Press buffer capacity

It is also noticeable that, for schedules with less press buffer capacity, as the press downtime is increased (reducing pressing throughput and enhancing the JIT effect of only pressing billets when they are essentially needed), the average bundle finishing time tends to be smaller.

4.4.2.3 Total number of panel shuffles

Like the average bundle finishing time, the absolute number of panel shuffles is much more related to the characteristics of jobs in the project and plant database and how they are scheduled than to the actual storage capacity of the plant. Bigger projects (more jobs to be scheduled) also tend to have a higher number of panel shuffles, independently of how they are scheduled. Nevertheless, the JIT option in the algorithm is capable of drastically reduce the total amount of panel shuffles, as it avoids that billets which are not going to be needed in the short future are pressed and end up being improperly stored at the buffer areas, see Figure 4-26.

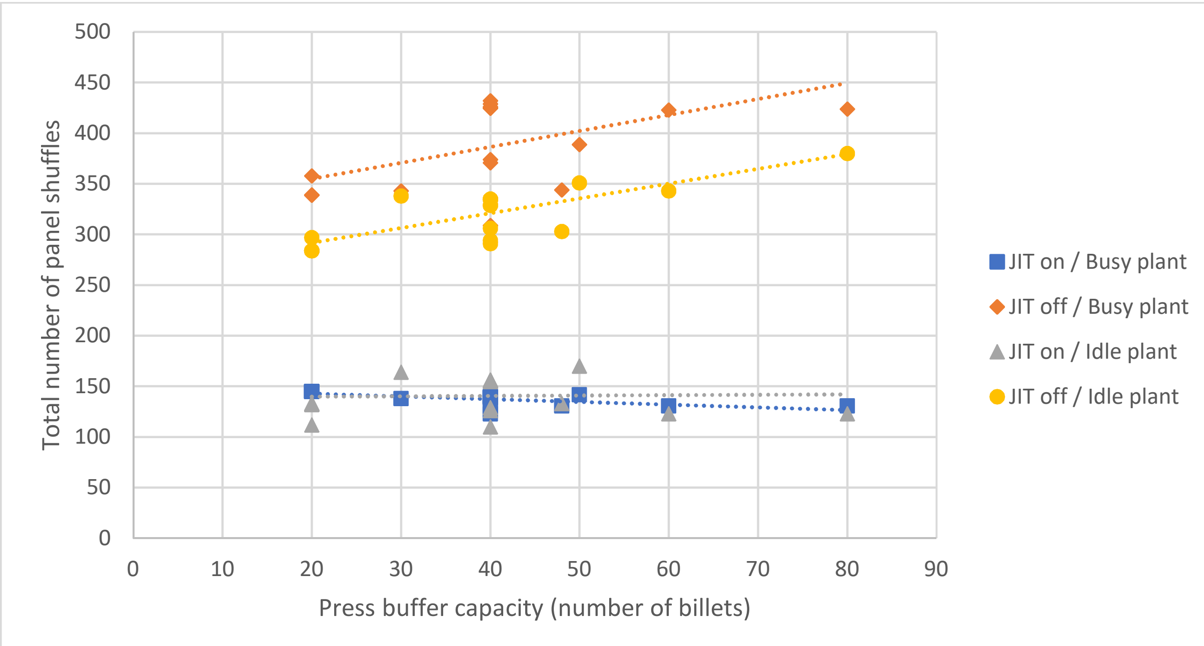


Figure 4-26 - Total number of panel shuffles and Press buffer capacity

Another important factor that intensely impacts the CNC and FQC stages process times, as well as the seem to have an influence on the total amount of panel shuffles is the average number of parts in each billet on each project. The larger the billets are and the more parts they yield, greatly increase the CNC stage process time and, the way the algorithm was built, overflows the FQC stage with a large number of panels to be finished and packed. In the same line of thought, bundle sizes and the bundle composition of each billet, is also a huge factor on finishing and packaging efficiency, and in reducing the number of panel shuffles.

Ideally, billets must have as less parts as possible, with a bundle composition as uniform as possible. Similarly, to minimize the number of panel shuffles and average bundle finishing time, it is advised to try to minimize bundles sizes. However, it is important to develop a trade-off study to better evaluate what would be the ideal, or minimum bundle size to efficiently conciliate finishing and packaging procedures with panel shuffles and average bundle finishing time.

4.4.3 Simultaneous FQC work areas (Js)

Variations in the number of simultaneous FQC work areas have close to no effect in reducing the number of panel shuffles in the FQC stage, as seen in Figure 4-27. At the same time, it also had little to no effect on the stage downtime and average bundle finishing time (see Figure 4-28). Additionally, it is possible that the slight variation observed in panel shuffles might be more related to the database itself, and how the algorithm works and schedule jobs, than to actual variations in parameter Js. More evidence and experimentation with the algorithm is necessary to proper evaluate this parameter.

Nevertheless, this analysis proves one of plant management's intuitive assumptions that the longer finished panels stay at the finishing area waiting for their bundle mates, the more panel shuffles would happen, and overall process productivity would be reduced. It is noticeable that looking at the same JIT scheduling option and plant status (idle or busy), both outputs (panel shuffles and average bundle finishing time) behaved similarly with variations in the number of FQC work areas, i.e. whenever the number of panel shuffles increase, the average bundle finishing time also increased.

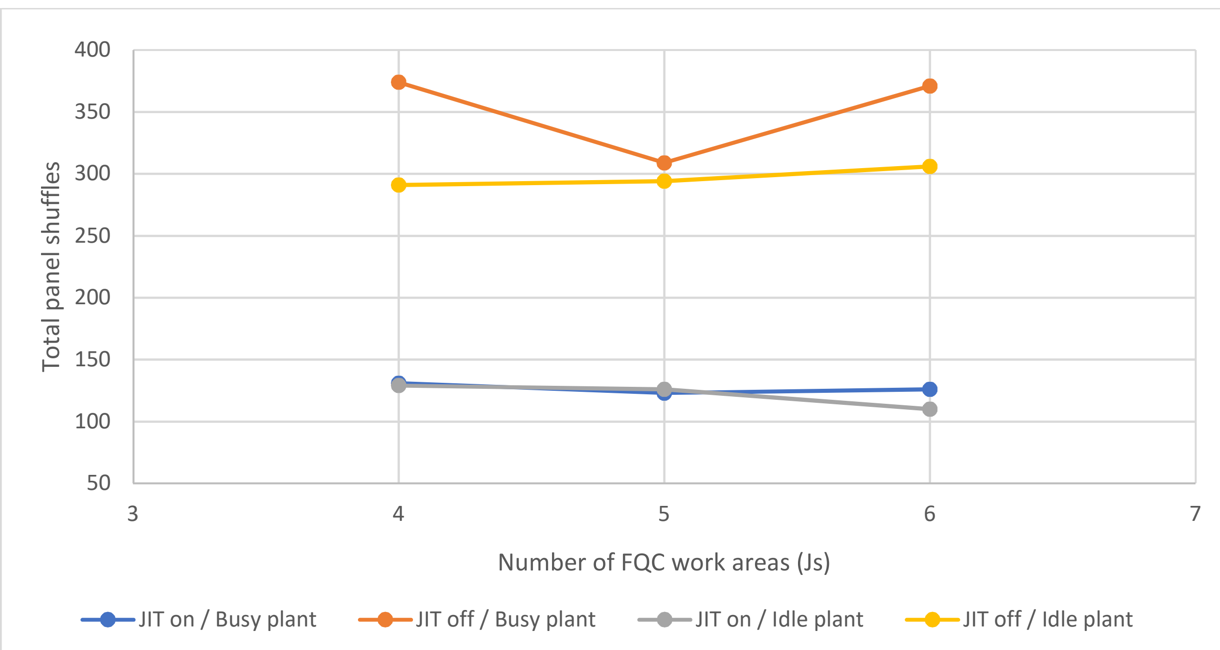


Figure 4-27 - Total panel shuffles and Number of FQC work areas (*Js*)

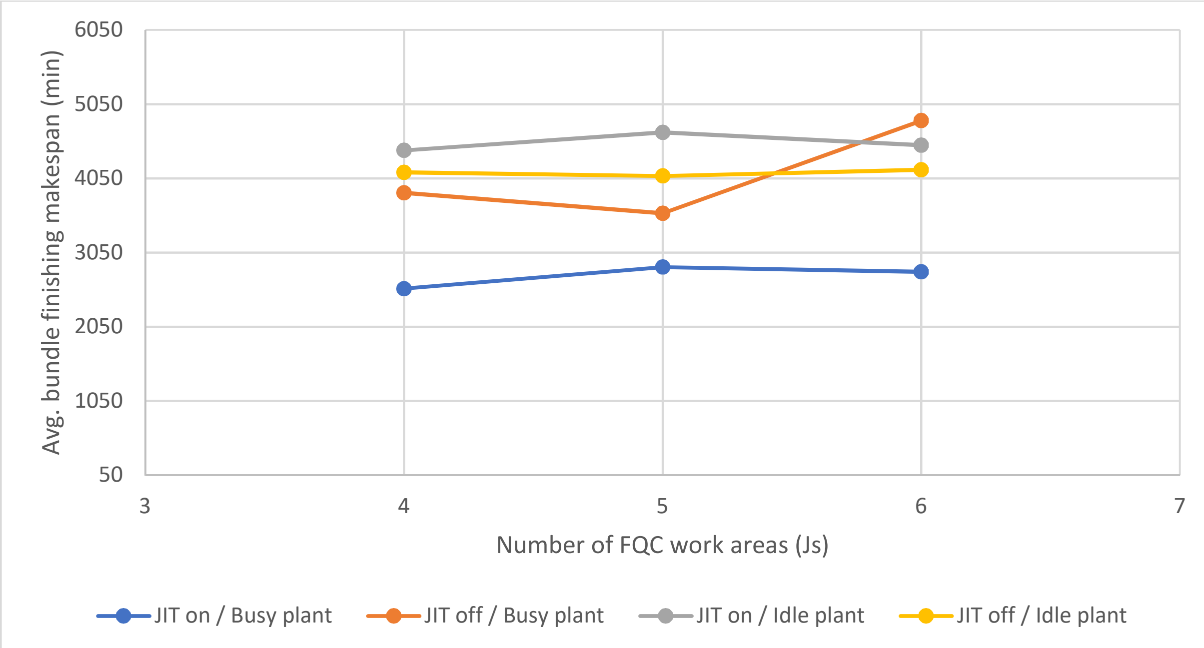


Figure 4-28 - Average bundle finishing makespan and Number of FQC work areas (*Js*)

4.4.4 Truck load assignment depth (*tld*)

The truck load assignment depth appeared to be the least influential scheduling parameter in the algorithm. However, in the scheduling algorithm, the assignment depth sensitivity is highly correlated with the total buffer storage capacity at the pressing stage, as described in Section 4.2.2.3. If there is not a large enough buffer area, the pool of available jobs to enter the pressing stage is automatically narrowed to a smaller range of truck loads in the assignment of the first billet to join the press. Even though tld might be high, due to buffer area constraints, and therefore, a smaller job pool in terms of truck load ID range, there will be just no billets with truck loads deep enough to be assigned to the press. This is the reason why alterations on the truck load depth had no effect on the scheduling outputs.

Therefore, more evidence and experimentation with the algorithm is necessary to proper evaluate the tld parameter. Figure 4-29 and Figure 4-30 show the behavior of total number of panel shuffles and average finishing makespan due to variations in the truck load depth assignment parameter, in conditions where the buffer areas are extremely constrained (2 buffer areas in the pressing stage, with a maximum stack of 10 panels, i.e. press buffer capacity of only 20 billets).

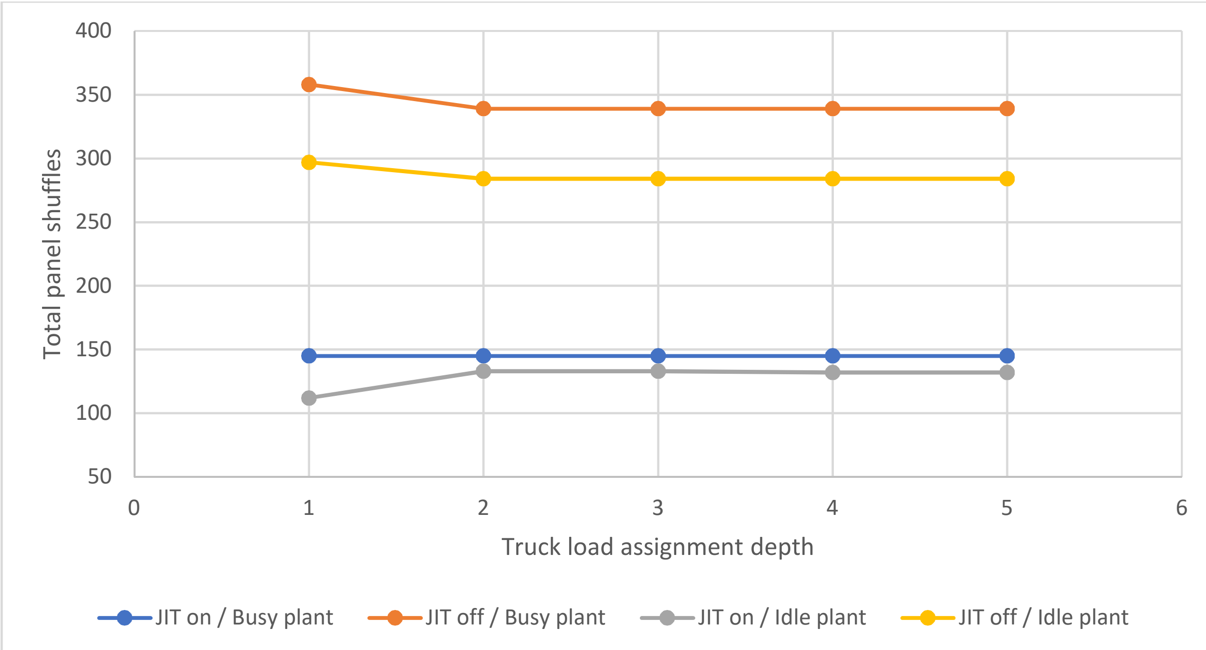


Figure 4-29 - Total panel shuffles and Tuck load assignment depth

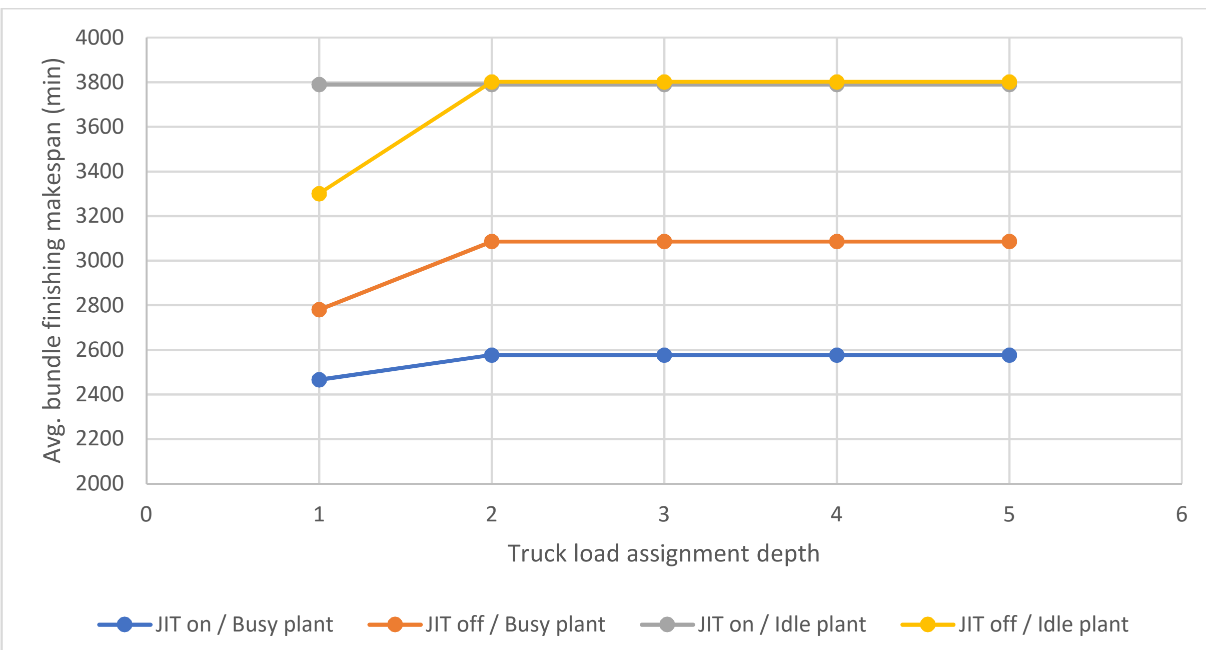


Figure 4-30 - Average bundle finishing makespan and Truck load assignment depth

4.5 Summary

The production schedule is fundamental in the overall manufacturing process efficiency. A poorly planned job scheduling may lead to several difficulties in production, leading to wasted time, resources, and ultimately, money. The production schedule is even more important when simultaneous projects with sequenced jobs and limiting buffer constraints are considered. The proposed simulation scheduling model allows CLT plant managers to evaluate different production scenarios and plant buffer configurations to improve scheduling results.

The developed model was encapsulated in a scheduling tool that combined a user-friendly interface to properly import relevant job data, with the previously developed CLT process time estimation models, and the scheduling algorithm itself.

A case study was conducted, and several production scenarios were simulated to better understand the capacity, improvements and limitations of the algorithm. The results of the case study proved the algorithm efficiency in reducing the number of panel shuffles when the JIT mode is active, and revealed that the average bundle finishing times are more related to jobs characteristics in the project and plant databases (e.g. quantity, process times, priority parameters - truck load and bundle IDs, and bundle composition) and to how these jobs are scheduled.

In terms of process efficiency and productivity, panel shuffles could impact the total project makespan, even though that was not observed on the case study. This is due to model assumption that shuffling procedures occur during the downstream stage process time. Nevertheless, in an extreme case, shuffling activities might have an impact on the makespan, in case they last longer than the process time of a current job.

Moreover, the proposed DES approach may be adapted to diverse manufacturing systems, incorporating their routines, events and limitations. Multiple benefits may be achieved with DES in manufacturing, including incorporating re-scheduling procedures. Adequate scheduling and re-scheduling routines are fundamental to improve manufacturing businesses costs and improve its flexibility (Aufenanger et al. 2008).

Chapter 5: Conclusions and Recommendations

Manufacturing scheduling and production sequence optimization is one of the few unexplored facets of customized CLT panel production lines. The increasing necessity for productivity and process improvement has resulted in the need for a production scheduling model to minimize plant support activities while optimizing plant resources and, at the same time, following production constraints. The finding will be used to enhance customized CLT panel manufacturing production management, providing the tools to better evaluate production scenarios, plant organization and, primarily the production schedule.

5.1 Summary and conclusions

This study's main objective was to explore, understand and develop a scheduling model for customizable CLT panels manufacturing. The developed scheduling model, although focused in CLT manufacturing applications, is adaptable and, with the necessary adjustments, could be used in other manufacturing fields where limited buffer areas and sequenced production constraints are present.

Initially, a comprehensive literature review was conducted to evaluate modelling approaches, scheduling problems solutions, better understand the intricacies of CLT as an industrial product, and the constraints of the production process.

An optimal analytical solution for the scheduling problem was not achieved due to its complexity, considering production process constraints and variables. A heuristic discrete event simulation and rule-based scheduling algorithm was then proposed to solve the problem.

The pathway to creating the scheduling algorithm demanded deep understanding and modeling of each production stage in CLT manufacturing. A comprehensive production work study and process map was developed at a real CLT manufacturing plant. The production process was submitted to detailed scrutiny and process times estimation models were developed for each stage of the manufacturing system. The developed process times estimation models were validated with alternative data from the same plant and on the same production environment, yielding satisfactory results. Considering this specific application of the developed process time estimation models used as inputs for the production scheduling algorithm, more important than the actual model precision is maintaining consistency in predicting jobs that take more, or less time than their concurring peers. In other words, for process time-based scheduling algorithms, the differences in process times between competing jobs at any given stage are more important than individual process time parameters.

The discrete event simulation algorithm combines job assignment and buffer area management sub-procedures to minimize average bundle finishing makespan and job shuffles in the buffer areas. Upon adaptations on which jobs compose the project and the plant databases, the algorithm can be used interactively to reschedule the production, every time unforeseen events happen, or, for any reason, the production order needs to be changed.

The scheduling model was materialized in a planning tool able to import project and plant databases, to allow user-configurable parameters settings and generate printable work orders for each stage of the production process. The generated schedules can be tuned though management scrutiny and be deployed to the shop floor for production.

A tool demonstration and sensitivity analysis were performed with a real database from two different projects and different plant conditions. The results showed how the scheduling algorithm behaves and how variations in the configurable parameters in the tool might influence the predicted outputs from the production process simulation. The study also showed that, SCHER-CLT scheduling performance in terms of the tracked objectives (panel shuffles and bundle finishing makespan) is impacted by buffer area constraints and scheduling parameters such as the JIT option.

Nevertheless, the scheduling simulation needs to be validated with the application of generated work orders, preferably in the same production plant. Once this is done, the feasibility of the automatically generated work orders can be effectively evaluated, and adjustments might be made to the tool. SCHER-CLT could be used as a way to tune the plant layout (buffer areas) and scheduling parameters for better production performance, for each project.

SCHER-CLT provides crucial insight for production planners. With the total production time provided from the model, plant management is able to make informed decisions to properly schedule concurring projects, optimizing limited resources in the plant. Preventive and corrective maintenance procedures may be scheduled to coincide with predicted stage downtimes in the agenda. Truck loading and shipping procedures may be arranged to smoothly fit the production schedule. Plant managers can count on a systematic, daily-generated production work order for each stage that can be updated as many times as needed, with the use of the rescheduling mechanism provided by the model.

Additionally, the productivity balance between production stages is crucial to achieve higher productivity levels in the plant. The studied manufacturing plant, and the customizable CLT panel manufacturing process, in general, showed a clear bottleneck at the second production stage. Thus, single machine resource plant setups are essentially unbalanced, causing a higher demand for buffer capacity at the pressing stage and less demand for unfinished panels buffer (after the CNC). This implication is further potentialized when considering that all parts originated from a billet in the CNC stage will be completed at the same time, which would be the total process time of that job.

Buffer capacity, finishing area size and production capacity should be individually defined based on the characteristics of each project, as well as plant current status. Projects with small panels and large bundles (in terms of number of parts) need larger finishing areas and fluctuating finishing teams, where additional workers could be assigned to the station, depending on the demand for finishing activities.

CNC process centers (with more than one PBA machines) could be applied to drastically increase the CNC production rate. However, in this scenario, to avoid more unnecessary panel shuffles and keep bundle finishing makespan on a reasonable level, the FQC stage resource would also have to increase by adding workers or teams to the FQC and packaging station, and by adding more FQC work areas.

Additionally, the biggest production constraint and bottleneck is the CNC stage. Whereas FQC capacity might be easily improved by adding more labor and workspace, the CNC requires capital investment, and most likely, a plant expansion. For that reason, it is important to maximize the CNC output in an orderly manner, providing the best next job readily available to join the CNC at each job assignment event.

Regarding the scheduling algorithm, the JIT option drastically reduces the total amount of panel shuffles. Even when only comparing the number of shuffles in the FQC stage, although in a smaller level, the quantity of shuffles is also reduced when the JIT mode switch is “turned on”. In situations where the pressing stage is still the most productive, the CNC stage continues to be the bottleneck, and the FQC stage’s production capacity is dimensioned according to the part yield from the CNC, the number of panel shuffles and the average bundle finishing makespan is related to how much stock is generated from the press, in comparison with the storage capacity. Therefore, if the pressing stage is smartly scheduled to yield billets as they are being needed, depending on billet composition and how bundles are composed, less panel shuffles are going to be needed and the average bundle makespan should be smaller.

Although valuable to the overall process efficiency, the proposed adaptations in the manufacturing schedule do not require CLT production process change qualification according to ANSI/APA PRG 320 section 8.6. Therefore, real applications of the scheduling tool have the potential to greatly improve the production process efficiency, maintaining quality and plant certification conditions.

The scheduling efficiency is not only a function of the plant layout and applied resources, but also on how the project was designed. Design team's processes play an important role in optimizing material consumption and combining similar parts into billets. Similar efficiency measures should be pursued when defining the billets composition in terms of truck loads and bundle IDs, as well as determining size and arrangement of package bundles.

Finally, the gathered database of real production times and manufacturing processes can also be used to modify the model and adjust it to strategic planning purposes. A robust planning tool with capabilities to not only estimate production process times and build efficient production schedules, but also evaluate and rank different projects and production scenarios. Production managers could use it to better size their production teams and plant resources, as manufacturing executives could use it to select projects that are better suited to the plant capacity and portfolio. The outcomes of this work are not only capable of increasing the process efficiency of customized CLT panel manufacturing but have the potential to influence and improve the whole business model, integrating the production line with strategic investments and project selection decisions.

5.2 Model assumptions and limitations

General flow shop assumptions and limitations are present in the proposed simulation model, but not limited to:

- Each job is processed by one machine (or stage) at a time, i.e. no job can be split into different machines;
- Each stage, once started, must be finished without switching to a different job while the previous is not completed. Although it was considered that no jobs were split and interrupted at any stage, in fact, in the CNC stage, depending on the framing demand, plant management

arranges for some jobs to be interrupted to allow for faster jobs to be processed first, avoiding idleness at the finishing stage. This relaxation was not added to the process time estimation model, nor to the scheduling model per se, as it violates one of the premises of flow shop scheduling problems. However, if such situation happens in a non-recurrent manner, plant management can always reschedule the remaining jobs re-entering project and current plant status in the scheduling model and change work order.

- Each machine is continuously available (no maintenance or breakdown downtime). Stage breakdown and unscheduled maintenance bring uncertainty to the system. However, the developed models (both time estimation and scheduling models) are deterministic. Job process times which are the most important input in the scheduling model, are essentially stochastic, i.e. susceptible to uncertainties. Especially in the FQC stage where human labor is more applied.
- Still in the uncertainties field, the only limiting resource in the production process it the machine. The model does not account for operator, tool or material shortages.
- Every operational stage can only be performed by one machine (no alternate route). The problem was simplified since it was considered that no stages had parallel machines (i.e. plant configurations with more than one press, more than one CNC or more than one FQC and packaging team). This limitation is present in the tool but not in the generic DES scheduling algorithm. The toll could accommodate these limitations upon a machine selection algorithm development and coding adaptations.
- Process times are independent for every job and are technically determined, based only on their characteristics, and on equipment capacity. However, in real-life applications, machine setup times might occur between jobs. In fact, the process times are also a function of the production schedule and should be calculated after each job assignment event. Nevertheless, counting with new process time estimation models that account for machine setup times, the dispatching rule-based scheduling algorithm can be easily adapted to consider machine setup time in the job priority function (Parthanadee and Buddhakulsomsiri 2010). Furthermore, if considering sequence-dependent setup times, an additional analysis could be included in the algorithm. What would be the trade-off between minimizing machine setup times (i.e. defining schedules to minimize machine setup time), considering the potential addition on panel shuffles due to the sequenced load assumption?

Additionally, besides the assumptions related to the flow shop formulation of the scheduling problem, the time estimation models are empirical and were developed for specific machinery and plant configuration existing at the Okanagan Falls CLT Plant. It is highly recommended that the process time estimation models are recalibrated and revalidated for applications on different production plants. Different adhesives used in the pressing stage may also lead to different process time, therefore, the process time estimation model should be adapted accordingly. Finally, regarding buffer area management, the algorithm does not account for billet / part size and geometry. In other words, the user needs to properly specify how many buffer areas the plant layout would accommodate after each production stage, and after that, the algorithm will not evaluate whether the assigned billets or parts would fit in the predefined spaces. Similarly, the algorithm does not consider the order in which the panels are bundled together. Additional panel shuffles might be necessary to reorganize panels before the bundle wrapping procedure. Therefore, the tool relies on management discretion to better evaluate and define how many buffer areas could be fitted in a limited, fixed plant layout, and how the panels will be organized in the bundle. On a real application, very large panels could be assigned to be stacked on top of much smaller panels, which could even potentially add safety risks to the production environment, if followed blindly. Good sense is always advised.

5.3 Contributions

The main contributions of this research are mostly applied to the field of manufacturing scheduling and productivity, especially for customizable CLT panels and other engineered wood products, according to the following:

- A comprehensive CLT production process mapping and work study were developed, identifying production constraints, bottlenecks and describing the production process in detail.
- Development of empirical process times estimation models for customizable CLT panels manufacturing. These models have the potential to roughly provide production times estimates that can be used in plant management planning and resource allocation, in different CLT plant applications.
- A generic discrete event simulation scheduling model was proposed for sequenced-loads and buffer-constrained production systems, with the objective of minimizing job shuffles and average bundle finishing time. This generic algorithm might be adapted to different

manufacturing systems and other engineered wood products under similar production constraints.

- The development of a plant-adaptable, user-friendly production scheduling and planning tool to customizable CLT panels manufacturing systems. The tool is able to accommodate different plant setups and buffer capacities, import job databases, account plant current conditions and simulate a rule-based scheduling solution to the problem. The results of the simulation are displayed in production work orders for each stage, tracking every job's positions and logistic operation during the production process.
- A real case study application of the proposed model with a real project database, and simulated plant scenarios to showcase the scheduling model and planning tool. The results were discussed and the outputs of the tool, interpreted.

5.4 Recommended future work

The following research streams were identified in the course of the study. Future studies can be directed in these areas to increase and complete the knowledge on sequenced, buffer constrained CLT production lines, but also expanding horizons to more general manufacturing systems.

- Analytically evaluate the production process involved in CLT manufacturing, especially the CNC stage, creating more robust models accounting for machine productivity parameters and cutting code processes.
- Incorporate sequence-dependent process times and adapt the scheduling algorithm to analyze the trade-off between scheduling jobs based on their setup time or priority parameter.
- Develop different scheduling rules and priority functions that could immediately be incorporated in the model and tool, accounting for different job-related metrics such as due-date, earliness, tardiness and slack, or buffer-related metrics such as buffer utilization rate or number of queued jobs.
- Incorporate a set of different time estimation models for each stage, based on different modelling techniques, plant and process parameters. The diverse models and settings could be chosen or configured by the user to adapt the process time estimation phase to the most likely to be applicable to their production set up.
- Improve the buffer management algorithm to consider panel sizes and geometry constraints before determining the temporary buffer area and stacking positions.

- Still using the DES rule-based scheduling algorithm, develop new scheduling algorithms based on different objectives such as minimizing bundle tardiness/earliness, and extending the JIT approach to downstream stages in the production line, reducing overall pressure over buffer management procedures.
- Incorporate important output metrics to the scheduling tool such as stage idle time and develop an FQC team sizing module to accommodate CNC panel yield.
- Conduct a validation study of the simulation model and scheduling tool to evaluate the feasibility of proposed work orders and buffer management directives in a real plant environment. The validation case study would be extremely valuable to properly debug and fine tune both job assignment and buffer management sub-algorithms. Finally, the applicability and workability of the scheduling tool, data import procedures, scheduling and rescheduling mechanisms would be evaluated by experienced professionals in a real, applied production project.

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Appendices

Appendix A - Customizable CLT panel manufacturing process time estimation validation data – PRESS LOADING TIME MODEL

DATE	BILLET ID	CYCLE	LAYERS	RAW WIDTH (mm)	RAW LENGTH (mm)	LOADING TIME (min)	EST. LOADING TIME (min)	% ERROR
2018/06/18	33816	5	7	3048	11255	15	18	21%
2018/06/22	33775	28	5	2438	12190	8	9	15%
2018/07/06	34041	85	7	2476	12190	12	13	10%
2018/07/04	34014	64	3	2438	7515	5	5	0%
2018/06/29	33941	38	3	2438	12190	5	5	8%
2018/06/22	33773	27	5	2438	12190	9	9	2%
2018/06/29	33958	44	3	2438	9385	5	5	3%
2018/07/03	33981	53	3	2438	12190	9	5	40%
2018/07/04	34025	68	3	2476	9385	4	5	33%
2018/06/29	33947	40	3	2476	6580	5	5	2%
2018/06/22	33848	32	3	3048	11255	11	8	26%
2018/06/20	33835	15	3	3048	12190	8	8	3%
2018/06/29	33943	39	3	2476	12190	6	6	7%
2018/06/28	33934	36	3	2438	7515	5	5	0%
2018/07/09	34052	96	7	2476	12190	14	13	6%
2018/07/06	34043	87	7	2476	12190	13	13	1%
2018/06/20	33834	14	3	3048	12190	6	8	38%
2018/07/03	34003	60	3	2438	9385	4	5	29%
2018/06/29	33952	42	3	2438	9385	5	5	3%
2018/07/04	34015	64	3	2438	7515	4	5	25%
2018/07/03	33994	57	3	2438	8450	4	5	27%
2018/07/06	34044	88	7	2476	12190	13	13	1%
2018/06/29	33950	41	3	2476	9385	4	5	33%
2018/06/28	33927	33	3	2438	9385	7	5	26%
2018/07/04	34031	71	7	2476	12190	14	13	6%
2018/06/20	33831	13	3	3048	12190	8	8	3%
2018/06/18	33760	10	5	2438	12190	9	9	2%
2018/07/06	34047	91	7	2476	12190	12	13	10%
2018/06/21	33846	17	3	3048	10320	11	8	26%
2018/06/18	33814	6	7	3048	11255	13	18	39%
2018/07/03	33990	56	3	2476	9385	5	5	7%
2018/06/29	33966	46	3	2438	7515	4	5	25%
2018/06/20	33838	16	3	3048	12240	6	8	38%
2018/06/28	33933	35	3	2438	7515	5	5	0%

DATE	BILLET ID	CYCLE	LAYERS	RAW WIDTH (mm)	RAW LENGTH (mm)	LOADING TIME (min)	EST. LOADING TIME (min)	% ERROR
2018/06/28	33935	36	3	2438	7515	5	5	0%
2018/06/28	33930	34	3	2438	9385	7	5	26%
2018/06/29	33945	39	3	2476	7515	7	5	26%
2018/07/04	34018	65	3	2438	11255	4	5	33%
2018/07/03	33976	52	3	2438	9385	12	5	57%
2018/07/03	33997	58	3	2438	8450	4	5	27%
2018/06/30	33979	50	3	2438	11255	4	5	33%
2018/06/29	33960	44	3	2438	6580	5	5	1%
2018/06/29	33956	43	3	2438	9385	4	5	29%
2018/06/22	33778	29	5	2438	12190	8	9	15%
2018/07/03	34000	59	3	2438	9385	5	5	3%
2018/06/21	33766	23	5	2438	12190	10	9	8%
2018/06/18	33756	9	5	2438	12190	9	9	2%
2018/07/03	33989	55	3	2476	12190	5	6	11%
2018/07/03	33998	58	3	2438	6580	3	5	64%
2018/07/04	34028	67	3	2476	12190	4	6	39%
2018/07/04	34008	62	3	2438	9385	5	5	3%
2018/07/06	34046	90	7	2476	12190	12	13	10%
2018/07/04	34023	68	3	2476	7515	9	5	42%

Appendix B - Customizable CLT panel manufacturing process time estimation validation data – PRESS UNLOADING TIME MODEL

DATE	BILLET ID	CYCLE	LAYERS	RAW WIDTH (m)	RAW LENGTH (m)	UNLOAD TIME (min)	EST. UNLOAD TIME (min)	% ERROR
2018/07/09	34056	100	7	2476	12190	10	11	13%
2018/07/04	34012	63	3	2438	9385	1	2	137%
2018/06/29	33970	48	3	2438	9385	4	2	41%
2018/06/29	33943	39	3	2476	12190	6	3	55%
2018/06/30	33979	50	3	2438	11255	1	2	146%
2018/07/03	33976	52	3	2438	9385	1	2	137%
2018/07/03	33999	59	3	2438	6580	1	2	125%
2018/07/04	34005	61	3	2438	9385	1	2	137%
2018/07/06	34045	89	7	2476	12190	9	11	26%
2018/06/20	33835	15	3	3048	12190	5	6	11%
2018/06/29	33944	39	3	2476	12190	6	3	55%
2018/06/29	33948	40	3	2476	9385	2	3	28%
2018/06/29	33959	44	3	2438	6580	4	2	44%
2018/06/29	33968	47	3	2438	7515	4	2	43%
2018/06/20	33830	13	3	3048	12190	5	6	11%
2018/06/18	33755	9	5	2438	12190	5	9	89%
2018/06/29	33950	41	3	2476	9385	4	3	36%
2018/06/22	33848	32	3	3048	11255	3	6	84%
2018/06/29	33945	39	3	2476	7515	7	2	65%
2018/06/29	33967	47	3	2438	7515	4	2	43%
2018/07/04	34026	67	3	2476	12190	1	3	169%
2018/06/29	33951	41	3	2476	9385	4	3	36%
2018/07/03	33997	58	3	2438	8450	1	2	133%
2018/06/18	33816	5	7	3048	11255	15	14	6%
2018/06/21	33841	18	3	3048	10320	6	5	9%
2018/06/18	33761	11	5	2438	12190	10	9	5%
2018/06/21	33845	19	3	3048	11255	7	6	21%
2018/07/04	34011	63	3	2438	9385	1	2	137%
2018/07/09	34051	95	7	2476	12190	11	11	3%
2018/07/06	34048	92	7	2476	12190	13	11	13%
2018/06/28	33930	34	3	2438	9385	3	2	21%
2018/06/18	33759	10	5	2438	12190	7	9	35%
2018/06/29	33965	46	3	2438	8450	4	2	42%
2018/07/03	33982	53	3	2438	12190	1	2	150%
2018/06/22	33768	24	5	2438	12190	10	9	5%
2018/06/29	33966	46	3	2438	7515	5	2	54%
2018/06/18	33814	6	7	3048	11255	11	14	29%
2018/07/09	34052	96	7	2476	12190	16	11	29%
2018/06/22	33850	31	3	3048	12190	6	6	8%

DATE	BILLET ID	CYCLE	LAYERS	RAW WIDTH (m)	RAW LENGTH (m)	UNLOAD TIME (min)	EST. UNLOAD TIME (min)	% ERROR
2018/06/29	33971	48	3	2438	9385	4	2	41%
2018/07/04	34019	65	3	2438	11255	2	2	23%
2018/07/04	34031	71	7	2476	12190	17	11	33%
2018/06/21	33766	23	5	2438	12190	10	9	5%
2018/06/22	33774	27	5	2438	12190	14	9	32%
2018/06/18	33810	1	7	3048	11255	15	14	6%
2018/07/06	34047	91	7	2476	12190	12	11	5%
2018/07/04	34028	67	3	2476	12190	1	3	169%
2018/06/21	33765	23	5	2438	12190	10	9	5%
2018/06/20	33832	14	3	3048	12190	4	6	39%
2018/06/28	33935	36	3	2438	7515	7	2	67%
2018/07/04	34008	62	3	2438	9385	2	2	19%
2018/06/20	33840	16	3	3048	11255	9	6	39%
2018/06/30	33980	50	3	2438	11255	1	2	146%
2018/06/29	33939	37	3	2438	11255	4	2	39%
2018/06/29	33942	38	3	2438	12190	3	2	17%

Appendix C - Customizable CLT panel manufacturing process time estimation validation data – TOTAL CNC PROCESS TIME MODEL

BILLET ID	CYCLE	# PARTS	LAYERS	WASTE %	TOTAL PROCESS TIME (min)	SOFTWARE ESTIMATED TIME (min)	ESTIMATED TIME (min)	ERROR %
34028	134	4	3	7%	110	29	119	8%
33990	94	5	3	11%	111	12	87	22%
34038	120	2	7	2%	135	34	133	1%
34020	163	2	3	5%	68	21	77	13%
34003	183	1	3	5%	60	15	52	13%
33952	112	1	3	3%	70	17	56	20%
33963	111	1	3	11%	88	17	60	32%
34034	125	2	7	2%	103	34	133	29%
33955	109	1	3	5%	38	15	52	37%
33805	64	2	3	28%	55	10	61	11%
33956	110	1	3	5%	82	18	60	27%
34039	130	2	7	2%	206	34	133	35%
34032	129	2	7	2%	122	34	133	9%
33992	137	2	3	14%	137	12	59	57%
34046	118	2	7	2%	121	34	133	10%
33979	92	1	3	5%	62	22	70	13%
33735	50	2	5	6%	138	15	75	45%
34012	170	1	3	5%	51	15	52	2%
34002	184	1	3	5%	47	18	60	27%
34048	115	2	7	2%	146	34	133	9%
33728	5	5	5	3%	358	22	121	66%
33973	86	1	3	5%	85	19	62	27%
34031	128	2	7	2%	100	34	133	33%
34007	169	1	3	3%	108	17	56	48%
33814	58	1	7	7%	59	5	51	13%
34008	173	1	3	5%	83	18	60	28%
33813	56	1	7	18%	83	5	57	31%
33712	3	7	5	21%	651	64	258	60%
33783	22	1	7	10%	38	5	53	40%
34045	117	2	7	2%	106	34	133	26%
34047	119	2	7	2%	216	34	133	38%
33808	29	2	3	4%	58	15	61	6%
33758	75	2	5	11%	41	2	45	10%
33966	96	1	3	9%	55	16	56	3%
33729	49	1	5	23%	76	12	67	12%
33996	174	1	3	5%	56	20	65	16%

BILLET ID	CYCLE	# PARTS	LAYERS	WASTE %	TOTAL PROCESS TIME (min)	SOFTWARE ESTIMATED TIME (min)	ESTIMATED TIME (min)	ERROR %
34027	114	2	3	6%	171	21	78	55%
34023	133	1	3	14%	61	15	57	7%
34018	160	2	3	5%	47	22	80	70%
33708	2	2	5	21%	171	8	65	62%
33795	30	2	5	3%	54	17	79	46%
34044	116	2	7	2%	124	34	133	7%
33965	136	2	3	5%	64	20	75	17%
33999	179	1	3	5%	72	7	32	56%
34015	176	1	3	13%	36	10	43	21%
34042	122	2	7	2%	132	34	133	1%
34009	168	1	3	5%	71	15	52	27%
34005	161	1	3	5%	61	18	60	2%
33732	69	1	5	24%	161	5	50	69%
33968	107	1	3	13%	30	10	43	45%
33731	67	1	5	23%	91	5	49	46%

Appendix D - Customizable CLT panel manufacturing process time estimation validation data – FQC PROCESS TIME MODEL

DATE	BUNDLE CYCLE	START TIME	ROUGH WIDTH (m)	ROUGH LENGTH (m)	ROUGH AREA (m^2)	WORK AREA (m2)	VISUAL FACES	FQC TIME (man x min)	EST. FQC TIME (man x min)	ERROR %
2018/06/02	7	1:37	3.50	6.50	22.75	45.50	1	118	83	30%
2018/06/29	59	7:25	2.50	7.50	18.75	37.50	1	84	73	13%
2018/09/04	101	14:00	3.00	5.50	16.50	33.00	1	59	68	15%
2018/07/09	73	13:14	2.00	7.00	14.00	14.00	0	4	14	253%
2018/09/04	102	18:25	3.00	6.00	18.00	36.00	1	64	71	12%
2018/06/28	56	22:14	2.00	6.00	12.00	24.00	0	25	26	3%
2018/07/05	64	4:17	1.50	5.50	8.25	8.25	0	9	7	18%
2018/09/01	91	2:29	3.00	5.50	16.50	16.50	0	12	17	42%
2018/06/02	6	1:37	3.50	6.50	22.75	45.50	1	112	83	26%
2018/07/09	79	22:47	1.50	4.50	6.75	6.75	0	12	6	53%
2018/06/13	29	11:53	0.75	4.50	3.38	6.75	1	46	37	19%
2018/06/16	43	2:23	2.50	5.00	12.50	12.50	0	7	12	76%
2018/06/15	39	10:00	2.00	7.80	15.60	31.20	1	62	66	6%
2018/07/05	66	18:06	2.50	1.75	4.38	8.75	1	43	39	8%
2018/06/12	27	23:12	2.50	3.50	8.75	17.50	1	64	50	22%
2018/09/04	99	8:33	3.00	6.00	18.00	36.00	1	62	71	15%
2018/06/12	27	23:12	2.50	3.50	8.75	17.50	1	75	50	34%
2018/07/11	89	9:44	1.25	3.50	4.38	4.38	0	5	3	44%
2018/06/22	54	22:43	1.50	2.00	3.00	6.00	1	85	36	57%
2018/09/04	100	10:38	2.50	5.50	13.75	27.50	1	55	61	12%
2018/06/12	17	3:30	2.50	8.50	21.25	42.50	1	67	79	18%
2018/06/02	9	5:03	3.50	6.50	22.75	45.50	0	74	51	31%
2018/06/15	38	5:20	2.50	5.00	12.50	25.00	1	116	59	50%
2018/07/10	86	16:36	2.00	7.00	14.00	14.00	0	7	14	102%
2018/09/01	94	8:30	2.50	5.00	12.50	12.50	1	61	44	28%
2018/09/01	95	16:43	2.00	4.50	9.00	18.00	1	75	50	33%
2018/09/04	98	6:05	3.00	6.00	18.00	36.00	1	69	71	4%
2018/07/09	81	22:47	1.75	4.00	7.00	7.00	0	13	6	55%
2018/06/12	23	10:23	1.00	3.50	3.50	7.00	0	26	6	77%
2018/06/15	37	1:30	2.00	5.50	11.00	22.00	1	64	55	14%
2018/09/02	96	10:23	2.50	4.50	11.25	22.50	1	88	56	37%
2018/07/04	63	17:58	1.00	5.00	5.00	10.00	1	66	41	38%
2018/06/21	52	16:50	1.00	3.00	3.00	6.00	1	33	36	10%
2018/06/19	45	3:33	3.00	10.00	30.00	30.00	0	23	33	43%

Appendix E - Customizable CLT panel manufacturing process time estimation validation data – PACKAGING PROCESS TIME MODEL

DATE	BUNDLE CYCLE	START TIME	ROUGH WIDTH (m)	ROUGH LENGTH (m)	ROUGH AREA (m^2)	VISUAL FACES	BUNDLE SIZE	PACKING TIME (man x min)	EST. PACKING TIME (man x min)	ERROR %
2018/06/30	60	6:26	2.00	8.00	16.00	0	2	58	53	9%
2018/06/16	41	0:34	2.50	9.00	22.50	0	1	10	33	231%
2018/09/04	101	13:41	3.00	6.00	18.00	1	2	71	55	23%
2018/06/29	60	22:00	2.00	7.00	14.00	0	2	58	51	12%
2018/06/28	57	22:14	2.00	6.00	12.00	1	1	26	27	3%
2018/06/11	16	6:01	3.00	6.50	19.50	1	1	42	32	24%
2018/07/05	67	23:56	2.75	5.75	15.81	0	1	53	29	46%
2018/06/21	52	16:50	1.50	3.50	5.25	2	2	41	47	14%
2018/06/14	32	1:41	2.00	4.00	8.00	1	1	31	24	22%
2018/09/04	103	18:30	3.00	5.50	16.50	1	2	68	54	21%
2018/06/13	29	11:53	0.75	4.50	3.38	1	1	21	21	0%
2018/06/20	47	2:33	1.50	4.50	6.75	1	1	45	23	48%
2018/07/04	62	16:21	1.50	6.50	9.75	0	1	17	25	44%
2018/07/06	71	20:33	2.25	3.25	7.31	1	2	42	48	13%
2018/06/12	18	3:30	1.00	7.00	7.00	1	1	21	23	12%
2018/06/02	6	1:37	3.50	6.50	22.75	1	1	28	34	21%
2018/07/04	63	17:58	1.00	5.00	5.00	1	1	34	22	35%
2018/09/04	102	18:25	3.00	6.00	18.00	1	2	52	55	5%
2018/06/15	39	10:00	2.00	7.80	15.60	1	1	23	29	27%

Appendix F - Case study – Project database

Life Cycle Management Laboratory

CLT SCHEDULING MODEL - PROJECT INPUT TAB

UBC

BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33844	EC207	139 VJ-1	1	4	3048	11255	5	2867	1837	1	12	68	13	10	137	36	39
33844	EC207a5	139 VJ-1	1	4	3048	11255	5	2867	1837	1	12	68	13	10	137	36	39
33844	EC210	139 VJ-1	1	6	3048	11255	5	2867	7163	1	12	68	13	10	137	54	50
33844	EC501	139 VJ-1	6	50	3048	11255	5	2095	276	1	12	68	13	10	137	30	72
33845	EC301	139 VJ-1	2	8	3048	11255	5	2095	276	1	12	68	13	10	137	30	65
33845	EC307	139 VJ-1	2	9	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33845	EC307a10	139 VJ-1	2	9	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33845	EC309	139 VJ-1	2	10	3048	11255	5	2905	7163	1	12	68	13	10	137	54	59
33846	EC201	139 VJ-1	1	1	3048	10320	5	2057	276	1	12	68	13	10	167	30	54
33846	EC201a13	139 VJ-1	1	1	3048	10320	5	2057	276	1	12	68	13	10	167	30	54
33846	EC203	139 VJ-1	1	2	3048	10320	5	2762	1633	1	12	68	13	10	167	35	39
33846	EC209	139 VJ-1	1	6	3048	10320	5	2762	7163	1	12	68	13	10	167	53	50
33846	EC401	139 VJ-1	4	33	3048	10320	5	2095	276	1	12	68	13	10	167	30	78
33846	EC401a17	139 VJ-1	4	33	3048	10320	5	2095	276	1	12	68	13	10	167	30	78
33847	EC208	139 VJ-2	1	5	3048	10320	5	705	4889	2	12	68	13	10	162	58	39
33847	EC208a19	139 VJ-2	1	5	3048	10320	5	705	4889	2	12	68	13	10	162	58	39
33847	EC211	139 VJ-2	1	7	3048	10320	5	2867	5200	2	12	68	13	10	162	71	30
33847	EC308	139 VJ-2	2	9	3048	10320	5	705	4889	2	12	68	13	10	162	58	66
33847	EC308a22	139 VJ-2	2	9	3048	10320	5	705	4889	2	12	68	13	10	162	58	66
33848	EC301a23	139 VJ-1	2	8	3048	11255	5	2095	276	1	12	68	13	10	137	30	65
33848	EC607	139 VJ-1	8	69	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33848	EC607a25	139 VJ-1	8	69	3048	11255	5	2905	1837	1	12	68	13	10	137	36	66
33848	EC609	139 VJ-1	8	70	3048	11255	5	2905	7163	1	12	68	13	10	137	54	66
33849	EC302	139 VJ-2	2	8	3048	11255	5	2095	353	2	12	68	13	10	135	54	65
33849	EC302a28	139 VJ-2	2	8	3048	11255	5	2095	353	2	12	68	13	10	135	54	65
33849	EC311	139 VJ-2	2	10	3048	11255	5	2905	5200	2	12	68	13	10	135	71	59
33849	EC611	139 VJ-2	8	70	3048	11255	5	2905	5200	2	12	68	13	10	135	71	66
33850	EC204	139 VJ-1	1	2	3048	12190	5	2762	1633	1	13	68	13	10	137	35	39
33850	EC403	139 VJ-1	4	33	3048	12190	5	2800	1633	1	13	68	13	10	137	35	78
33850	EC503	139 VJ-1	6	50	3048	12190	5	2800	1633	1	13	68	13	10	137	35	72
33850	EC510	139 VJ-1	6	51	3048	12190	5	2800	7163	1	13	68	13	10	137	53	80
33851	EC304	139 VJ-1	2	8	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65
33851	EC310	139 VJ-1	2	10	3048	12190	5	2800	7163	1	13	68	13	10	137	53	59
33851	EC504	139 VJ-1	6	50	3048	12190	5	2800	1633	1	13	68	13	10	137	35	72
33851	EC604	139 VJ-1	8	68	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65
33852	EC303	139 VJ-1	2	8	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65
33852	EC404	139 VJ-1	4	33	3048	12190	5	2800	1633	1	13	68	13	10	137	35	78
33852	EC603	139 VJ-1	8	68	3048	12190	5	2800	1633	1	13	68	13	10	137	35	65
33852	EC610	139 VJ-1	8	70	3048	12190	5	2800	7163	1	13	68	13	10	137	53	66
33853	EC410	139 VJ-1	4	34	3048	7515	5	2800	7163	1	12	68	13	10	102	53	76
33853	EC501a44	139 VJ-1	6	50	3048	7515	5	2095	276	1	12	68	13	10	102	30	72
33854	EC305	139 VJ-2	2	9	2438	11255	5	2095	1733	2	10	68	10	10	192	58	66
33854	EC305a46	139 VJ-2	2	9	2438	11255	5	2095	1733	2	10	68	10	10	192	58	66

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CLT SCHEDULING MODEL - PROJECT INPUT TAB

BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33854	EC402	139 VJ-2	4	33	2438	11255	5	2095	353	2	10	68	10	10	192	54	78
33854	EC502	139 VJ-2	6	50	2438	11255	5	2095	353	2	10	68	10	10	192	54	72
33854	EC505	139 VJ-2	6	50	2438	11255	5	2095	1733	2	10	68	10	10	192	58	72
33854	EC505a50	139 VJ-2	6	50	2438	11255	5	2095	1733	2	10	68	10	10	192	58	72
33854	EC605	139 VJ-2	8	69	2438	11255	5	2095	1733	2	10	68	10	10	192	58	66
33854	EC605a52	139 VJ-2	8	69	2438	11255	5	2095	1733	2	10	68	10	10	192	58	66
33855	EC202	139 VJ-2	1	1	2438	8450	5	2057	353	2	9	68	10	10	177	54	54
33855	EC202a54	139 VJ-2	1	1	2438	8450	5	2057	353	2	9	68	10	10	177	54	54
33855	EC205	139 VJ-2	1	3	2438	8450	5	2057	1733	2	9	68	10	10	177	58	39
33855	EC205a56	139 VJ-2	1	3	2438	8450	5	2057	1733	2	9	68	10	10	177	58	39
33855	EC402a57	139 VJ-2	4	33	2438	8450	5	2095	353	2	9	68	10	10	177	54	78
33855	EC405	139 VJ-2	4	33	2438	8450	5	2095	1733	2	9	68	10	10	177	58	78
33855	EC405a59	139 VJ-2	4	33	2438	8450	5	2095	1733	2	9	68	10	10	177	58	78
33856	BP348	105 VJ-1	3	24	3048	9385	3	1500	6410	1	9	68	6	10	124	41	67
33856	BP628	105 VJ-1	9	79	3048	9385	3	1500	2916	1	9	68	6	10	124	35	80
33856	BP628a62	105 VJ-1	9	79	3048	9385	3	1500	2916	1	9	68	6	10	124	35	80
33856	BP648	105 VJ-1	9	82	3048	9385	3	1500	6410	1	9	68	6	10	124	41	67
33857	BP447	105 VJ-1	5	44	3048	9385	3	1500	6400	1	9	68	6	10	124	41	67
33857	BP528	105 VJ-1	7	61	3048	9385	3	1500	2916	1	9	68	6	10	124	35	66
33857	BP528a66	105 VJ-1	7	61	3048	9385	3	1500	2916	1	9	68	6	10	124	35	66
33857	BP547	105 VJ-1	7	63	3048	9385	3	1500	6400	1	9	68	6	10	124	41	54
33858	BP429	105 VJ-1	5	42	3048	10320	3	1500	3642	1	9	68	6	10	129	36	61
33858	BP430	105 VJ-1	5	42	3048	10320	3	1500	3692	1	9	68	6	10	129	36	61
33858	BP451	105 VJ-1	5	45	3048	10320	3	1500	6540	1	9	68	6	10	129	41	62
33858	BP451a71	105 VJ-1	5	45	3048	10320	3	1500	6540	1	9	68	6	10	129	41	62
33859	FP372	105 V	2	16	2438	9385	3	2400	9070	0	6	68	3	10	113	24	59
33860	FP373	105 V	2	17	2438	9385	3	2400	9070	0	6	68	3	10	102	24	77
33861	FP369	105 V	2	15	2438	9385	3	2400	9063	0	6	68	3	10	102	24	72
33862	FP380	105 V	2	17	2438	9385	3	2400	9266	0	6	68	3	10	110	24	77
33863	FP370	105 V	2	16	2438	9385	3	2400	9063	0	6	68	3	10	113	24	59
33864	FP374	105 V	2	17	2438	9385	3	2400	9070	0	6	68	3	10	105	24	77
33865	FP371	105 V	2	16	2438	9385	3	2400	9063	0	6	68	3	10	105	24	59
33866	FP366	105 V	2	15	2438	8450	3	2400	8340	0	6	68	3	10	110	22	72
33867	FP365	105 V	3	27	2438	8450	3	2400	8308	0	6	68	3	10	108	22	32
33868	FP327	105 V	2	11	2438	8450	3	2370	7773	0	6	68	3	10	108	20	64
33869	FP325	105 V	3	18	2438	8450	3	2091	1715	0	6	68	3	10	128	2	66
33869	FP358	105 V	3	25	2438	8450	3	2400	6637	0	6	68	3	10	128	17	68
33870	FP324	105 V	2	11	2438	8450	3	2077	1714	0	6	68	3	10	130	2	64
33870	FP354	105 V	3	25	2438	8450	3	2400	6628	0	6	68	3	10	130	17	68
33871	FP349	105 V	2	13	2438	6580	3	2398	6414	0	5	68	3	10	82	16	67
33872	FP385	105 V	2	17	2438	6580	3	2205	6302	0	5	68	3	10	90	14	77
33873	FP350	105 V	3	24	2438	6580	3	2373	6420	0	5	68	3	10	82	16	67
33874	FP356	105 V	2	14	2438	7515	3	2400	6636	0	6	68	3	10	92	17	62

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UBC

BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33875	FP363	105 V	2	15	2438	7515	3	2400	6984	0	6	68	3	10	105	18	72
33876	FP352	105 V	2	14	2438	7515	3	2400	6624	0	6	68	3	10	92	17	62
33877	FP381	105 V	3	31	2438	9385	3	2400	9268	0	6	68	3	10	108	24	50
33878	FP376	105 V	3	29	2438	9385	3	2400	9077	0	6	68	3	10	113	24	50
33879	FP375	105 V	3	29	2438	9385	3	2400	9077	0	6	68	3	10	102	24	50
33880	FP357	105 V	2	14	2476	7515	3	2424	6636	0	6	68	3	10	102	17	62
33881	FP353	105 V	2	14	2476	7515	3	2424	6624	0	6	68	3	10	105	17	62
33882	FP322	105 V	3	18	2476	9385	3	425	1678	0	6	68	3	10	153	2	66
33882	FP323	105 V	2	11	2476	9385	3	423	1714	0	6	68	3	10	153	2	64
33882	FP379	105 V	3	31	2476	9385	3	2400	9077	0	6	68	3	10	153	24	50
33883	FP336	105 V	2	12	2476	9385	3	849	3444	0	6	68	3	10	115	2	47
33883	FP367	105 V	3	28	2476	9385	3	2438	8480	0	6	68	3	10	115	22	32
33884	FP335	105 V	3	20	2476	9385	3	839	3442	0	6	68	3	10	117	2	47
33884	FP368	105 V	2	15	2476	9385	3	2438	8486	0	6	68	3	10	117	22	72
33885	FP345	105 V	2	13	2476	12190	3	2205	5881	0	6	68	3	10	133	13	67
33885	FP346	105 V	3	23	2476	12190	3	2247	5883	0	6	68	3	10	133	14	27
33886	FP333	105 V	2	12	2476	11255	3	848	3395	0	6	68	3	10	135	2	47
33886	FP341	105 V	2	13	2476	11255	3	2438	5134	0	6	68	3	10	135	13	67
33886	FP344	105 V	3	22	2476	11255	3	1555	5788	0	6	68	3	10	135	9	25
33887	FP340	105 V	2	13	2476	11255	3	2438	5132	0	6	68	3	10	128	13	67
33887	FP343	105 V	2	13	2476	11255	3	1592	5781	0	6	68	3	10	128	9	67
33888	FP378	105 V	3	30	2438	9385	3	2400	9077	0	6	68	3	10	113	24	59
33889	FP377	105 V	3	30	2438	9385	3	2400	9077	0	6	68	3	10	105	24	59
33890	FP377a113	105 V	3	30	2438	9385	3	2400	9077	0	6	68	3	10	105	24	59
33891	FP326	105 V	3	18	2438	10320	3	10269	2130	0	6	68	3	10	84	24	66
33892	FP426	105 V	5	41	2438	10320	3	10269	2130	0	6	68	3	10	84	24	66
33893	FP320	105 V	2	11	2438	9385	3	4517	1551	0	6	68	3	10	115	6	64
33893	FP321	105 V	3	18	2438	9385	3	4517	1552	0	6	68	3	10	115	6	66
33894	FP420	105 V	4	34	2438	9385	3	4517	1551	0	6	68	3	10	115	6	76
33894	FP421	105 V	5	41	2438	9385	3	4517	1552	0	6	68	3	10	115	6	66
33895	FP382	105 V	3	32	2438	11255	3	2400	9667	0	6	68	3	10	130	25	34
33895	FP384	105 V	2	17	2438	11255	3	996	3012	0	6	68	3	10	130	2	77
33896	FP331	105 V	3	20	2438	11255	3	929	3245	0	6	68	3	10	135	2	47
33896	FP383	105 V	2	17	2438	11255	3	2381	9681	0	6	68	3	10	135	25	77
33897	FP332	105 V	2	12	2438	11255	3	999	3265	0	6	68	3	10	153	2	47
33897	FP334	105 V	3	20	2438	11255	3	840	3410	0	6	68	3	10	153	2	47
33897	FP364	105 V	3	26	2438	11255	3	2400	7781	0	6	68	3	10	153	20	48
33898	FP342	105 V	3	21	2438	12190	3	2400	5134	0	6	68	3	10	128	13	43
33898	FP361	105 V	2	15	2438	12190	3	2400	6663	0	6	68	3	10	128	17	72
33899	FP339	105 V	3	21	2438	12190	3	2400	5132	0	6	68	3	10	120	13	43
33899	FP360	105 V	3	25	2438	12190	3	2400	6662	0	6	68	3	10	120	17	68
33900	FP445	105 V	4	37	2438	12190	3	2205	5881	0	6	68	3	10	133	13	68
33900	FP446	105 V	5	44	2438	12190	3	2247	5883	0	6	68	3	10	133	14	67

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BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33901	FP362	105 V	3	26	2438	7515	3	2370	6984	0	6	68	3	10	102	18	48
33902	FP355	105 V	3	25	2438	7515	3	2400	6628	0	6	68	3	10	92	17	68
33903	FP359	105 V	3	25	2438	7515	3	2400	6637	0	6	68	3	10	92	17	68
33904	BP329	105 VJ-1	3	19	3048	10320	3	1500	3642	1	9	68	6	10	127	36	56
33904	BP330	105 VJ-1	3	19	3048	10320	3	1500	3692	1	9	68	6	10	127	36	56
33904	BP351	105 VJ-1	3	24	3048	10320	3	1500	6540	1	9	68	6	10	127	41	67
33904	BP351a139	105 VJ-1	3	24	3048	10320	3	1500	6540	1	9	68	6	10	127	41	67
33905	BP328	105 VJ-1	3	19	3048	9385	3	1500	2916	1	9	68	6	10	124	35	56
33905	BP328a141	105 VJ-1	3	19	3048	9385	3	1500	2916	1	9	68	6	10	124	35	56
33905	BP448	105 VJ-1	5	44	3048	9385	3	1500	6410	1	9	68	6	10	124	41	67
33905	BP548	105 VJ-1	7	63	3048	9385	3	1500	6410	1	9	68	6	10	124	41	54
33906	BP347	105 VJ-1	3	24	3048	9385	3	1500	6400	1	9	68	6	10	124	41	67
33906	BP428	105 VJ-1	5	42	3048	9385	3	1500	2916	1	9	68	6	10	124	35	61
33906	BP428a146	105 VJ-1	5	42	3048	9385	3	1500	2916	1	9	68	6	10	124	35	61
33906	BP647	105 VJ-1	9	82	3048	9385	3	1500	6400	1	9	68	6	10	124	41	67
33907	EC407	139 VJ-1	4	33	3048	11255	5	2905	1837	1	12	68	13	10	137	36	78
33907	EC407a149	139 VJ-1	4	33	3048	11255	5	2905	1837	1	12	68	13	10	137	36	78
33907	EC409	139 VJ-1	4	34	3048	11255	5	2905	7163	1	12	68	13	10	137	54	76
33907	EC601	139 VJ-1	8	68	3048	11255	5	2095	276	1	12	68	13	10	137	30	65
33908	EC411	139 VJ-2	4	34	3048	11255	5	2905	5200	2	12	68	13	10	135	71	76
33908	EC511	139 VJ-2	6	51	3048	11255	5	2905	5200	2	12	68	13	10	135	71	80
33908	EC602	139 VJ-2	8	68	3048	11255	5	2095	353	2	12	68	13	10	135	54	65
33908	EC602a155	139 VJ-2	8	68	3048	11255	5	2095	353	2	12	68	13	10	135	54	65
33909	EC507	139 VJ-1	6	51	3048	11255	5	2905	1837	1	12	68	13	10	137	36	80
33909	EC507a157	139 VJ-1	6	51	3048	11255	5	2905	1837	1	12	68	13	10	137	36	80
33909	EC509	139 VJ-1	6	51	3048	11255	5	2905	7163	1	12	68	13	10	137	54	80
33909	EC601a159	139 VJ-1	8	68	3048	11255	5	2095	276	1	12	68	13	10	137	30	65
33910	EC408	139 VJ-2	4	34	2438	10320	5	705	4889	2	10	68	10	10	190	58	76
33910	EC408a161	139 VJ-2	4	34	2438	10320	5	705	4889	2	10	68	10	10	190	58	76
33910	EC502a162	139 VJ-2	6	50	2438	10320	5	2095	353	2	10	68	10	10	190	54	72
33910	EC508	139 VJ-2	6	51	2438	10320	5	705	4889	2	10	68	10	10	190	58	80
33910	EC508a164	139 VJ-2	6	51	2438	10320	5	705	4889	2	10	68	10	10	190	58	80
33910	EC608	139 VJ-2	8	69	2438	10320	5	705	4889	2	10	68	10	10	190	58	66
33910	EC608a166	139 VJ-2	8	69	2438	10320	5	705	4889	2	10	68	10	10	190	58	66
33911	BP529	105 VJ-1	7	61	3048	10320	3	1500	3642	1	9	68	6	10	127	36	66
33911	BP530	105 VJ-1	7	61	3048	10320	3	1500	3692	1	9	68	6	10	127	36	66
33911	BP551	105 VJ-1	7	64	3048	10320	3	1500	6540	1	9	68	6	10	127	41	68
33911	BP551a170	105 VJ-1	7	64	3048	10320	3	1500	6540	1	9	68	6	10	127	41	68
33912	BP629	105 VJ-1	9	79	3048	10320	3	1500	3642	1	9	68	6	10	127	36	80
33912	BP630	105 VJ-1	9	80	3048	10320	3	1500	3692	1	9	68	6	10	127	36	56
33912	BP651	105 VJ-1	9	82	3048	10320	3	1500	6540	1	9	68	6	10	127	41	67
33912	BP651a174	105 VJ-1	9	82	3048	10320	3	1500	6540	1	9	68	6	10	127	41	67
33913	FP466	105 V	4	39	2438	8450	3	2400	8340	0	6	68	3	10	110	22	83

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BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33914	FP465	105 V	5	47	2438	8450	3	2400	8308	0	6	68	3	10	108	22	59
33915	FP427	105 V	4	35	2438	8450	3	2370	7773	0	6	68	3	10	108	20	57
33916	FP449	105 V	4	37	2438	6580	3	2398	6414	0	5	68	3	10	82	16	68
33917	FP450	105 V	5	44	2438	6580	3	2373	6420	0	5	68	3	10	82	16	67
33918	FP444	105 V	5	44	2438	6580	3	1555	5788	0	5	68	3	10	84	9	67
33919	FP472	105 V	4	39	2438	9385	3	2400	9070	0	6	68	3	10	113	24	83
33920	FP473	105 V	4	39	2438	9385	3	2400	9070	0	6	68	3	10	102	24	83
33921	FP480	105 V	4	40	2438	9385	3	2400	9266	0	6	68	3	10	110	24	51
33922	FP470	105 V	4	39	2438	9385	3	2400	9063	0	6	68	3	10	113	24	83
33923	FP469	105 V	4	39	2438	9385	3	2400	9063	0	6	68	3	10	102	24	83
33924	FP474	105 V	4	39	2438	9385	3	2400	9070	0	6	68	3	10	105	24	83
33925	FP471	105 V	4	39	2438	9385	3	2400	9063	0	6	68	3	10	105	24	83
33926	FP476	105 V	5	48	2438	9385	3	2400	9077	0	6	68	3	10	113	24	76
33927	FP481	105 V	5	49	2438	9385	3	2400	9268	0	6	68	3	10	108	24	51
33928	FP475	105 V	5	48	2438	9385	3	2400	9077	0	6	68	3	10	102	24	76
33929	FP478	105 V	5	48	2438	9385	3	2400	9077	0	6	68	3	10	113	24	76
33930	FP477	105 V	5	48	2438	9385	3	2400	9077	0	6	68	3	10	105	24	76
33931	FP477a193	105 V	5	48	2438	9385	3	2400	9077	0	6	68	3	10	105	24	76
33932	FP452	105 V	4	37	2438	7515	3	2400	6624	0	6	68	3	10	92	17	68
33933	FP463	105 V	4	38	2438	7515	3	2400	6984	0	6	68	3	10	105	18	63
33934	FP462	105 V	5	46	2438	7515	3	2370	6984	0	6	68	3	10	102	18	63
33935	FP455	105 V	5	45	2438	7515	3	2400	6628	0	6	68	3	10	92	17	62
33936	FP425	105 V	5	41	2438	8450	3	2091	1715	0	6	68	3	10	128	2	66
33936	FP458	105 V	5	46	2438	8450	3	2400	6637	0	6	68	3	10	128	17	63
33937	FP424	105 V	4	35	2438	8450	3	2077	1714	0	6	68	3	10	130	2	57
33937	FP454	105 V	5	45	2438	8450	3	2400	6628	0	6	68	3	10	130	17	62
33938	FP431	105 V	5	42	2438	11255	3	929	3245	0	6	68	3	10	130	2	61
33938	FP483	105 V	4	40	2438	11255	3	2381	9681	0	6	68	3	10	130	25	51
33939	FP432	105 V	4	36	2438	11255	3	999	3265	0	6	68	3	10	153	2	65
33939	FP434	105 V	5	43	2438	11255	3	840	3410	0	6	68	3	10	153	2	60
33939	FP464	105 V	5	47	2438	11255	3	2400	7781	0	6	68	3	10	153	20	59
33940	FP482	105 V	5	49	2438	10320	3	2400	9667	0	6	68	3	10	110	25	51
33941	FP442	105 V	5	43	2438	12190	3	2400	5134	0	6	68	3	10	128	13	60
33941	FP461	105 V	4	38	2438	12190	3	2400	6663	0	6	68	3	10	128	17	63
33942	FP439	105 V	5	43	2438	12190	3	2400	5132	0	6	68	3	10	128	13	60
33942	FP460	105 V	5	46	2438	12190	3	2400	6662	0	6	68	3	10	128	17	63
33943	FP441	105 V	4	36	2476	12190	3	2438	5134	0	6	68	3	10	128	13	65
33943	FP459	105 V	5	46	2476	12190	3	2400	6637	0	6	68	3	10	128	17	63
33944	FP440	105 V	4	36	2476	12190	3	2438	5132	0	6	68	3	10	130	13	65
33944	FP456	105 V	4	38	2476	12190	3	2400	6636	0	6	68	3	10	130	17	63
33945	FP457	105 V	4	38	2476	7515	3	2424	6636	0	6	68	3	10	102	17	63
33946	FP453	105 V	4	37	2476	7515	3	2424	6624	0	6	68	3	10	105	17	68
33947	FP433	105 V	4	36	2476	6580	3	848	3395	0	6	68	3	10	107	2	65

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BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET WIDTH (mm)	RAW BILLET LENGTH (mm)	RAW BILLET # of LAYERS	PART ROUGH WIDTH (mm)	PART ROUGH LENGTH (mm)	PART # of VISUAL FACES	ESTIMATED PROCESS TIME (min) PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33947	FP443	105 V	4	37	2476	6580	3	1592	5781	0	6	68	3	10	107	9	68
33948	FP422	105 V	5	41	2476	9385	3	425	1678	0	6	68	3	10	153	2	66
33948	FP423	105 V	4	35	2476	9385	3	423	1714	0	6	68	3	10	153	2	57
33948	FP479	105 V	5	48	2476	9385	3	2400	9077	0	6	68	3	10	153	24	76
33949	FP436	105 V	4	36	2476	9385	3	849	3444	0	6	68	3	10	117	2	65
33949	FP468	105 V	4	39	2476	9385	3	2438	8486	0	6	68	3	10	117	22	83
33950	FP435	105 V	5	43	2476	9385	3	839	3442	0	6	68	3	10	122	2	60
33950	FP467	105 V	5	47	2476	9385	3	2438	8480	0	6	68	3	10	122	22	59
33951	FP522	105 V	7	60	2476	9385	3	425	1678	0	6	68	3	10	153	2	66
33951	FP523	105 V	6	52	2476	9385	3	423	1714	0	6	68	3	10	153	2	50
33951	FP579	105 V	7	67	2476	9385	3	2400	9077	0	6	68	3	10	153	24	84
33952	FP580	105 V	6	58	2438	9385	3	2400	9266	0	6	68	3	10	110	24	77
33953	FP573	105 V	6	59	2438	9385	3	2400	9070	0	6	68	3	10	102	24	66
33954	FP574	105 V	6	59	2438	9385	3	2400	9070	0	6	68	3	10	105	24	66
33955	FP571	105 V	6	59	2438	9385	3	2400	9063	0	6	68	3	10	105	24	66
33956	FP570	105 V	6	58	2438	9385	3	2400	9063	0	6	68	3	10	113	24	77
33957	FP572	105 V	6	59	2438	9385	3	2400	9070	0	6	68	3	10	113	24	66
33958	FP569	105 V	6	58	2438	9385	3	2400	9063	0	6	68	3	10	102	24	77
33959	FP549	105 V	6	55	2438	6580	3	2398	6414	0	5	68	3	10	82	16	55
33960	FP550	105 V	7	64	2438	6580	3	2373	6420	0	5	68	3	10	82	16	68
33961	FP566	105 V	6	58	2438	8450	3	2400	8340	0	6	68	3	10	110	22	77
33962	FP565	105 V	7	66	2438	8450	3	2400	8308	0	6	68	3	10	108	22	59
33963	FP527	105 V	6	53	2438	8450	3	2370	7773	0	6	68	3	10	108	20	64
33964	FP524	105 V	6	52	2438	8450	3	2077	1714	0	6	68	3	10	130	2	50
33964	FP554	105 V	7	64	2438	8450	3	2400	6628	0	6	68	3	10	130	17	68
33965	FP525	105 V	7	60	2438	8450	3	2091	1715	0	6	68	3	10	128	2	66
33965	FP558	105 V	7	65	2438	8450	3	2400	6637	0	6	68	3	10	128	17	63
33966	FP563	105 V	6	57	2438	7515	3	2400	6984	0	6	68	3	10	105	18	46
33967	FP562	105 V	7	65	2438	7515	3	2370	6984	0	6	68	3	10	102	18	63
33968	FP555	105 V	7	64	2438	7515	3	2400	6628	0	6	68	3	10	92	17	68
33969	FP552	105 V	6	56	2438	7515	3	2400	6624	0	6	68	3	10	92	17	62
33970	FP581	105 V	7	67	2438	9385	3	2400	9268	0	6	68	3	10	108	24	84
33971	FP576	105 V	7	67	2438	9385	3	2400	9077	0	6	68	3	10	113	24	84
33972	FP575	105 V	7	67	2438	9385	3	2400	9077	0	6	68	3	10	102	24	84
33973	FP578	105 V	7	67	2438	9385	3	2400	9077	0	6	68	3	10	113	24	84
33974	FP577	105 V	7	67	2438	9385	3	2400	9077	0	6	68	3	10	105	24	84
33975	FP577a255	105 V	7	67	2438	9385	3	2400	9077	0	6	68	3	10	105	24	84
33976	FP526	105 V	7	60	2438	10320	3	10269	2130	0	6	68	3	10	84	24	66
33977	FP520	105 V	6	52	2438	9385	3	4517	1551	0	6	68	3	10	110	6	50
33977	FP521	105 V	7	60	2438	9385	3	4517	1552	0	6	68	3	10	110	6	66
33978	FP582	105 V	7	67	2438	10320	3	2400	9667	0	6	68	3	10	110	25	84
33979	FP531	105 V	7	61	2438	11255	3	929	3245	0	6	68	3	10	130	2	66
33979	FP583	105 V	6	58	2438	11255	3	2381	9681	0	6	68	3	10	130	25	77

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BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33980	FP532	105 V	6	53	2438	11255	3	999	3265	0	6	68	3	10	153	2	64
33980	FP534	105 V	7	61	2438	11255	3	840	3410	0	6	68	3	10	153	2	66
33980	FP564	105 V	7	66	2438	11255	3	2400	7781	0	6	68	3	10	153	20	59
33981	FP542	105 V	7	62	2438	12190	3	2400	5134	0	6	68	3	10	128	13	60
33981	FP561	105 V	6	57	2438	12190	3	2400	6663	0	6	68	3	10	128	17	46
33982	FP539	105 V	7	62	2438	12190	3	2400	5132	0	6	68	3	10	128	13	60
33982	FP560	105 V	7	65	2438	12190	3	2400	6662	0	6	68	3	10	128	17	63
33983	FP544	105 V	7	62	2438	12190	3	1555	5788	0	6	68	3	10	120	9	60
33983	FP546	105 V	7	63	2438	12190	3	2247	5883	0	6	68	3	10	120	14	54
33984	FP557	105 V	6	56	2476	7515	3	2424	6636	0	6	68	3	10	102	17	62
33985	FP553	105 V	6	56	2476	7515	3	2424	6624	0	6	68	3	10	105	17	62
33986	FP657	105 V	8	75	2476	7515	3	2424	6636	0	6	68	3	10	102	17	56
33987	FP541	105 V	6	54	2476	12190	3	2438	5134	0	6	68	3	10	128	13	43
33987	FP559	105 V	7	65	2476	12190	3	2400	6637	0	6	68	3	10	128	17	63
33988	FP540	105 V	6	54	2476	12190	3	2438	5132	0	6	68	3	10	128	13	43
33988	FP556	105 V	6	56	2476	12190	3	2400	6636	0	6	68	3	10	128	17	62
33989	FP533	105 V	6	53	2476	12190	3	848	3395	0	6	68	3	10	178	2	64
33989	FP535	105 V	7	62	2476	12190	3	839	3442	0	6	68	3	10	178	2	60
33989	FP543	105 V	6	55	2476	12190	3	1592	5781	0	6	68	3	10	178	9	55
33989	FP545	105 V	6	55	2476	12190	3	2205	5881	0	6	68	3	10	178	13	55
33990	FP568	105 V	6	58	2476	9385	3	2438	8486	0	6	68	3	10	97	22	77
33991	FP536	105 V	6	53	2476	9385	3	849	3444	0	6	68	3	10	120	2	64
33991	FP567	105 V	7	66	2476	9385	3	2438	8480	0	6	68	3	10	120	22	59
33992	FP668	105 V	8	76	2476	9385	3	2438	8486	0	6	68	3	10	97	22	72
33993	FP666	105 V	8	76	2438	8450	3	2400	8340	0	6	68	3	10	110	22	72
33994	FP665	105 V	9	84	2438	8450	3	2400	8308	0	6	68	3	10	108	22	65
33995	FP627	105 V	8	71	2438	8450	3	2370	7773	0	6	68	3	10	108	20	57
33996	FP625	105 V	9	79	2438	8450	3	2091	1715	0	6	68	3	10	128	2	80
33996	FP659	105 V	9	83	2438	8450	3	2400	6637	0	6	68	3	10	128	17	68
33997	FP624	105 V	8	71	2438	8450	3	2077	1714	0	6	68	3	10	148	2	57
33997	FP655	105 V	9	83	2438	8450	3	2400	6628	0	6	68	3	10	148	17	68
33998	FP649	105 V	8	74	2438	6580	3	2398	6414	0	5	68	3	10	82	16	62
33999	FP650	105 V	9	82	2438	6580	3	2373	6420	0	5	68	3	10	82	16	67
34000	FP671	105 V	8	76	2438	9385	3	2400	9063	0	6	68	3	10	105	24	72
34001	FP680	105 V	8	78	2438	9385	3	2400	9266	0	6	68	3	10	110	24	51
34002	FP673	105 V	8	77	2438	9385	3	2400	9070	0	6	68	3	10	113	24	59
34003	FP674	105 V	8	77	2438	9385	3	2400	9070	0	6	68	3	10	102	24	59
34004	FP669	105 V	8	76	2438	9385	3	2400	9063	0	6	68	3	10	102	24	72
34005	FP670	105 V	8	76	2438	9385	3	2400	9063	0	6	68	3	10	113	24	72
34006	FP672	105 V	8	77	2438	9385	3	2400	9070	0	6	68	3	10	105	24	59
34007	FP681	105 V	9	86	2438	9385	3	2400	9268	0	6	68	3	10	108	24	51
34008	FP678	105 V	9	85	2438	9385	3	2400	9077	0	6	68	3	10	113	24	76
34009	FP677	105 V	9	85	2438	9385	3	2400	9077	0	6	68	3	10	102	24	76

Life Cycle Management Laboratory

CLT SCHEDULING MODEL - PROJECT INPUT TAB

BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
34010	FP675	105 V	9	85	2438	9385	3	2400	9077	0	6	68	3	10	113	24	76
34011	FP676	105 V	9	85	2438	9385	3	2400	9077	0	6	68	3	10	105	24	76
34012	FP676a307	105 V	9	85	2438	9385	3	2400	9077	0	6	68	3	10	105	24	76
34013	FP652	105 V	8	74	2438	7515	3	2400	6624	0	6	68	3	10	92	17	62
34014	FP663	105 V	8	75	2438	7515	3	2400	6984	0	6	68	3	10	105	18	56
34015	FP654	105 V	9	83	2438	7515	3	2400	6628	0	6	68	3	10	92	17	68
34016	FP662	105 V	9	84	2438	7515	3	2370	6984	0	6	68	3	10	102	18	65
34017	FP682	105 V	9	86	2438	10320	3	2400	9667	0	6	68	3	10	110	25	51
34018	FP631	105 V	9	80	2438	11255	3	929	3245	0	6	68	3	10	130	2	56
34018	FP683	105 V	8	78	2438	11255	3	2381	9681	0	6	68	3	10	130	25	51
34019	FP632	105 V	8	72	2438	11255	3	999	3265	0	6	68	3	10	153	2	60
34019	FP634	105 V	9	80	2438	11255	3	840	3410	0	6	68	3	10	153	2	56
34019	FP664	105 V	9	84	2438	11255	3	2400	7781	0	6	68	3	10	153	20	65
34020	FP642	105 V	9	81	2438	12190	3	2400	5134	0	6	68	3	10	128	13	61
34020	FP661	105 V	8	75	2438	12190	3	2400	6663	0	6	68	3	10	128	17	56
34021	FP639	105 V	9	81	2438	12190	3	2400	5132	0	6	68	3	10	128	13	61
34021	FP660	105 V	9	83	2438	12190	3	2400	6662	0	6	68	3	10	128	17	68
34022	FP644	105 V	9	81	2438	12190	3	1555	5788	0	6	68	3	10	120	9	61
34022	FP646	105 V	9	81	2438	12190	3	2247	5883	0	6	68	3	10	120	14	61
34023	FP653	105 V	8	74	2476	7515	3	2424	6624	0	6	68	3	10	105	17	62
34024	FP622	105 V	9	79	2476	9385	3	425	1678	0	6	68	3	10	153	2	80
34024	FP623	105 V	8	71	2476	9385	3	423	1714	0	6	68	3	10	153	2	57
34024	FP679	105 V	9	85	2476	9385	3	2400	9077	0	6	68	3	10	153	24	76
34025	FP636	105 V	8	72	2476	9385	3	849	3444	0	6	68	3	10	120	2	60
34025	FP667	105 V	9	84	2476	9385	3	2438	8480	0	6	68	3	10	120	22	65
34026	FP641	105 V	8	73	2476	12190	3	2438	5134	0	6	68	3	10	130	13	53
34026	FP658	105 V	9	83	2476	12190	3	2400	6637	0	6	68	3	10	130	17	68
34027	FP640	105 V	8	72	2476	12190	3	2438	5132	0	6	68	3	10	128	13	60
34027	FP656	105 V	8	74	2476	12190	3	2400	6636	0	6	68	3	10	128	17	62
34028	FP633	105 V	8	72	2476	12190	3	848	3395	0	6	68	3	10	170	2	60
34028	FP635	105 V	9	80	2476	12190	3	839	3442	0	6	68	3	10	170	2	56
34028	FP643	105 V	8	73	2476	12190	3	1592	5781	0	6	68	3	10	170	9	53
34028	FP645	105 V	8	73	2476	12190	3	2205	5881	0	6	68	3	10	170	13	53
34029	FP626	105 V	9	79	2438	10320	3	10269	2130	0	6	68	3	10	84	24	80
34030	FP620	105 V	8	70	2438	9385	3	4517	1551	0	6	68	3	10	115	6	66
34030	FP621	105 V	9	79	2438	9385	3	4517	1552	0	6	68	3	10	115	6	80

Appendix G - Case study – Plant database

Life Cycle Management Laboratory

CLT SCHEDULING MODEL - PLANT CURRENT STATS INPUT TAB

UBC

BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33783	FP1	245 V	1	1	2438	10320	7	2400	9393	0	13	68	12	10	54	25	34
33784	FP1a5	245 V	1	2	2438	10320	7	2400	9393	0	13	68	12	10	54	25	34
33785	FP1a6	245 V	1	3	2438	10320	7	2400	9393	0	13	68	12	10	54	25	34
33786	FP1a7	245 V	1	4	2438	10320	7	2400	9393	0	13	68	12	10	54	25	34
33787	FP1a8	245 V	1	5	2438	10320	7	2400	9393	0	13	68	12	10	54	25	34
33788	FP2	245 V	1	6	2438	10320	7	2400	9393	0	13	68	12	10	54	25	34
33789	FP4	245 V	1	7	2438	10320	7	1777	9393	0	13	68	12	10	66	18	30
33790	FP3	245 V	1	8	2438	10320	7	2044	9393	0	13	68	12	10	68	21	31
33791	WP9	139 V	1	10	3048	12190	5	2400	5791	0	13	68	13	10	90	14	54
33791	WP10	139 V	1	10	3048	12190	5	2400	5445	0	13	68	13	10	90	14	54
33792	WP7	139 V	1	9	3048	12190	5	2470	5791	0	13	68	13	10	91	15	45
33792	WP9a15	139 V	1	10	3048	12190	5	2400	5791	0	13	68	13	10	91	14	54
33793	WP8	139 V	2	12	3048	9385	5	2470	5026	0	12	68	13	10	109	13	61
33793	WP25	139 V	2	11	3048	9385	5	2400	5026	0	12	68	13	10	109	12	53
33794	WP22	139 V	2	14	3048	10320	5	2400	5191	0	12	68	13	10	79	13	61
33794	WP24	139 V	2	12	3048	10320	5	2400	5026	0	12	68	13	10	79	12	61
33795	WP23	139 V	2	11	2438	10320	5	2400	5185	0	10	68	10	10	79	13	53
33795	WP26	139 V	2	11	2438	10320	5	2400	5026	0	10	68	10	10	79	12	53
33796	WP16	139 V	2	14	2438	11255	5	2400	5491	0	10	68	10	10	57	14	61
33796	WP27	139 V	1	9	2438	11255	5	2260	5785	0	10	68	10	10	57	14	45
33797	WP18	139 V	2	14	2438	11255	5	2400	5391	0	10	68	10	10	56	13	61
33797	WP20	139 V	2	14	2438	11255	5	2400	5291	0	10	68	10	10	56	13	61
33798	WP19	139 V	2	16	2438	11255	5	2400	5385	0	10	68	10	10	56	13	66
33798	WP21	139 V	2	16	2438	11255	5	2400	5285	0	10	68	10	10	56	13	66
33799	WP12	139 V	2	12	2438	11255	5	2400	5691	0	10	68	10	10	53	14	61
33799	WP14	139 V	2	12	2438	11255	5	2400	5591	0	10	68	10	10	53	14	61
33800	WP15	139 V	2	13	2438	11255	5	2400	5585	0	10	68	10	10	54	14	66
33800	WP17	139 V	2	15	2438	11255	5	2400	5485	0	10	68	10	10	54	14	77
33801	WP11	139 V	2	16	2438	12190	5	2400	5785	0	10	68	10	10	56	14	66
33801	WP13	139 V	2	13	2438	12190	5	2400	5685	0	10	68	10	10	56	14	66
33802	WP29	139 V	2	16	2438	8450	5	1572	2712	0	9	68	10	10	74	3	66
33802	WP28	139 V	2	16	2438	8450	5	1559	5091	0	9	68	10	10	74	7	66
33803	WP30	87 V	2	13	2438	11255	3	2400	5500	0	6	68	3	10	42	14	66
33803	WP31	87 V	2	13	2438	11255	3	2400	5400	0	6	68	3	10	42	13	66
33804	WP33	87 V	2	13	2438	11255	3	2024	5300	0	6	68	3	10	61	11	66
33804	WP34	87 V	2	15	2438	11255	3	2010	5397	0	6	68	3	10	61	11	77
33805	WP35	87 V	2	15	2438	11255	3	2010	5216	0	6	68	3	10	62	10	77
33805	WP42	87 V	2	15	2438	11255	3	1703	5397	0	6	68	3	10	62	9	77
33806	WP37	87 V	2	15	2438	11255	3	2001	5216	0	6	68	3	10	54	10	77
33806	WP41	87 V	2	17	2438	11255	3	1760	5282	0	6	68	3	10	54	9	51
33807	WP39	87 V	2	17	2438	9385	3	1764	3811	0	6	68	3	10	54	6	51
33807	WP32	87 V	2	15	2438	9385	3	2380	5500	0	6	68	3	10	54	14	77
33808	WP36	87 V	2	15	2438	7515	3	2001	5397	0	6	68	3	10	65	11	77

Life Cycle Management Laboratory

CLT SCHEDULING MODEL - PLANT CURRENT STATS INPUT TAB

UBC

BILLET ID	PART ID *	MATERIAL TYPE	TRUCK LOAD	PACKAGE BUNDLE	RAW BILLET			PART			ESTIMATED PROCESS TIME (min)						
					WIDTH (mm)	LENGTH (mm)	# of LAYERS	ROUGH WIDTH (mm)	ROUGH LENGTH (mm)	# of VISUAL FACES	PRESS LOADING	PRESSING	PRESS UNLOADING	PRESS WAIT SETUP	TOTAL CNC PROCESS	FQC	PACKAGING
33808	WP40	87 V	2	17	2438	7515	3	1764	3811	0	6	68	3	10	65	6	51
33809	WP38	87 V	2	15	2438	5645	3	1951	5323	0	5	68	3	10	35	10	77
33810	RP5	245 E-XL	3	19	3048	11255	7	3000	10668	0	19	68	15	10	52	36	40
33811	RP5a50	245 E-XL	3	20	3048	11255	7	3000	10668	0	19	68	15	10	52	36	40
33812	RP5a51	245 E-XL	3	21	3048	11255	7	3000	10668	0	19	68	15	10	52	36	40
33813	RP6	245 E-XL	3	18	3048	11255	7	2645	10668	0	19	68	15	10	58	31	37
33814	RP5a53	245 E-XL	3	22	3048	11255	7	3000	10668	0	19	68	15	10	52	36	40
33815	RP5a54	245 E-XL	3	23	3048	11255	7	3000	10668	0	19	68	15	10	52	36	40
33816	RP5a55	245 E-XL	3	24	3048	11255	7	3000	10668	0	19	68	15	10	52	36	40

Appendix H - Case study – Press work order

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name: Starting date: Operator:	Simulation 1 - Project / 10/24/2018 / Bruno	UBC
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
				SHIFT 1, DAY 1			
33783	0	0	0	0.00001	0.00001	Plant current stats	Plant current stats
33784	0	0	0	0.00001	0.00002	Plant current stats	Plant current stats
33785	0	0	0	0.00001	0.00003	Plant current stats	Plant current stats
33786	0	0	0	0.00001	0.00004	Plant current stats	Plant current stats
33787	0	0	0	0.00001	0.00005	Plant current stats	Plant current stats
33788	0	0	0	0.00001	0.00006	Plant current stats	Plant current stats
33789	0	0	0	0.00001	0.00007	Plant current stats	Plant current stats
33790	0	0	0	0.00001	0.00008	Plant current stats	Plant current stats
33791	0	0	0	0.00001	0.0001	Plant current stats	Plant current stats
33792	0	0	0	0.00001	0.00009	Plant current stats	Plant current stats
33792	0	0	0	0.00001	0.0001	Plant current stats	Plant current stats
33793	0	0	0	0.00002	0.00011	Plant current stats	Plant current stats
33793	0	0	0	0.00002	0.00012	Plant current stats	Plant current stats
33794	0	0	0	0.00002	0.00012	Plant current stats	Plant current stats
33794	0	0	0	0.00002	0.00014	Plant current stats	Plant current stats
33795	0	0	0	0.00002	0.00011	Plant current stats	Plant current stats
33796	0	0	0	0.00001	0.00009	Plant current stats	Plant current stats
33796	0	0	0	0.00002	0.00014	Plant current stats	Plant current stats
33797	0	0	0	0.00002	0.00014	Plant current stats	Press Stacking Area 2, Position 4
33798	0	0	0	0.00002	0.00016	Plant current stats	Press Stacking Area 1, Position 5
33799	0	0	0	0.00002	0.00012	Plant current stats	Plant current stats
33800	0	0	0	0.00002	0.00013	Plant current stats	Plant current stats
33800	0	0	0	0.00002	0.00015	Plant current stats	Plant current stats
33801	0	0	0	0.00002	0.00013	Plant current stats	Plant current stats
33801	0	0	0	0.00002	0.00016	Plant current stats	Plant current stats
33802	0	0	0	0.00002	0.00016	Plant current stats	Plant current stats
33803	0	0	0	0.00002	0.00013	Plant current stats	Plant current stats
33804	0	0	0	0.00002	0.00013	Plant current stats	Plant current stats
33804	0	0	0	0.00002	0.00015	Plant current stats	Plant current stats
33805	0	0	0	0.00002	0.00015	Plant current stats	Plant current stats
33806	0	0	0	0.00002	0.00015	Plant current stats	Plant current stats
33806	0	0	0	0.00002	0.00017	Plant current stats	Plant current stats

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE			Project name:	Simulation 1 - Project		UBC
				Starting date:	10/24/2018		
				Operator:	Bruno		
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
33810	0	0	0	0.00003	0.00019	Plant current stats	Press Stacking Area 2, Position 1
33811	0	0	0	0.00003	0.0002	Plant current stats	Press Stacking Area 2, Position 2
33812	0	0	0	0.00003	0.00021	Plant current stats	Press Stacking Area 2, Position 3
33813	0	0	0	0.00003	0.00018	Plant current stats	Press Stacking Area 1, Position 4
33814	0	0	0	0.00003	0.00022	Plant current stats	Press Stacking Area 1, Position 3
33815	0	0	0	0.00003	0.00023	Plant current stats	Press Stacking Area 1, Position 2
33816	0	0	0	0.00003	0.00024	Plant current stats	Press Stacking Area 1, Position 1
33807	0	87	0	0.00002	0.00015	Plant current stats	Press Stacking Area 2 Position 4
33807	0	87	0	0.00002	0.00017	Plant current stats	Press Stacking Area 2 Position 4
33808	0	87	0	0.00002	0.00015	Plant current stats	Press Stacking Area 1 Position 6
33808	0	87	0	0.00002	0.00017	Plant current stats	Press Stacking Area 1 Position 6
33809	0	87	0	0.00002	0.00015	Plant current stats	Press Stacking Area 1 Position 7
33846	87	433	1	1	1	Raw material	Press Stacking Area 2 Position 2
33846	87	433	1	1	2	Raw material	Press Stacking Area 2 Position 2
33846	87	433	1	1	6	Raw material	Press Stacking Area 2 Position 2
33846	87	433	1	4	33	Raw material	Press Stacking Area 2 Position 2
33850	87	433	1	1	2	Raw material	Press Stacking Area 2 Position 1
33850	87	433	1	4	33	Raw material	Press Stacking Area 2 Position 1
33850	87	433	1	6	50	Raw material	Press Stacking Area 2 Position 1
33850	87	433	1	6	51	Raw material	Press Stacking Area 2 Position 1
Downtime	191	210	-			-	-
Downtime	212	264	-			-	-
Downtime	266	316	-			-	-
Downtime	325	372	-			-	-
Downtime	376	424	-			-	-
33854	433	651	2	2	9	Raw material	Press Stacking Area 2 Position 1
33854	433	651	2	4	33	Raw material	Press Stacking Area 2 Position 1

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE	Project name:	Simulation 1 - Project	UBC
		Starting date:	10/24/2018	
		Operator:	Bruno	

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
33854	433	651	2	6	50	Raw material	Press Stacking Area 2 Position 1
33854	433	651	2	8	69	Raw material	Press Stacking Area 2 Position 1
33855	433	651	2	1	1	Raw material	Press Stacking Area 2 Position 2
33855	433	651	2	1	3	Raw material	Press Stacking Area 2 Position 2
33855	433	651	2	4	33	Raw material	Press Stacking Area 2 Position 2
SHIFT 2, DAY 1							
Downtime	51	163	-			-	-
33844	171	309	3	1	4	Raw material	Press Stacking Area 2 Position 3
33844	171	309	3	1	6	Raw material	Press Stacking Area 2 Position 3
33844	171	309	3	6	50	Raw material	Press Stacking Area 2 Position 3
33847	171	309	3	1	5	Raw material	Press Stacking Area 2 Position 2
33847	171	309	3	1	7	Raw material	Press Stacking Area 2 Position 2
33847	171	309	3	2	9	Raw material	Press Stacking Area 2 Position 2
Downtime	274	300	-			-	-
33845	309	623	4	2	8	Raw material	Press Stacking Area 2 Position 3
33845	309	623	4	2	9	Raw material	Press Stacking Area 2 Position 3
33845	309	623	4	2	10	Raw material	Press Stacking Area 2 Position 3
33848	309	623	4	2	8	Raw material	Press Stacking Area 2 Position 2
33848	309	623	4	8	69	Raw material	Press Stacking Area 2 Position 2
33848	309	623	4	8	70	Raw material	Press Stacking Area 2 Position 2
Downtime	412	477	-			-	-
SHIFT 3, DAY 1							
Downtime	11	134	-			-	-
33852	143	578	5	2	8	Raw material	Press Stacking Area 2 Position 2

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE		Project name:	Simulation 1 - Project	
			Starting date:	10/24/2018	
			Operator:	Bruno	

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
33852	143	578	5	4	33	Raw material	Press Stacking Area 2 Position 2
33852	143	578	5	8	68	Raw material	Press Stacking Area 2 Position 2
33852	143	578	5	8	70	Raw material	Press Stacking Area 2 Position 2
33907	143	578	5	4	33	Raw material	Press Stacking Area 2 Position 1
33907	143	578	5	4	34	Raw material	Press Stacking Area 2 Position 1
33907	143	578	5	8	68	Raw material	Press Stacking Area 2 Position 1
Downtime	247	296	-			-	-
Downtime	311	433	-			-	-
Downtime	441	570	-			-	-
SHIFT 1, DAY 2							
33849	98	202	6	2	8	Raw material	Press Stacking Area 2 Position 3
33849	98	202	6	2	10	Raw material	Press Stacking Area 2 Position 3
33849	98	202	6	8	70	Raw material	Press Stacking Area 2 Position 3
33851	98	202	6	2	8	Raw material	Press Stacking Area 2 Position 4
33851	98	202	6	2	10	Raw material	Press Stacking Area 2 Position 4
33851	98	202	6	6	50	Raw material	Press Stacking Area 2 Position 4
33851	98	202	6	8	68	Raw material	Press Stacking Area 2 Position 4
33853	202	700	7	4	34	Raw material	Press Stacking Area 2 Position 2
33853	202	700	7	6	50	Raw material	Press Stacking Area 2 Position 2
33909	202	700	7	6	51	Raw material	Press Stacking Area 2 Position 1
33909	202	700	7	8	68	Raw material	Press Stacking Area 2 Position 1
Downtime	305	419	-			-	-
Downtime	428	554	-			-	-
SHIFT 2, DAY 2							
Downtime	88	211	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	UBC
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
33910	220	318	8	4	34	Raw material	Press Stacking Area 2 Position 3
33910	220	318	8	6	50	Raw material	Press Stacking Area 2 Position 3
33910	220	318	8	6	51	Raw material	Press Stacking Area 2 Position 3
33910	220	318	8	8	69	Raw material	Press Stacking Area 2 Position 3
33868	318	405	9	2	11	Raw material	Press Stacking Area 2 Position 4
33870	318	405	9	2	11	Raw material	Press Stacking Area 2 Position 3
33870	318	405	9	3	25	Raw material	Press Stacking Area 2 Position 3
33893	318	405	9	2	11	Raw material	Press Stacking Area 2 Position 5
33893	318	405	9	3	18	Raw material	Press Stacking Area 2 Position 5
33869	405	766	10	3	18	Raw material	Press Stacking Area 2 Position 3
33869	405	766	10	3	25	Raw material	Press Stacking Area 2 Position 3
33891	405	766	10	3	18	Raw material	Press Stacking Area 2 Position 4
33894	405	981	10	4	34	Raw material	Press Stacking Area 2 Position 3
33894	405	981	10	5	41	Raw material	Press Stacking Area 2 Position 3
SHIFT 3, DAY 2							
Downtime	12	58	-			-	-
Downtime	72	173	-			-	-
Downtime	175	281	-			-	-
Downtime	286	411	-			-	-
Downtime	412	495	-			-	-
SHIFT 1, DAY 3							
33882	21	108	11	2	11	Raw material	Press Stacking Area 2 Position 6
33882	21	108	11	3	18	Raw material	Press Stacking Area 2 Position 6
33882	21	108	11	3	31	Raw material	Press Stacking Area 2 Position 6
33883	21	108	11	2	12	Raw material	Press Stacking Area 2 Position 5

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
33883	21	108	11	3	28	Raw material	Press Stacking Area 2 Position 5
33886	21	108	11	2	12	Raw material	Press Stacking Area 2 Position 4
33886	21	108	11	2	13	Raw material	Press Stacking Area 2 Position 4
33886	21	108	11	3	22	Raw material	Press Stacking Area 2 Position 4
33871	108	412	12	2	13	Raw material	Press Stacking Area 2 Position 5
33874	108	412	12	2	14	Raw material	Press Stacking Area 2 Position 4
33897	108	412	12	2	12	Raw material	Press Stacking Area 2 Position 6
33897	108	412	12	3	20	Raw material	Press Stacking Area 2 Position 6
33897	108	412	12	3	26	Raw material	Press Stacking Area 2 Position 6
Downtime	195	296	-			-	-
Downtime	297	411	-			-	-
33899	412	785	13	3	21	Raw material	Press Stacking Area 2 Position 4
33899	412	785	13	3	25	Raw material	Press Stacking Area 2 Position 4
33902	412	785	13	3	25	Raw material	Press Stacking Area 2 Position 6
33903	412	785	13	3	25	Raw material	Press Stacking Area 2 Position 5
			SHIFT 2, DAY 3				
Downtime	19	66	-			-	-
Downtime	67	219	-			-	-
Downtime	220	301	-			-	-
33885	305	392	14	2	13	Raw material	Press Stacking Area 2 Position 7
33885	305	392	14	3	23	Raw material	Press Stacking Area 2 Position 7
33887	305	392	14	2	13	Raw material	Press Stacking Area 2 Position 8
33884	305	524	14	2	15	Raw material	Press Stacking Area 2 Position 7
33884	305	524	14	3	20	Raw material	Press Stacking Area 2 Position 7
Downtime	392	393	-			-	-
Downtime	398	521	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name:	Simulation 1 - Project	UBC
					Starting date:	10/24/2018	
					Operator:	Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
				SHIFT 3, DAY 3			
33861	44	131	15	2	15	Raw material	Press Stacking Area 2 Position 8
33875	44	131	15	2	15	Raw material	Press Stacking Area 2 Position 9
33876	44	131	15	2	14	Raw material	Press Stacking Area 2 Position 10
33881	131	218	16	2	14	Raw material	Press Stacking Area 2 Position 10
33880	131	271	16	2	14	Raw material	Press Stacking Area 2 Position 10
Downtime	218	266	-			-	-
33865	271	583	17	2	16	Raw material	Press Stacking Area 2 Position 8
33866	271	583	17	2	15	Raw material	Press Stacking Area 2 Position 10
33898	271	583	17	2	15	Raw material	Press Stacking Area 2 Position 9
33898	271	583	17	3	21	Raw material	Press Stacking Area 2 Position 9
Downtime	358	371	-			-	-
Downtime	376	473	-			-	-
Downtime	478	578	-			-	-
				SHIFT 1, DAY 4			
33859	103	316	18	2	16	Raw material	Press Stacking Area 2 Position 10
33863	103	316	18	2	16	Raw material	Press Stacking Area 2 Position 9
33896	103	670	18	2	17	Raw material	Press Stacking Area 2 Position 8
33896	103	670	18	3	20	Raw material	Press Stacking Area 2 Position 8
Downtime	190	200	-			-	-
Downtime	206	310	-			-	-
Downtime	316	438	-			-	-
Downtime	442	551	-			-	-
				SHIFT 2, DAY 4			
Downtime	77	184	-			-	-
33860	190	277	19	2	17	Raw material	Press Stacking Area 2 Position 10

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE		Project name:	Simulation 1 - Project	
			Starting date:	10/24/2018	
			Operator:	Bruno	

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
33864	190	277	19	2	17	Raw material	Press Stacking Area 2 Position 9
33872	190	295	19	2	17	Raw material	Press Stacking Area 2 Position 10
Downtime	277	289	-			-	-
33862	295	722	20	2	17	Raw material	Press Stacking Area 2 Position 9
33873	295	722	20	3	24	Raw material	Press Stacking Area 2 Position 7
33895	295	722	20	2	17	Raw material	Press Stacking Area 2 Position 8
33895	295	722	20	3	32	Raw material	Press Stacking Area 2 Position 8
Downtime	382	391	-			-	-
Downtime	397	481	-			-	-
SHIFT 3, DAY 4							
Downtime	5	106	-			-	-
Downtime	112	241	-			-	-
33856	242	474	21	3	24	Raw material	Press Stacking Area 2 Position 8
33856	242	474	21	9	79	Raw material	Press Stacking Area 2 Position 8
33856	242	474	21	9	82	Raw material	Press Stacking Area 2 Position 8
33904	242	474	21	3	19	Raw material	Press Stacking Area 2 Position 9
33904	242	474	21	3	24	Raw material	Press Stacking Area 2 Position 9
33905	242	474	21	3	19	Raw material	Press Stacking Area 2 Position 10
33905	242	474	21	5	44	Raw material	Press Stacking Area 2 Position 10
33905	242	474	21	7	63	Raw material	Press Stacking Area 2 Position 10
Downtime	335	358	-			-	-
Downtime	359	468	-			-	-
33906	474	731	22	3	24	Raw material	Press Stacking Area 2 Position 9
33906	474	731	22	5	42	Raw material	Press Stacking Area 2 Position 9
33906	474	731	22	9	82	Raw material	Press Stacking Area 2 Position 9

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE	Project name:	Simulation 1 - Project
		Starting date:	10/24/2018
		Operator:	Bruno

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
SHIFT 1, DAY 5							
Downtime	87	118	-			-	-
Downtime	119	242	-			-	-
33867	251	888	23	3	27	Raw material	Press Stacking Area 2 Position 5
33879	251	888	23	3	29	Raw material	Press Stacking Area 2 Position 4
33901	251	888	23	3	26	Raw material	Press Stacking Area 2 Position 6
Downtime	338	369	-			-	-
Downtime	378	493	-			-	-
SHIFT 2, DAY 5							
Downtime	22	137	-			-	-
Downtime	146	219	-			-	-
Downtime	223	311	-			-	-
Downtime	316	403	-			-	-
33878	408	739	24	3	29	Raw material	Press Stacking Area 2 Position 6
33889	408	739	24	3	30	Raw material	Press Stacking Area 2 Position 5
33890	408	739	24	3	30	Raw material	Press Stacking Area 2 Position 4
SHIFT 3, DAY 5							
Downtime	15	43	-			-	-
Downtime	47	145	-			-	-
Downtime	150	253	-			-	-
33900	259	684	25	4	37	Raw material	Press Stacking Area 2 Position 3
33900	259	684	25	5	44	Raw material	Press Stacking Area 2 Position 3
33917	259	684	25	5	44	Raw material	Press Stacking Area 2 Position 4
33918	259	684	25	5	44	Raw material	Press Stacking Area 2 Position 5
Downtime	346	355	-			-	-
Downtime	361	468	-			-	-
Downtime	474	573	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
SHIFT 1, DAY 6							
Downtime	99	198	-			-	-
33877	204	291	26	3	31	Raw material	Press Stacking Area 2 Position 7
33888	204	291	26	3	30	Raw material	Press Stacking Area 2 Position 8
33915	204	291	26	4	35	Raw material	Press Stacking Area 2 Position 6
33908	291	432	27	4	34	Raw material	Press Stacking Area 2 Position 7
33908	291	432	27	6	51	Raw material	Press Stacking Area 2 Position 7
33908	291	432	27	8	68	Raw material	Press Stacking Area 2 Position 7
Downtime	394	426	-			-	-
33916	432	683	28	4	37	Raw material	Press Stacking Area 2 Position 6
33937	432	683	28	4	35	Raw material	Press Stacking Area 2 Position 8
33937	432	683	28	5	45	Raw material	Press Stacking Area 2 Position 8
33939	432	683	28	4	36	Raw material	Press Stacking Area 2 Position 7
33939	432	683	28	5	43	Raw material	Press Stacking Area 2 Position 7
33939	432	683	28	5	47	Raw material	Press Stacking Area 2 Position 7
SHIFT 2, DAY 6							
Downtime	39	54	-			-	-
Downtime	60	189	-			-	-
33947	203	302	29	4	36	Raw material	Press Stacking Area 2 Position 9
33947	203	302	29	4	37	Raw material	Press Stacking Area 2 Position 9
33948	203	302	29	4	35	Raw material	Press Stacking Area 2 Position 10
33948	203	302	29	5	41	Raw material	Press Stacking Area 2 Position 10
33948	203	302	29	5	48	Raw material	Press Stacking Area 2 Position 10
33949	203	302	29	4	36	Raw material	Press Stacking Area 2 Position 8
33949	203	302	29	4	39	Raw material	Press Stacking Area 2 Position 8

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name:	Simulation 1 - Project	
					Starting date:	10/24/2018	
					Operator:	Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
Downtime	290	297	-			-	-
33943	302	805	30	4	36	Raw material	Press Stacking Area 2 Position 9
33943	302	805	30	5	46	Raw material	Press Stacking Area 2 Position 9
33944	302	805	30	4	36	Raw material	Press Stacking Area 2 Position 8
33944	302	805	30	4	38	Raw material	Press Stacking Area 2 Position 8
33946	302	805	30	4	37	Raw material	Press Stacking Area 2 Position 7
Downtime	389	427	-			-	-
Downtime	428	580	-			-	-
SHIFT 3, DAY 6							
Downtime	101	207	-			-	-
Downtime	208	324	-			-	-
33932	325	845	31	4	37	Raw material	Press Stacking Area 2 Position 8
33933	325	845	31	4	38	Raw material	Press Stacking Area 2 Position 7
33941	325	845	31	4	38	Raw material	Press Stacking Area 2 Position 6
33941	325	845	31	5	43	Raw material	Press Stacking Area 2 Position 6
Downtime	412	477	-			-	-
Downtime	478	605	-			-	-
SHIFT 1, DAY 7							
Downtime	129	255	-			-	-
Downtime	259	360	-			-	-
33945	365	644	32	4	38	Raw material	Press Stacking Area 2 Position 7
33950	365	644	32	5	43	Raw material	Press Stacking Area 2 Position 6
33950	365	644	32	5	47	Raw material	Press Stacking Area 2 Position 6
Downtime	452	534	-			-	-
SHIFT 2, DAY 7							
Downtime	59	159	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE		Project name:	Simulation 1 - Project			
			Starting date:	10/24/2018			
			Operator:	Bruno			
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
33920	164	291	33	4	39	Raw material	Press Stacking Area 2 Position 9
33923	164	291	33	4	39	Raw material	Press Stacking Area 2 Position 8
33924	164	291	33	4	39	Raw material	Press Stacking Area 2 Position 7
Downtime	251	287	-			-	-
33919	291	378	34	4	39	Raw material	Press Stacking Area 2 Position 10
33913	291	394	34	4	39	Raw material	Press Stacking Area 2 Position 10
33925	291	508	34	4	39	Raw material	Press Stacking Area 2 Position 10
Downtime	378	389	-			-	-
Downtime	394	502	-			-	-
SHIFT 3, DAY 7							
33921	28	447	35	4	40	Raw material	Press Stacking Area 2 Position 8
33922	28	447	35	4	39	Raw material	Press Stacking Area 2 Position 9
33938	28	447	35	4	40	Raw material	Press Stacking Area 2 Position 7
33938	28	447	35	5	42	Raw material	Press Stacking Area 2 Position 7
Downtime	115	132	-			-	-
Downtime	138	237	-			-	-
Downtime	243	339	-			-	-
Downtime	345	441	-			-	-
33892	447	775	36	5	41	Raw material	Press Stacking Area 2 Position 9
33936	447	775	36	5	41	Raw material	Press Stacking Area 2 Position 8
33936	447	775	36	5	46	Raw material	Press Stacking Area 2 Position 8
33942	447	775	36	5	43	Raw material	Press Stacking Area 2 Position 7
33942	447	775	36	5	46	Raw material	Press Stacking Area 2 Position 7
SHIFT 1, DAY 8							
Downtime	54	66	-			-	-
Downtime	72	179	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE		Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	UBC

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
Downtime	185	289	-			-	-
33857	295	763	37	5	44	Raw material	Press Stacking Area 2 Position 6
33857	295	763	37	7	61	Raw material	Press Stacking Area 2 Position 6
33857	295	763	37	7	63	Raw material	Press Stacking Area 2 Position 6
33858	295	763	37	5	42	Raw material	Press Stacking Area 2 Position 7
33858	295	763	37	5	45	Raw material	Press Stacking Area 2 Position 7
Downtime	388	419	-			-	-
Downtime	420	503	-			-	-
SHIFT 2, DAY 8							
Downtime	29	151	-			-	-
Downtime	152	279	-			-	-
33914	283	824	38	5	47	Raw material	Press Stacking Area 2 Position 3
33934	283	824	38	5	46	Raw material	Press Stacking Area 2 Position 4
33935	283	824	38	5	45	Raw material	Press Stacking Area 2 Position 5
Downtime	370	401	-			-	-
Downtime	402	530	-			-	-
SHIFT 3, DAY 8							
Downtime	59	174	-			-	-
Downtime	183	258	-			-	-
Downtime	261	340	-			-	-
33928	344	672	39	5	48	Raw material	Press Stacking Area 2 Position 5
33930	344	672	39	5	48	Raw material	Press Stacking Area 2 Position 4
33931	344	672	39	5	48	Raw material	Press Stacking Area 2 Position 3
Downtime	431	473	-			-	-
Downtime	477	565	-			-	-
SHIFT 1, DAY 9							

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE			Project name:	Simulation 1 - Project	
				Starting date:	10/24/2018	
				Operator:	Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
Downtime	90	187	-			-	-
33926	192	508	40	5	48	Raw material	Press Stacking Area 2 Position 5
33927	192	508	40	5	49	Raw material	Press Stacking Area 2 Position 3
33929	192	508	40	5	48	Raw material	Press Stacking Area 2 Position 4
Downtime	279	295	-			-	-
Downtime	301	397	-			-	-
Downtime	403	502	-			-	-
			SHIFT 2, DAY 9				
33940	28	571	41	5	49	Raw material	Press Stacking Area 2 Position 3
33964	28	571	41	6	52	Raw material	Press Stacking Area 2 Position 1
33964	28	571	41	7	64	Raw material	Press Stacking Area 2 Position 1
33977	28	571	41	6	52	Raw material	Press Stacking Area 2 Position 2
33977	28	571	41	7	60	Raw material	Press Stacking Area 2 Position 2
Downtime	115	127	-			-	-
Downtime	133	240	-			-	-
Downtime	246	353	-			-	-
Downtime	359	461	-			-	-
Downtime	467	563	-			-	-
			SHIFT 3, DAY 9				
33951	91	442	42	6	52	Raw material	Press Stacking Area 2 Position 3
33951	91	442	42	7	60	Raw material	Press Stacking Area 2 Position 3
33951	91	442	42	7	67	Raw material	Press Stacking Area 2 Position 3
33989	91	442	42	6	53	Raw material	Press Stacking Area 2 Position 1
33989	91	442	42	6	55	Raw material	Press Stacking Area 2 Position 1
33989	91	442	42	7	62	Raw material	Press Stacking Area 2 Position 1
33991	91	442	42	6	53	Raw material	Press Stacking Area 2 Position 2

Life Cycle Management Laboratory		CLT SCHEDULING MODEL PRESS SCHEDULE			Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
33991	91	442	42	7	66	Raw material	Press Stacking Area 2 Position 2
Downtime	178	220	-			-	-
Downtime	229	330	-			-	-
Downtime	337	440	-			-	-
33963	442	571	43	6	53	Raw material	Press Stacking Area 2 Position 3
33979	442	952	43	6	58	Raw material	Press Stacking Area 2 Position 2
33979	442	952	43	7	61	Raw material	Press Stacking Area 2 Position 2
33980	442	952	43	6	53	Raw material	Press Stacking Area 2 Position 1
33980	442	952	43	7	61	Raw material	Press Stacking Area 2 Position 1
33980	442	952	43	7	66	Raw material	Press Stacking Area 2 Position 1
SHIFT 1, DAY 10							
Downtime	49	90	-			-	-
Downtime	91	243	-			-	-
Downtime	244	351	-			-	-
Downtime	356	471	-			-	-
33984	472	559	44	6	56	Raw material	Press Stacking Area 2 Position 3
33987	472	559	44	6	54	Raw material	Press Stacking Area 2 Position 5
33987	472	559	44	7	65	Raw material	Press Stacking Area 2 Position 5
33988	472	559	44	6	54	Raw material	Press Stacking Area 2 Position 4
33988	472	559	44	6	56	Raw material	Press Stacking Area 2 Position 4
SHIFT 2, DAY 10							
33959	79	429	45	6	55	Raw material	Press Stacking Area 2 Position 5
33966	79	429	45	6	57	Raw material	Press Stacking Area 2 Position 3
33969	79	429	45	6	56	Raw material	Press Stacking Area 2 Position 4
Downtime	166	169	-			-	-
Downtime	170	297	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE			Project name:	Simulation 1 - Project	
				Starting date:	10/24/2018	
				Operator:	Bruno	

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
Downtime	301	425	-			-	-
33985	429	706	46	6	56	Raw material	Press Stacking Area 2 Position 4
33990	429	706	46	6	58	Raw material	Press Stacking Area 2 Position 3
SHIFT 3, DAY 10							
Downtime	36	47	-			-	-
Downtime	52	129	-			-	-
Downtime	133	221	-			-	-
33958	226	331	47	6	58	Raw material	Press Stacking Area 2 Position 5
33961	226	331	47	6	58	Raw material	Press Stacking Area 2 Position 4
33981	226	331	47	6	57	Raw material	Press Stacking Area 2 Position 6
33981	226	331	47	7	62	Raw material	Press Stacking Area 2 Position 6
Downtime	313	326	-			-	-
33952	331	777	48	6	58	Raw material	Press Stacking Area 2 Position 5
33953	331	777	48	6	59	Raw material	Press Stacking Area 2 Position 3
33956	331	777	48	6	58	Raw material	Press Stacking Area 2 Position 4
Downtime	418	431	-			-	-
Downtime	436	559	-			-	-
SHIFT 1, DAY 11							
Downtime	83	181	-			-	-
Downtime	187	291	-			-	-
33954	297	504	49	6	59	Raw material	Press Stacking Area 2 Position 6
33955	297	504	49	6	59	Raw material	Press Stacking Area 2 Position 5
33957	297	504	49	6	59	Raw material	Press Stacking Area 2 Position 4
Downtime	384	388	-			-	-
Downtime	394	498	-			-	-
SHIFT 2, DAY 11							

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE			Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**

BILLET ID	START TIME STEP (min)	END TIME STEP (min)	PRESS CYCLE	TRUCK LOAD	BUNDLE	COMING FROM	GOING TO
33965	24	687	50	7	60	Raw material	Press Stacking Area 2 Position 2
33965	24	687	50	7	65	Raw material	Press Stacking Area 2 Position 2
33976	24	687	50	7	60	Raw material	Press Stacking Area 2 Position 3
33983	24	687	50	7	62	Raw material	Press Stacking Area 2 Position 1
33983	24	687	50	7	63	Raw material	Press Stacking Area 2 Position 1
Downtime	111	131	-			-	-
Downtime	137	236	-			-	-
Downtime	242	341	-			-	-
Downtime	347	454	-			-	-
Downtime	460	556	-			-	-
SHIFT 3, DAY 11							
Downtime	82	206	-			-	-
33911	207	449	51	7	61	Raw material	Press Stacking Area 2 Position 2
33911	207	449	51	7	64	Raw material	Press Stacking Area 2 Position 2
Downtime	300	359	-			-	-
Downtime	360	443	-			-	-
33960	449	707	52	7	64	Raw material	Press Stacking Area 2 Position 2
33968	449	707	52	7	64	Raw material	Press Stacking Area 2 Position 1
33982	449	707	52	7	62	Raw material	Press Stacking Area 2 Position 3
33982	449	707	52	7	65	Raw material	Press Stacking Area 2 Position 3
SHIFT 1, DAY 12							
Downtime	56	91	-			-	-
Downtime	92	218	-			-	-
33962	227	552	53	7	66	Raw material	Press Stacking Area 2 Position 2
33967	227	552	53	7	65	Raw material	Press Stacking Area 2 Position 3
33972	227	552	53	7	67	Raw material	Press Stacking Area 2 Position 1
Downtime	314	338	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE			Project name:	Simulation 1 - Project		
				Starting date:	10/24/2018		
				Operator:	Bruno		
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
Downtime	341	466	-			-	-
Downtime	470	548	-			-	-
			SHIFT 2, DAY 12				
33970	72	267	54	7	67	Raw material	Press Stacking Area 2 Position 2
33974	72	267	54	7	67	Raw material	Press Stacking Area 2 Position 4
33975	72	267	54	7	67	Raw material	Press Stacking Area 2 Position 3
Downtime	159	160	-			-	-
Downtime	165	262	-			-	-
33971	267	354	55	7	67	Raw material	Press Stacking Area 2 Position 6
33973	267	354	55	7	67	Raw material	Press Stacking Area 2 Position 5
33978	267	354	55	7	67	Raw material	Press Stacking Area 2 Position 7
33995	354	1030	56	8	71	Raw material	Press Stacking Area 2 Position 2
33997	354	1030	56	8	71	Raw material	Press Stacking Area 2 Position 1
33997	354	1030	56	9	83	Raw material	Press Stacking Area 2 Position 1
34030	354	1030	56	8	70	Raw material	Press Stacking Area 2 Position 3
34030	354	1030	56	9	79	Raw material	Press Stacking Area 2 Position 3
Downtime	441	480	-			-	-
			SHIFT 3, DAY 12				
Downtime	7	113	-			-	-
Downtime	119	226	-			-	-
Downtime	232	331	-			-	-
Downtime	337	436	-			-	-
Downtime	442	544	-			-	-
			SHIFT 1, DAY 13				
34024	70	394	57	8	71	Raw material	Press Stacking Area 2 Position 3

Life Cycle Management Laboratory		CLT SCHEDULING MODEL PRESS SCHEDULE			Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
34024	70	394	57	9	79	Raw material	Press Stacking Area 2 Position 3
34024	70	394	57	9	85	Raw material	Press Stacking Area 2 Position 3
34025	70	394	57	8	72	Raw material	Press Stacking Area 2 Position 2
34025	70	394	57	9	84	Raw material	Press Stacking Area 2 Position 2
34027	70	394	57	8	72	Raw material	Press Stacking Area 2 Position 1
34027	70	394	57	8	74	Raw material	Press Stacking Area 2 Position 1
Downtime	157	166	-			-	-
Downtime	172	281	-			-	-
Downtime	283	389	-			-	-
34019	394	538	58	8	72	Raw material	Press Stacking Area 2 Position 3
34019	394	538	58	9	80	Raw material	Press Stacking Area 2 Position 3
34019	394	538	58	9	84	Raw material	Press Stacking Area 2 Position 3
33996	394	964	58	9	79	Raw material	Press Stacking Area 2 Position 1
33996	394	964	58	9	83	Raw material	Press Stacking Area 2 Position 1
34029	394	964	58	9	79	Raw material	Press Stacking Area 2 Position 2
SHIFT 2, DAY 13							
Downtime	1	57	-			-	-
Downtime	58	210	-			-	-
Downtime	211	363	-			-	-
Downtime	364	483	-			-	-
SHIFT 3, DAY 13							
34023	4	91	59	8	74	Raw material	Press Stacking Area 2 Position 3
34026	4	91	59	8	73	Raw material	Press Stacking Area 2 Position 4
34026	4	91	59	9	83	Raw material	Press Stacking Area 2 Position 4
34028	4	91	59	8	72	Raw material	Press Stacking Area 2 Position 5

Life Cycle Management Laboratory		CLT SCHEDULING MODEL PRESS SCHEDULE			Project name: Starting date: Operator:	Simulation 1 - Project / 10/24/2018 / Bruno	
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
34028	4	91	59	8	73	Raw material	Press Stacking Area 2 Position 5
34028	4	91	59	9	80	Raw material	Press Stacking Area 2 Position 5
33998	91	435	60	8	74	Raw material	Press Stacking Area 2 Position 5
34013	91	435	60	8	74	Raw material	Press Stacking Area 2 Position 4
34014	91	435	60	8	75	Raw material	Press Stacking Area 2 Position 3
Downtime	178	301	-			-	-
Downtime	302	431	-			-	-
33986	435	715	61	8	75	Raw material	Press Stacking Area 2 Position 4
33992	435	715	61	8	76	Raw material	Press Stacking Area 2 Position 3
SHIFT 1, DAY 14							
Downtime	42	56	-			-	-
Downtime	61	138	-			-	-
Downtime	142	230	-			-	-
34000	235	340	62	8	76	Raw material	Press Stacking Area 2 Position 4
34004	235	340	62	8	76	Raw material	Press Stacking Area 2 Position 5
34020	235	340	62	8	75	Raw material	Press Stacking Area 2 Position 6
34020	235	340	62	9	81	Raw material	Press Stacking Area 2 Position 6
Downtime	322	335	-			-	-
33993	340	442	63	8	76	Raw material	Press Stacking Area 2 Position 6
34015	340	1069	63	9	83	Raw material	Press Stacking Area 2 Position 2
34021	340	1069	63	9	81	Raw material	Press Stacking Area 2 Position 1
34021	340	1069	63	9	83	Raw material	Press Stacking Area 2 Position 1
Downtime	427	437	-			-	-
Downtime	442	565	-			-	-
SHIFT 2, DAY 14							
Downtime	89	195	-			-	-

Life Cycle Management Laboratory		CLT SCHEDULING MODEL PRESS SCHEDULE			Project name: Starting date: Operator:	Simulation 1 - Project 10/24/2018 Bruno	UBC
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
Downtime	201	297	-			-	-
Downtime	303	402	-			-	-
Downtime	408	499	-			-	-
SHIFT 3, DAY 14							
Downtime	25	103	-			-	-
34003	109	196	64	8	77	Raw material	Press Stacking Area 2 Position 4
34005	109	196	64	8	76	Raw material	Press Stacking Area 2 Position 5
34006	109	196	64	8	77	Raw material	Press Stacking Area 2 Position 3
33912	196	452	65	9	79	Raw material	Press Stacking Area 2 Position 3
33912	196	452	65	9	80	Raw material	Press Stacking Area 2 Position 3
33912	196	452	65	9	82	Raw material	Press Stacking Area 2 Position 3
Downtime	289	344	-			-	-
Downtime	350	446	-			-	-
34001	452	539	66	8	78	Raw material	Press Stacking Area 2 Position 5
34002	452	539	66	8	77	Raw material	Press Stacking Area 2 Position 6
34018	452	539	66	8	78	Raw material	Press Stacking Area 2 Position 4
34018	452	539	66	9	80	Raw material	Press Stacking Area 2 Position 4
SHIFT 1, DAY 15							
33999	59	648	67	9	82	Raw material	Press Stacking Area 2 Position 2
34016	59	648	67	9	84	Raw material	Press Stacking Area 2 Position 1
34022	59	648	67	9	81	Raw material	Press Stacking Area 2 Position 3
Downtime	146	184	-			-	-
Downtime	190	294	-			-	-
Downtime	300	424	-			-	-
Downtime	425	551	-			-	-

Life Cycle Management Laboratory	CLT SCHEDULING MODEL PRESS SCHEDULE				Project name: Starting date: Operator:	Simulation 1 - Project / 10/24/2018 / Bruno	UBC
BILLET ID	**START TIME STEP (min)**	**END TIME STEP (min)**	**PRESS CYCLE**	**TRUCK LOAD**	**BUNDLE**	**COMING FROM**	**GOING TO**
				SHIFT 2, DAY 15			
Downtime	80	163	-			-	-
33994	168	497	68	9	84	Raw material	Press Stacking Area 2 Position 3
34009	168	497	68	9	85	Raw material	Press Stacking Area 2 Position 2
34011	168	497	68	9	85	Raw material	Press Stacking Area 2 Position 1
Downtime	255	291	-			-	-
Downtime	295	411	-			-	-
Downtime	414	493	-			-	-
				SHIFT 3, DAY 15			
34008	17	120	69	9	85	Raw material	Press Stacking Area 2 Position 4
34010	17	120	69	9	85	Raw material	Press Stacking Area 2 Position 3
34012	17	120	69	9	85	Raw material	Press Stacking Area 2 Position 5
Downtime	104	115	-			-	-
34007	120	662	70	9	86	Raw material	Press Stacking Area 2 Position 2
34017	120	662	70	9	86	Raw material	Press Stacking Area 2 Position 1
Downtime	207	223	-			-	-
Downtime	229	328	-			-	-
Downtime	334	441	-			-	-
Downtime	447	554	-			-	-
				SHIFT 1, DAY 16			
Downtime	80	176	-			-	-

Appendix I - Scheduling simulation results

#	JIT	*tld*	*Pb*	*Cb*	*Fb*	*Ms*	*Js*	Project time (min)	Panel shuffles				Press Down Time (min)	Max. bundle finish (min)	Avg. bundle finish (min)
									Press	CNC	FQC	Total			
1	on	1	2	2	2	10	3	22330	0	0	145	145	14521	16042	2466
2	on	2	2	2	2	10	3	22330	0	0	145	145	14826	16042	2577
3	on	3	2	2	2	10	3	22330	0	0	145	145	14826	16042	2577
4	on	4	2	2	2	10	3	22330	0	0	145	145	14826	16042	2577
5	on	5	2	2	2	10	3	22330	0	0	145	145	14826	16042	2577
6	on	3	3	2	2	10	3	22330	0	0	138	138	14266	21373	2908
7	on	3	4	2	2	10	3	22330	0	0	140	140	13826	21237	3448
8	on	3	5	2	2	10	3	22330	0	0	142	142	13004	21551	3873
9	on	3	4	3	2	10	3	22330	0	0	140	140	13826	21237	3448
10	on	3	4	4	2	10	3	23330	0	0	140	140	13826	21237	3448
11	on	3	4	5	2	10	3	23330	0	0	140	140	13826	21237	3448
12	on	3	4	4	3	10	3	23330	0	0	139	139	13822	21237	3407
13	on	3	4	4	4	10	3	23330	0	0	139	139	13822	21237	3407
14	on	3	4	4	5	10	3	23330	0	0	139	139	13822	21237	3407
15	on	3	4	4	4	10	4	23330	0	0	131	131	13868	21183	2565
16	on	3	4	4	4	10	5	23330	0	0	123	123	13826	21237	2855
17	on	3	4	4	4	10	6	23330	0	0	126	126	13826	21237	2793
18	on	3	4	4	4	12	3	23330	0	0	131	131	13822	21237	3407
19	on	3	4	4	4	15	3	23330	0	0	131	131	13822	21237	3407
20	on	3	4	4	4	20	3	23330	0	0	131	131	13822	21237	3407
21	off	1	2	2	2	10	3	22325	185	20	153	358	12971	21726	2780
22	off	2	2	2	2	10	3	22325	174	16	149	339	13281	21726	3086
23	off	3	2	2	2	10	3	22325	174	16	149	339	13265	21726	3086
24	off	4	2	2	2	10	3	22325	174	16	149	339	13265	21726	3086
25	off	5	2	2	2	10	3	22325	174	16	149	339	13265	21726	3086
26	off	3	3	2	2	10	3	22325	181	23	139	343	12319	21478	3446
27	off	3	4	2	2	10	3	22325	176	27	222	425	10876	21259	4898
28	off	3	5	2	2	10	3	22325	164	34	191	389	9884	18915	3524
29	off	3	4	3	2	10	3	22325	176	27	222	425	10876	21259	4898
30	off	3	4	4	2	10	3	22325	176	27	222	425	10876	21259	4898
31	off	3	4	5	2	10	3	22325	176	27	222	425	10876	21259	4898
32	off	3	4	4	3	10	3	22325	178	31	217	426	10872	21259	4819
33	off	3	4	4	4	10	3	22325	175	29	228	432	10893	21259	4824
34	off	3	4	4	5	10	3	22325	177	29	223	429	10848	21259	4817
35	off	3	4	4	4	10	4	22325	167	25	182	374	11007	21203	3856
36	off	3	4	4	4	10	5	22325	164	22	123	309	11018	21245	3580
37	off	3	4	4	4	10	6	22325	145	21	205	371	10792	21135	4828
38	off	3	4	4	4	12	3	22325	174	24	146	344	10159	21259	4371
39	off	3	4	4	4	15	3	22325	186	22	215	423	8842	21259	4922
40	off	3	4	4	4	20	3	22325	192	25	207	424	6801	21259	4700

#	JIT	*tld*	*Pb*	*Cb*	*Fb*	*Ms*	*Js*	Project time (min)	Panel shuffles				Press Down Time (min)	Max. bundle finish (min)	Avg. bundle finish (min)
									Press	CNC	FQC	Total			
41	on	1	2	2	2	10	3	21766	0	0	112	112	13543	21523	3790
42	on	2	2	2	2	10	3	21766	0	0	133	133	13823	21523	3790
43	on	3	2	2	2	10	3	21766	0	0	133	133	13823	21523	3790
44	on	4	2	2	2	10	3	21766	0	0	132	132	13823	21523	3790
45	on	5	2	2	2	10	3	21766	0	0	132	132	13823	21523	3790
46	on	3	3	2	2	10	3	21766	0	0	164	164	13171	21523	5436
47	on	3	4	2	2	10	3	21766	0	0	156	156	12178	21523	5229
48	on	3	5	2	2	10	3	21766	0	0	170	170	10796	21523	5203
49	on	3	4	3	2	10	3	21766	0	0	156	156	12178	21523	5229
50	on	3	4	4	2	10	3	21766	0	0	156	156	12178	21523	5229
51	on	3	4	5	2	10	3	21766	0	0	156	156	12178	21523	5229
52	on	3	4	4	3	10	3	21766	0	0	155	155	12178	21523	5229
53	on	3	4	4	4	10	3	21766	0	0	155	155	12178	21523	5229
54	on	3	4	4	5	10	3	21766	0	0	155	155	12178	21523	5229
55	on	3	4	4	4	10	4	21766	0	0	129	129	12151	21053	4427
56	on	3	4	4	4	10	5	21766	0	0	126	126	12132	21515	4670
57	on	3	4	4	4	10	6	21766	0	0	110	110	12152	21038	4497
58	on	3	4	4	4	12	3	21766	0	0	133	133	12184	21523	5221
59	on	3	4	4	4	15	3	21766	0	0	123	123	12514	21523	4079
60	on	3	4	4	4	20	3	21766	0	0	123	123	12514	21523	4079
61	off	1	2	2	2	10	3	21785	160	24	113	297	11953	21346	3301
62	off	2	2	2	2	10	3	21785	151	19	114	284	12327	21346	3802
63	off	3	2	2	2	10	3	21785	151	19	114	284	12327	21346	3802
64	off	4	2	2	2	10	3	21785	151	19	114	284	12327	21346	3802
65	off	5	2	2	2	10	3	21785	151	19	114	284	12327	21346	3802
66	off	3	3	2	2	10	3	21785	135	23	180	338	11213	21346	4562
67	off	3	4	2	2	10	3	21785	164	20	151	335	10251	21346	4112
68	off	3	5	2	2	10	3	21785	131	24	196	351	8914	21346	5057
69	off	3	4	3	2	10	3	21785	164	20	151	335	10251	21346	4112
70	off	3	4	4	2	10	3	21785	164	20	151	335	10251	21346	4112
71	off	3	4	5	2	10	3	21785	164	20	151	335	10251	21346	4112
72	off	3	4	4	3	10	3	21785	164	19	152	335	10273	21346	4126
73	off	3	4	4	4	10	3	21785	165	18	146	329	10254	21346	4124
74	off	3	4	4	5	10	3	21785	165	18	146	329	10254	21346	4124
75	off	3	4	4	4	10	4	21785	168	18	105	291	10291	21346	4131
76	off	3	4	4	4	10	5	21785	168	21	105	294	10278	21346	4082
77	off	3	4	4	4	10	6	21785	170	14	122	306	10258	21338	4166
78	off	3	4	4	4	12	3	21785	165	19	119	303	9275	21346	4179
79	off	3	4	4	4	15	3	21785	163	26	154	343	8013	21346	4618
80	off	3	4	4	4	20	3	21785	166	24	190	380	5967	21346	4772