A Framework for Design of Panelized Wood Framing Prefabrication Utilizing Multi-panels and Crew Balancing

by

Ziad Ajweh

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

Department of Civil and Environmental Engineering
University of Alberta

Abstract

The construction industry is highly competitive and continually striving towards improving its performance in terms of time, cost, quality, and safety. Improved performance is essential to survival in today's construction market. In this regard, measuring productivity can facilitate improved performance by establishing performance baselines, identifying problems, optimizing resources, creating dashboards and benchmarking, and evaluating improvement measures. Obtaining a framework for measuring productivity in construction confronts a problem within the complexity of the construction industry's features and variability.

The focus of this research is on establishing labour productivity modules for the fabrication stage of panels in panelized home buildings. Numerous techniques, such as lean concepts, last planner system, and line of balance are applied in order to assess production line performance in the machine assembly line, while a regression model is used to estimate productivity in the manual assembly line. Both modules are implemented and verified in a home building manufacturer in Edmonton in order to improve the overall performance of the assembly lines.

Preface

This thesis is an original work by Ziad Ajweh. No part of this thesis has been previously published.

The literature review in Chapter 2 includes a reference to a collaborative study based upon which Ziad Ajweh co-authored a paper along with Dr. Bashar Younes, Dr. Ahmed Bouferguène, Dr. Mohamed Al-Hussein, and Dr. Haitao Yu. This paper is cited as part of the thesis' literature review, but does not contain material published as part of this thesis. The author's contributions to this paper involved developing the simulation model and contributing to the analysis of the results.

The paper is cited in the list of references as follows: Younes, B., Bouferguène, A., Al-Hussein, M., Yu, H. & Ajweh, Z. (2013). "Aged-invoice management: a lean and post-lean simulation approach." *4th Construction Specialty Conference*, Montreal, Quebec, Canada.

Acknowledgements

I would like to thank Dr. Mohamed Al-Hussein and Dr. Mustafa Gül for their invaluable supervision. I would also like to extend my gratitude to the Landmark team: Mr. Reza Nasseri (CEO), Mr. Curt Beyer (VP), Mr. Michael Schmidt (Plant Manager), Dr. Haitao Yu (Senior Researcher), Mr. Alfred Porsche (Drafting Manager), Mr. Francisco Villarroel (Manufacturing Engineer) in addition to the production managers, engineers, drafters, schedulers, technicians, crew leaders, labour, and others at Landmark Building Solutions, for their kindness, supervision, collaboration, support, and assistance.

I owe my deepest gratitude to my parents for instilling in me the desire to learn and the motivation to succeed. I would like to express my appreciation to all others who supported me, both directly and indirectly, through friendship and encouragement. I would like to express my gratitude to NSERC, which provided funding for this research. Many thanks to all those within the Construction Engineering and Management Group as well as the Department of Civil and Environmental Engineering at the University of Alberta for their support and kind words.

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

ANN Artificial Neural Network

CAD Computer-Aided Design

CAM Computer-Aided Manufacturing

CEO Chief Executive Officer

CII Construction Industry Institute

CIM Computer-Integrated Manufacturing

CMHC Canada Mortgage and Housing Corporation

CMHI Canadian Manufactured Housing Institute

CNC Computerized Numerical Control

CP Collected Productivity

CSA Canadian Standards Association

CURT The Construction Users Roundtable

EPMS Engineering Productivity Metric System

FMS Flexible Manufacturing System

IFC Issued For Construction

IPA Independent Project Analysis

KPIs Key Performance Indicators

LOB Line of Balance

LPS Last Planner System

MBI Modular Building Institute

NIST National Institute of Standards and Technology NIST

NAHB National Association of Home Builders

PMR Productivity Model Results

PQA Product Quantity Analysis

VF Validation Factor

VSM Value Stream Map

Chapter 1 : Introduction

1.1 Motivation

In recent decades, North America has undergone drastic changes in housing production and associated costs. Based on information from Canada Mortgage and Housing Corporation (CMHC), between 2004 and 2012 annual expenditures on residential construction increased in Canada by approximately 51% (from $69,571 million to $105,109 million) (CMHC, 2013). During the same time period, the National Association of Home Builders (NAHB) indicated that the total construction cost for single-family homes had increased by 10% (from 51.7% to 61.7% of the total sales price). However, based on roughly the same total sales prices between 2002 and 2013, the overall profit had decreased 2.7% (from 12.0% to 9.3%) (NAHB, 2014). In other words, builders' profit margins dropped while their construction costs were elevated.

Homebuilders understand that, in diminishing the cost by improving the capacity of labour throughput, profit can be gained. Theoretically, the latter could be achieved by refining the capacity of labour throughput, increasing the utilization of facilities and machines, and reducing waste.

Given that construction productivity is a broad topic, researchers have published numerous articles in this field. Within this body of research, no explicit consensus has been reached on the most suitable productivity measuring system or model.

Contrary to popular belief, defining, measuring, or improving productivity in construction is a challenging task (Modular Building Institute (MBI), 2010). The crucial problem revolves around the complexity of the construction industry's features and variability. It is thus necessary to develop a simple production model for the homebuilding industry. This model should reflect the traditional techniques used by other construction sectors in order to plan and control the home building process (Yu, 2010).

1.2 Research Objectives and Goals

This research focuses on panelized construction and the fabrication stage. The scope of work encompasses the fabrication stage at the factory level. This research is built upon the following hypothesis: ***"Design of panelized wood framing production line utilizing multi-panels and***

crew balancing enhances labour productivity and profitability". The main objective of this research is to develop a framework to improve labour productivity for panelized wood-framing in the housing industry. By developing a productivity model, a panelized company can define an appropriate baseline of performance. Defining the proper performance baseline leads to subsequent application of improvement tools, including lean principles, last planner, and line of balance. Furthermore, establishing this benchmark aids companies in the decision-making process for estimating, allocating resources, arranging shifts, tracking productivity and throughputs, identifying possible bottlenecks, and implementing improvements. A better assessment of profitability will thus be obtained. In analyzing the data, total cycle time, takt time, lead time, and total man-hours and costs can be attributed to a particular model or job.

The data will be acquired through the use of historical data and time study. This study focuses on two production lines based on two types of production mechanisms: machine-based and manual-based, with a comparative study of the panel production of these two lines at the fabrication stage presented.

Accordingly, the main targets can be listed as follows:

- Identifying the main factors that influence products in the machine-based and manual assembly lines for panelized construction.
- Decreasing resource waste in the machine-based and manual assembly lines by determining the required resources based on defined daily demand.
- Improving the overall performance of the assembly lines.

1.3 Thesis Organization

This thesis consists of five chapters. Chapter 2 presents a literature review and background. The literature review on productivity includes numerous definitions of measurements and tools, as well as a summary of various productivity studies. In addition, the literature review contains a list of industry concepts and a glossary of items used in this thesis. Additional background information is presented in Chapter 2, including an introduction to manufacturing technology, a comparison of construction and manufacturing, and a discussion of the benefits to handling factory-built homes. Chapter 3 consists of three main elements: (1) a comparative study between manual and machine-based stations in off-site construction; (2) identification of the research processes and methodology road map, as well as general key-factors impacting the productivity in panelized construction; and (3) determination of productivity models' architecture and parameters. Chapter 4 includes the application of the proposed research processes and methodology road map, including: (1) a description of the processes and activities in panelized construction; and (2) a description of a wall panel's production features and characters. The first case study focuses on the machine assembly line. It considers the following: integrated data collection, product quantity analysis, product cycle time, and exploring implementation strategies within possible scenarios using simulation. Following the verification of the simulation model, certain scenarios are analyzed based on the simulation model's outputs. The second case study concerns the manual production of panels. Similar to the previous case study, a study is carried out on the manual assembly line to estimate the required man-hours in this station. This includes introducing the production family matrix in the manual station, integrating the data collection, building the regression model, verifying the regression model, and implementing the outcomes. Chapter 5 offers a general conclusion, academic and industrial research contributions, research limitations, and recommendations for future research.

Chapter 2 : Literature Review and Relative Background

The development of manufacturing technology and the examination of the research were performed in the context of productivity in construction. Prior to defining the concepts within the glossary, it is imperative to consider the development of manufacturing technology. It is equally important to evaluate the construction productivity in comparison to manufacturing productivity.

2.1 Literature on Productivity Measurement in Construction

Productivity is defined as, "something that everyone wants to improve, but understanding that 'something' and knowing how to improve productivity is a complex subject in practice" (Armentrout, 1986). That said, "productivity" is difficult to convey or measure (MBI, 2010; Armentrout, 1986). In his PhD thesis, Stefan Tangen discussed many productivity-related aspects and triple-*p* (Productivity, Profitability, and Performance) models (Tangen, 2004). Using various angles and references, he summarized, presented, and organized various definitions of productivity, as presented in Table (2-1).

Table 2-1: Examples of Verbal and Mathematical Definitions of Productivity (Tangen, 2004)

Definition	Reference
Productivity = Faculty to produce	(Littré, 1883)
Productivity is what man can accomplish with material, capital and technology. Productivity is mainly an issue of personal manner. Productivity is an attitude that we must continuously strive ourselves and the things around us.	(Japan Productivity Centre, 1958 (from Björkman, 1991))
Productivity = Units of output / Units of input	(Chew, 1988)
Productivity = Actual Output / Expected Resources Used	(Sink and Tuttle, 1989)
Productivity = Total income / (Cost + goal profit)	(Fisher, 1990)
Productivity = Value added / Input of production factors	(Aspén, 1991)
Productivity is defined as the ratio of what is produced to what is required to produce it. Productivity measures the relationship between output, such as good and services produced, and inputs that include labour, capital, material and other resources.	(Hill, 1993)

Productivity (output per hour of work) is the central long-run factor determining any population's average of living.	(Thurow, 1993)
Productivity = the quality or state of bringing forth, of generating, of causing to exist, of yielding large result or yielding abundantly.	(Koss and Lewis, 1993)
Productivity means how much and how well we produce from the resources used. If we produce more or better goods from the same resources, we increase productivity. Or if we produce the same goods from lesser resources, we also increase productivity. By 'resources', we mean all human and physical resources, i.e., the people who produce the goods or provide the services, and the assets with which the people can produce the goods or provide the services.	(Bernolak, 1997)
Productivity is a comparison of the physical inputs to a factory with the physical outputs from the factory.	(Kaplan and Cooper, 1998)
Productivity = Efficiency * Effectiveness = Value adding time /Total time	(Jackson and Petersson, 1999)
Productivity = (Output / Input) * Quality = Efficiency * Utilisation *Quality	(Al-Darrab, 2000)
Productivity is the ability to satisfy the market's need for goods and services with a minimum of total resource consumption.	(Moseng and Rolstadås, 2001)
Productivity refers to the ratio between the actual result of the transformation process and the actual resources used.	(Jan van Ree, 2002)
Productivity = Customer value / Used resources	Discussed definition within this research project (K. Björklund)

There are several ways to control productivity, particularly through using one of the three following distinct approaches: retrospective, reactive, and proactive. The main differences in the latter approaches are generally found while gathering data and in the problem-solving process. Within the proactive approach, the data is collected first and the related information impacts the productivity of activities prior to actually beginning this activity or process. Within the reactive approach, however, the collected data is gathered simultaneously to the process execution. Lastly, in the retrospective approach, the gathered data and information is gathered from previous projects. Based on the approach selected to gather the data, solving problems in construction processes can be unstable. While the reactive and retrospective tactics seek to resolve problems rather than avoid them, the proactive approach does just the opposite and avoids the possibility of complications in the first place (Gao et al., 2012).

2.1.1 Productivity Measurement

Measurement Perceptions: measurement is defined as "a quantitatively expressed reduction of uncertainty based on one or more observations" (Hubbard, 2010). Each measurement is derived from unique objectives. As such, determining a clear objective results in an efficient measurement. Measuring a particular item is significant due to the fact that one cannot speak to something without having a certain degree of knowledge. This approach can be applied to all aspects of life. Measurement can also be defined as the allocation of numbers or symbols to "objects, events, people, characteristics, and so forth according to specific set of rules" (Johnson and Christensen, 2008). People normally try to measure things with the aim of figuring out if there is any occurred problem. Charles Kettering is an American inventor and holds 300 patents, including the electrical ignition of automobiles. Kettering has famously stated that, "A problem well stated is a problem half solved […]" (Charles Kettering, as cited in Hubbard, 2010).

Although construction companies are often faced with challenges, the main obstacle they face is based on how measurement occurs, what the baseline of production or productivity is, how the performance is, and what improvements can be reached. When a Chief Executive Officer (CEO) or a manager begins questioning the latter issues, it signifies that this particular company will achieve various gains, resulting in the development of a management system, the improvement of the capacity of labour throughput, an increase in the utilization of facilities and machines, and the effort of disposing of as much waste as possible.

The above is attainable through the implementation of appropriate methods. Although some measurements may appear immeasurable, as a result of misunderstanding the essential measurement methods, the individual must understand that the essential measurement methods, including a variety of sampling procedures or a number of controlled experiments, can be employed to resolve the problems (Hubbard, 2010).

Lord Kelvin, British physicist and a member of the House of Lords was stated, "When you can measure what you are speaking about, and express it in numbers, you know something about it;

but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science" (Kelvin, as cited in Hubbard, 2010).

Tangen offered two recommendations to design a successful measure. The first recommendation is that the design is considered beneficial, valuable, and useful to the organization. The second proposal is that the organization should use the design without wasting any resources in order to collect information (Tangen, 2004). In other words, the more beneficial the information is, and the more it is utilized to its greatest potential, the more successful a company will be in accomplishing a certain standard of performance. In addition to the quality of the information, the information regained from a measure should also be directed to the correct person at an optimal time, resulting in a more efficient way of managing the information and data.

Consequently, as cited in Tangen's work, Tangen, Kennerley, Neely et al., Kaplan and Norton, and Globerson listed many considerable points regarding the purpose of measure and its equations, summarized as follows:

- The main focus in the equation is employed first to the objective criteria before subjective.
- Trying to use ratios rather than fixed numbers.
- Demanding to apply group measures instead of individual performance measures.
- Ideally, the equation is easily measured, easily understood, precise as possible and planned with people whose performance is measured.
- The equation should not be used to support negative behaviours indirectly, or to be derived from ambiguous weightning.

Construction Productivity Measurement: contractors within the construction industry require the proper tools to improve performance through external or internal benchmarking (Park et al., 2005). Moreover, whenever progress is required, improving the performance can be accomplished at a later time. Measuring productivity may not result directly from improvements to performance. In addition to other researchers, the authors quoted in the Construction Industry Institute (CII) revolved their research around productivity in construction. As such, few attempts were made to establish a baseline productivity system.

In contrast, a number of researchers disagree on a standard productivity measurement system (Park et al., 2005). As cited in Park et al.'s work, Oglesby et al., stated that this may be as a result of the difficulties to achieve a standard method to assess construction labour productivity due to the complexities and features of construction projects (Oglesby et al., 1989). Furthermore, the Construction Users Roundtable (CURT) recommended two general types of construction measures: results measures and in-process measures. The former tracks outcomes after the fact, whereas the latter tracks the leading indicators and forestalls problems before they occur (CURT, 2005).

Two common measures of productivity are used: single-factor labour productivity and multi-factor productivity (Huang et al., 2009; Slack et al., 2010). Slack et al. defined single-factor productivity as a ratio of output from the operation to one input to the operations. The authors also indicated that multi-factors productivity is a ratio of output from the operation to all inputs to the operation (Slack et al., 2010).

$$\boldsymbol{Single\ factor\ productivty = \frac{Output\ from\ the\ operation}{One\ input\ to\ the\ operation}} \qquad [\mathbf{1}]$$

$$\boldsymbol{Multi\ factors\ productivty = \frac{Output\ from\ the\ operation}{All\ input\ to\ the\ operation}} \qquad [\mathbf{2}]$$

A number of researchers and/or managers prefer to use the term of engineering productivity. Engineering productivity is explained as a ratio of direct engineering work hours to the engineering outputs, as measured by Issued for Construction (IFC) quantities (Kim, 2007; Liao et al., 2009).

Based on the construction process, Huang et al. stated that the measures of construction productivity must be reviewed on three levels, as follows: task, project, and industry (Huang et al., 2009).

The task level refers to specific construction activities with single factor measures and focuses on labour productivity (Huang et al., 2009). In the R.S. Means book "Building Construction Cost Data, it states that, based on an eight-hour day, typical task-level metrics estimate how much a given output produces by the nominated crew, during daylight hours, in moderate temperatures. The labour cost, on the other hand, is based on productivity data that is uninfluenced by abnormal variations and reflects a typical average. Cost estimations can be done based on a square foot area of a wall or a plan, which can also be considered as a single factor measures within typical task-level metrics (Mewis et al., 2007).

The project level of productivity measures is the number of tasks required for the construction of a new facility or the renovation of an existing, already built facility. Within the project level, productivity measures are beneficial in calculating how an individual project compares to the overall average in the reference data set. The project level's purpose is for internal uses, such as the cost estimation during bid preparation (Huang et al., 2009).

The above authors also stated, "At the industry level, productivity—the amount (or value) of output produced per unit of input—provides a measure of industrial efficiency" (Huang et al., 2009). They indicate that growths in labour productivity are referred to as increases in labour quality, worker efforts, and other factors that extend to technology or increase capital utilization. Although many studies were published about factors that impact construction productivity, Huang concluded that the four factors were: skilled labour availability, technology utilization, offsite fabrication and modularization, and the use of industry best practices (Huang et al., 2009).

Manufacturing Productivity Measurement: using eight algorithms, Mundel presented an approach to measure the productivity of a manufacturing organization. The algorithms are assigned with forms to make it simpler for firms to make the computations. Mundel prefers applying the terms of the eight algorithms rather than one long equation, which leads to abridging the calculations. This simplifies the analysis and overall process for a manager or user (Mundel, 1985). Mundel's approach is based on eight concepts, which include the following:

- Resource inputs, partial, capital costs.
- Resource inputs, partial, energy, tooling, and direct labour.
- Resource inputs, partial, indirect labour.
- Sum of resource inputs.
- Outputs, partial, direct values.
- Outputs, partial, overhead, energy, tooling, and labour earned.
- Sum of outputs.
- Computation of the productivity measure.

Micro and Macro–Measures: reaching the right decisions in management often requires data based on both micro- and macro- levels of measuring. This data is used as a powerful tool in decision-making and management. Micro-measures are the measures that have taken place at the separate levels of the project, leading to actual project outcomes with predictable results, as chosen in specific goals of the project.

Macro-measures are the measures that have been established for a benchmarking purpose to compare and analyze results on a larger scale. Benchmarking, which can be external within the company or internal outside the company, is typically accelerated and accomplished for for-profit benchmarking companies, such as the Independent Project Analysis (IPA) or by industry associations like the CII or CURT (CURT, 2005).

2.1.2 **Productivity Studies**

Many researchers have studied productivity in numerous construction sectors. A number of previous productivity studies in different construction sectors were summarized as followings:

- Song and AbouRizk indicated that labour productivity evaluations heavily depend on either the available productivity data or a distinctively associated experience (Song & AbouRizk, 2008). They discussed different productivity data sources, including: contract documents, time study, progress reports, and project databases. A number of productivity modelling techniques were presented, such as: regression models, expert systems, artificial intelligence, and simulation. As demonstrated in Figure 2-1, a framework for productivity modelling was established, using historical data. Song and AbouRizk presented two productivity modelling techniques used for model steel drafting and steel fabrication productivities, including the Artificial Neural Network (ANN) and simulation (Song and AbouRizk, 2008). Song and AbouRizk offered criteria shaping a proper output measurement method. The criteria included: achieving a high correlation between a quantifiable output measurement and labour hours, separating output measurement from productivity—influencing factors such as labour skills, and shaping the output measurement to be tractable and cost effective to execute (Song & AbouRizk, 2008). The authors stated that historical data must be collected based on the first criterion because both other criteria can be assessed applying subjective judgment. Their methodology was subsequently developed and applied to model steel drafting and fabrication productivities.

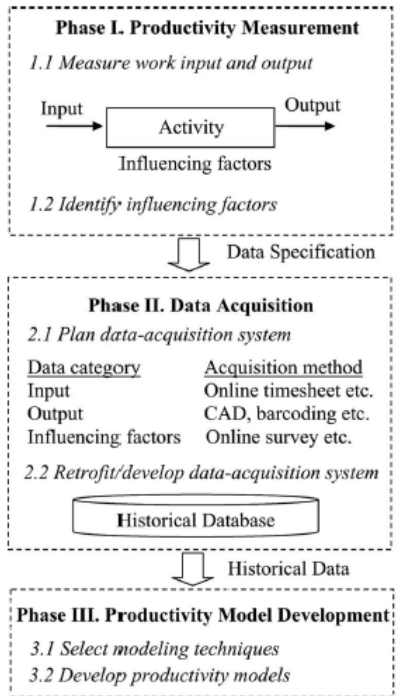


Figure 2-1: Framework for Productivity Model Using Historical Data (Song and AbouRizk, 2008)

- Dissanayake et al. developed a model based on a hybrid neural network merging with a general regression neural network, ambiguous logic, and genetic algorithms to recognize and quantify factors manipulate construction labour productivity and to predict the performance (Dissanayake et al., 2005). This model was developed and implemented for hydro testing of pipe fabrication in a pipe fabrication yard.
- Lu established the ANN model using estimating tools to provide estimators with information on labour productivity in bidding stages. He extended his model to measure and analyze labour productivity in industrial construction. Lu’s model was used as a case study for pipe installation in the fields and spool fabrication in the fabrication shop (Lu, 2001).
- Sonmez and Rowings presented a productivity model about concrete pouring, formwork, and concrete finishing tasks. The authors developed the model based on neural networks and regression modelling techniques. Their research, which was heavily based on productivity issues, discovered that many factors impact each task with variations in the

effects. With this, different factors can have a similar influence on numerous tasks but with different rates of impact. Models containing only some noteworthy factors are more efficient and more predictable than others, depending on many insignificant factors (Sonmez and Rowings, 1998).

- Based on the statistical analysis of the piling process regression, Zayad and Halpin attempted to create regression models to schedule and price out pile construction projects. The regression models are used to assess piling processes productivity, cycle time, and cost, while considering the effects of numerous piling process factors (Zayed and Halpin, 2005).
- Chao and Skibniewski took a different approach to estimate construction operating productivity. They presented their experiment using the neural network model. The neural network model demonstrated the ability of modelling the multifaceted relationships between the productivity of operations and job conditions, resulting in the determination of rational estimation (Chao and Skibniewski, 1994).
- For estimating purposes, AbouRizk established a model based on an ANN as an estimation of labour production rates for industrial construction activities. The latter corresponded with existing estimating practices. As part of this model, a two-stage artificial neural network is used to predict, "[an] efficiency multiplier (an index) based on input factors identified by the user." The authors also stated that a multiplier is directed as to regulate an average production rate, offered in man-hours/unit on a specific project (AbouRizk et al., 2001).
- McCabe et al. developed a model based on the integration between the belief network (Bayesian) and the computer simulation as an automated approach for improving construction operations and overall performance (McCabe et al., 2001).
- As a related topic to panelized construction process improvement, in her MSc thesis, Leila Shafai presented a simulation based process flow improvement for wood framing home building production lines. Shafai formulated the time required for each task based on linear regression models, then using those regression as inputs for simulation model. The simulation model was used later for process improvement plans and mainly reducing the overall home completion time (Shafai, 2012).

2.2 Literature on Management Items Related to Productivity in Construction

2.2.1 Profitability

There is a difference between the concepts of "profitability" and "profit." "Profit" is defined as the summary for what a company accomplished in the past. "Profitability" is based on a company's capability to gain profit from projects in the future (Tamer et al., 2012). There is no significant correlation between a large firm and profitability, given that profitability is not based on the firm size. The latter can be attributed to the fact that large firms can contribute using greater resources (Yee, et al.2006). Unambiguously, "profitability" and "productivity" are mutually dependent, but "profitability" can be impacted by spent cost for the inputs and the outputs charge (Tangen, 2004). Improving productivity can result in competitive advantages and increased profitability (Liao et al., 2009; Ebrahimy & Rokni, 2010).

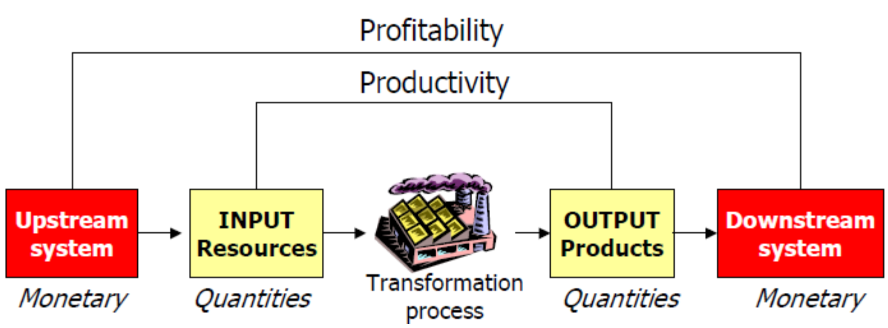


Figure 2-2: Major Aspects Influencing Profitability (Tangen, 2004)

Other factors can influence "profitability," such as changes in productivity price recovery or the quantity of resources concluding in the change of profit (Tangen, 2004 & Stainer, 1997). A supply chain, also known as time compression, can reduce costs and increase revenues. This means that speeding up the flow of materials and products down the chain can improve the operational efficiency of supply chain and increase the profitability (Slack et al., 2010).

2.2.2 Performance

Various managers and/or researchers within the engineering industry state that using the term "performance" rather than "productivity" in a case performance offers a more unambiguous understanding of the issues. According to Armentrout, it is imperative to relate productivity management in terms of engineering management. Armentrout states that accomplishing "productivity measurement" within an engineering organization can present challenges as well as have negative impacts. As such, it is preferable to refer to "productivity measurement" as "performance measurement" because it identifies the desired results more clearly (Armentrout, 1986). Performance measures are divided into seven categories, as follows: effectiveness, efficiency, quality, productivity, quality of work life, profitability, and innovation (Armentrout, 1986).

A strong correlation exists between productivity management and productivity measurement. Whether or not is feasible to measure productivity management directly, it can be achieved within an engineering organization (Armentrout, 1986). Additional studies, particularly those of Tangen and Slack's research, state that performance is more extensive than productivity (Tangen, 2004; Slack et al., 2010). As shown in Figure 2-3, in addition to productivity, performance includes cost objectives and other non-cost objectives, including flexibility, dependability, quality, and speed.

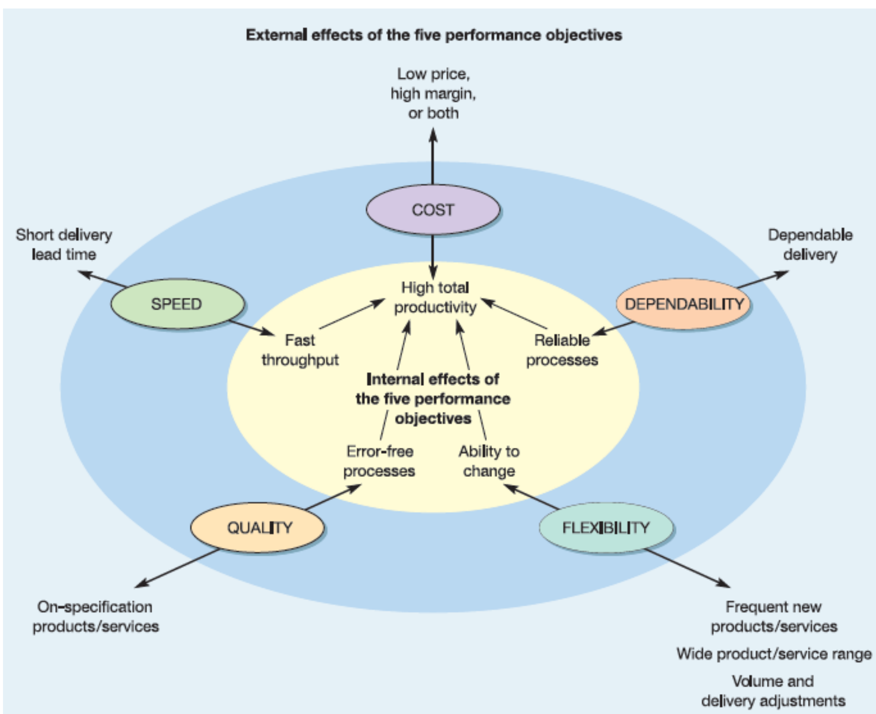


Figure 2-3: Performance Objectives Influence Productivity (Slack et al., 2010)

2.2.3 Effectiveness and Efficiency

Typically, efficiency relates to the utilization of a specific operation. Efficiency is presented as a ration, which compares the minimum resources required to perform a specific process, or as an operation, wherein the resources are used for the required operation. However, effectiveness is generally connected to the formed value for the client as well as to the desired manufacturing system. Effectiveness is presented as the ability of satisfying the foreseen objective (Tangen, 2004). Based on Tangen's studies, the main difference is attributed to the efficiency linked to the internal performance of the operation, also known as inputs, as shown in Figure 2-4. Effectiveness is connected to the external performance, referred to as outputs (Tangen, 2004).

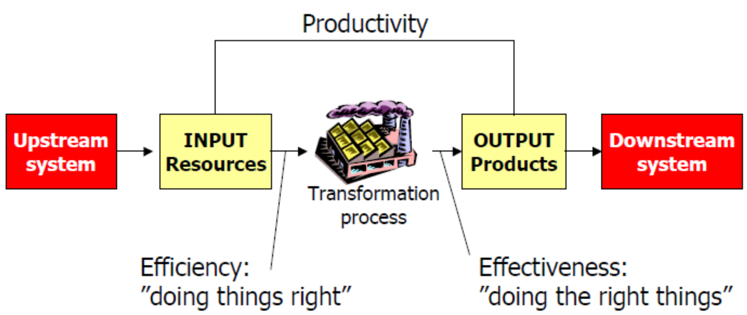


Figure 2-4: Efficiency and Effectiveness Aspects (Tangen, 2004)

2.2.4 The Triple-*p* model

In reviewing the performance terms above, confusion may arise while considering alternate definitions. To minimize any misinterpretation of those terms, and to demonstrate the linkages between the terms, the terminology model is presented. Tangen developed the triple-*p* models to offer a thorough understanding of how productivity, profitability, performance, effectiveness, and efficiency are interrelated and diverse. The triple-*p* model involves the five concepts shown in Figure 2-5 (Tangen, 2005).

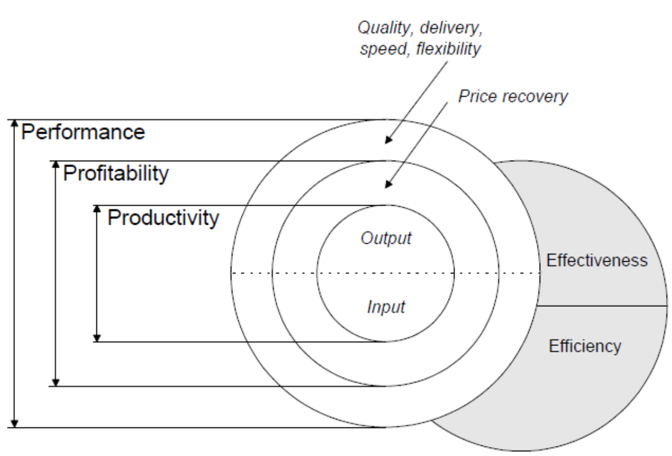


Figure 2-5: The Triple-*p* model (Tangen, 2005)

According to Tangen, the triple-*p* model demonstrates the integration between the five terms and summarizes their relationship (Tangen, 2005). As shown in Figure 2-4, productivity is presented as a ration between inputs and outputs. Profitability is attainable as inputs to outputs, with the addition of pricing factors, inevitably affecting profitability. Performance is attainable through the inclusion of productivity, profitability, and other non-cost factors like flexibility, dependability, quality, and speed. Effectiveness is considered an external performance, signifying how well the anticipated results are accomplished. Efficiency reflects the internal performance of a process and demonstrates how well the utilization of the transformation process‘s resources is done (Tangen, 2005).

2.2.5 **Flexible Manufacturing System (FMS)**

Bernold, a researcher, defined Flexible Manufacturing System (FMS) as, “a production facility consisting of computer- controlled machines or work stations connected by an automated material- handling system, which are used to produce variable parts in low and medium volume” (Bernold et al., 1990).

FMS can result in numerous advantages, including, “increased productivity, lower costs, reduced work-in-progress, decreased waiting times, and increased equipment utilization” (Mayer and Kazakidis, 2007). Applying FMS in construction can be derived from a number of the principle features, including: materiel handling, quality, inspection, manual labour, supervision, automation, tools and machines. FMS is outlined primarily in modular construction, prefabricated houses, and precast concrete.

2.2.6 **Benchmarking**

Benchmarking is typically used as a measuring tool of the performance per unit of measure. Consequently, as cited in Kim’s work, Construction Industry Institute’s (CII’s) defined “benchmarking” as, “[a] systematic process of measuring one’s performance against results from recognized leaders for the purpose of determining best practices that lead to superior performance when adapted and implemented” (CII 1993; CII 2002; Kim, 2007).

Benchmarking, in terms of construction productivity, is regarded as a continual improvement approach. In construction, a standardized Engineering Productivity Metric System (EPMS) must be developed for the purpose of benchmarking (Liao et al., 2009), as engineering productivity is explained as a ratio of direct engineering work hours to the engineering outputs, as measured by Issued for Construction (IFC) quantities (Kim, 2007; Liao et al., 2009).

In recent decades, benchmarking has received a significant amount of consideration (Thomas, 2012). By applying EPMS for benchmarking engineering productivity, performance is afforded at various levels of details. This influences project managers to become better acquainted with possible improvements, resulting in having a greater knowledge on how the usage of resources was effectively done to generate the outputs. Liao et al. presented an EPMS model with numerous categories, such as factors affecting engineering productivity supported by data analyses and industry experience (Liao et al., 2011).

Thomas suggested that, in following the steps related to conducting the labour productivity benchmarking study, a contractor can achieve optimal productivity after recognizing its variability. This includes a focus on creating a productivity baseline (Thomas, 2012). Thomas' steps were summarized, as follows:

- Defining "What" the objective is.
- Determining "How" performances will be weighed up or assessed by identifying project selection and characterizing the key performance indicators (KPIs).
- Verifying "Who" the best is.
- Selecting practices for evaluating.
- Finding a process for selection as a fundamental principle.
- Classifying and identifying "Why" a project is the best based on what mentioned above and described in the previous steps.

2.2.7 Last Planner System

Ballard defined the Last Planner System (LPS) as, "[a] mechanism for transforming what SHOULD be done into what CAN be done, thus forming an inventory of ready work, from which Weekly Work Plans can be formed. Including assignments on Weekly Work Plans is a commitment by the Last Planners (foremen, squad bosses) to what they actually WILL do" (Ballard, 2000).

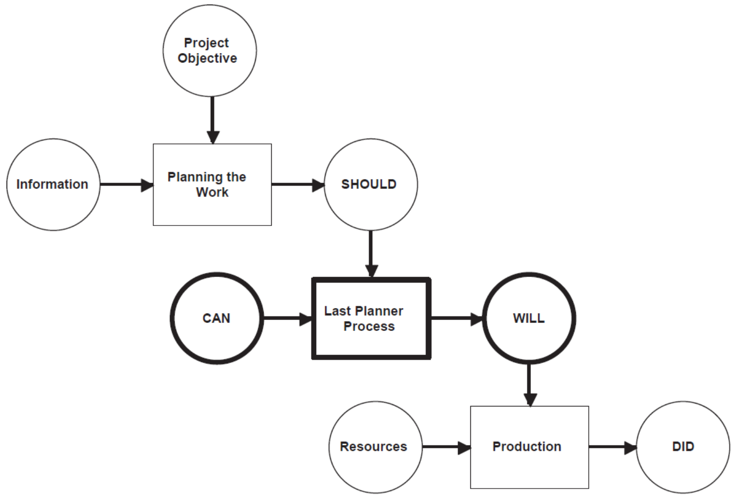


Figure 2-6: The Last Planner System (Ballard, 2000)

Ballard introduced the LPS as one of production management systems related to the planning and control phases. To achieve the desirable targets, the planning stage launches goals and desired sequences of events. The control phase attempts to enforce those events to be approximately exact to the required sequences. Once the established sequence is no longer viable, the control phase participates in planning all over again. When the events fail to conform to plan, learning is initiated by the control phase. In dynamic environments of the production system—an uncertain and variable system—it is difficult to implement reliable planning prior to planning the events (Ballard, 2000). Planning reliability is improved by planning ahead, making ready processes, and committing to dependable labour resources. These items inevitably enhance monitoring and improving the overall production control (Cho et al., 2009; Ballard, 2000).

In construction work processes and events, variations occur as a result of the discrepancies between what was planned for and what actually happened. Such a variation is derived from an amount of uncertainty which arises due to leaving things to chance. Therefore, variation is considered a form of waste, especially when it causes a delay and results in substantial effects on labour productivity (Liu et al., 2011). Construction processes are complex and can contain numerous interdependent tasks. Due to the variation of task durations, downstream tasks are affected, resulting in the interference of the schedule and/or in decreased productivity (Wambeke et al., 2012). With LPS comes uncertainty and constraints on scheduled tasks. Monitoring focuses on planning reliability in LPS, not on financial metrics. An obligation to cost and progress measures is necessary, regardless of whether or not the management decisions are based on planning reliability (Kim and Ballard, 2010).

Managers strive to improve productivity through the implementation of various approaches, including: changing technology, improving methods, enhancing skills, and motiving employees. However, it is important to begin with decreasing the work flow variation from the plan (Liu et al., 2011).

2.2.8 **Line of Balance**

In certain kinds of construction, including pipelines or high-rise buildings, repetitive activities, referred to as "linear construction, occurs. Linear construction involves repetitive units. As other types of constructions, time and cost is effectively managed through different constraints, which imposes the efficiency in balancing the crews as to achieve the aforementioned goals. Line-of-balance (LOB) is a variation of linear scheduling methods allowing the balance of operations for activities to continuously be performed. The clear benefit of the LOB methodology is that it provides a production rate and duration information in the form of easily interpreted graphics (Arditi et al., 2002).

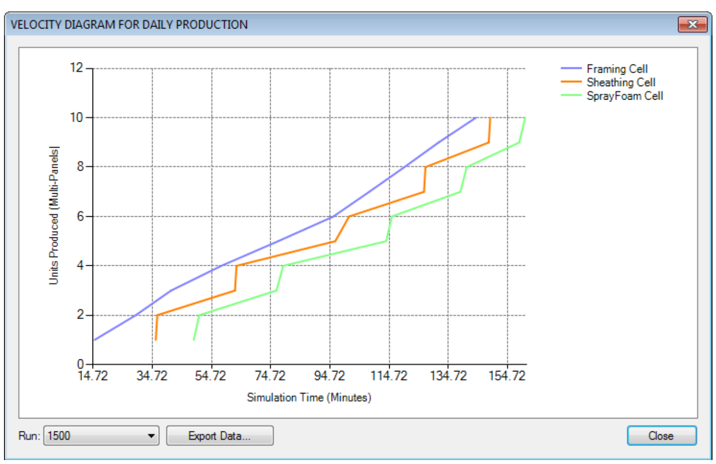


Figure 2-7: Velocity Diagram for Nonlinear Activity Due to Different Multi-panels Sequencing in Panelized Construction

Nonlinear activity is characterized by repetitive operations, where the output of operations is not uniform at every unit. For example, in panelized construction the produced unit can differ based on the customer requirements and house designs. A discrete, or non-repetitive activity, is a one-off activity that does not repeat itself in every unit. For instance, the daily production varies based on the different units' types which each have a different cycle time and pass by different processes. In LOB calculations, nonlinear activities are treated differently due to the variations in the cycle time of these activities, from unit to unit. Similar to the way in which non-linear activities are treated, the discrete activities occur infrequently in repetitive projects. They are handled by inserting them directly into the final LOB diagram, based on their precedence relationships (Arditi et al., 2002). To schedule repetitive projects, logic dependency and resources' constraints are essential (Ammar, 2013; Arditi et al., 2002)

2.2.9 **Value Stream Mapping**

Mike Rother and John Shook's 1998 novel "Learning to See" introduced the concept of value stream mapping (VSM) to the continuous-improvement world (Nash and Poling, 2008). Rother and Shook indicated that, "whenever there is a product from a customer, there is a value stream. The challenge lies in seeing it." The authors continue by stating that VSM is "a pencil and paper tool that helps to see and understand the flow of material and information as a product makes its way through the value stream. What we mean by value stream mapping is simple: Follow a product's production path from customer to supplier, and carefully draw a visual representation of every process in the material and information flow. Then ask a set of key questions and draw a 'future state' map of how value should flow" (Rother and Shook, 2003). Mark Nash and Sheila Poling, authors, state that identifying the areas that require focus for improvements can create a challenge. However, it can be achieved by anyone, regardless of the chosen discipline or approach (Nash and Poling, 2008).

Mapping the Current Value Stream Map (CVSM) facilitates the presentation of what the project team was facing and initiates a starting point to improve, as presented in the Future Value Stream Map (FVSM). Using the VSM can assist in problem-solving and is accomplished by identifying a process or product matrix. Typically, two approaches are used to map the value stream. The first method contributes to the use of a product matrix, while the second approach is used by some companies as a fast-hitting approach to detect the target and immediately start mapping (Nash and Poling, 2008). The matrix approach provides a valuable framework to base the required map. A family is a group of products that pass through similar processing or assembly steps and over common equipment in the downstream processes (Rother and Shook, 2003).

Product family matrix is used to identify group products into families, based on whether they pass through similar steps in the downstream processes.

Fast-hitting approach (ready, aim, map), is accomplished through the detection of the basic contents of a value stream. It is then mapped. As previously mentioned, a target area or an improvement process must be identified (Nash and Poling, 2008). Nash and Poling stated that the fast-hitting approach is beneficial when it aligns with Taiichi Ohno's philosophy "Just do it". This approach is supported by James Womack and Daniel Jones in their book "Lean Thinking" where they indicate that it is advantageous to map the whole value stream for all of the product families.

2.2.10 Post Lean simulation

Simulation analysis is a tool used in construction management and decision support systems. It is a significant factor in automated project planning and control. Given that simulation analysis is used in numerous construction academies and in the research community, it is still important to apply it daily despite its obstacles (AbouRizk et al., 2011). AbouRizk et al. defined simulation analysis as, "[construction] simulation, a fast-growing field, is the science of developing and experimenting with computer-based representations of construction systems to understand their underlying behaviour" (AbouRizk et al., 2011).

Applying lean in an organization provides high quality products and superior customer service in a short time at a low cost. Lean manufacturing theory is based on numerous principles, including (Al-Sudairi et al., 1999; Womack and Jones, 1996):

- Specify value by specific product.
- Identify the value stream for each product.
- Create value flow without interruptions.
- Allow the customer pull value from the producer.
- Consider the operating methods.
- Release resources for delivery when necessary.
- Strive for perfection.

For construction researchers, transferring these philosophies from manufacturing to the construction is an ongoing interest (Al-Sudairi et al., 1999). Accordingly, the construction industry has attempted to benefit from manufacturing technologies, particularly in the implementation of industrialized construction methods, including the application of modular and manufactured buildings. This is realized through the use of lean tools and techniques, such as 5S (sort, straighten, shine, standardize, and sustain), standardized work, takt time planning, variation management, and value stream mapping (Yu et al., 2013). Normally, takt time is derived from available working time and customer's demand. Based on daily planning, takt time equals the available working time per day, divided by the customer's daily demand. Combining lean manufacturing framework and simulation often leads to enhanced performance within an organization. Post-lean simulation is used to test the effectiveness of the projected changes or to test different scenarios prior to execute improvement plans (Younes et al., 2013).

2.3 Relative Background

2.3.1 Manufacturing Technology (MANTECH) Assets

In 1914, Model T Ford cars introduced the concept of "assembly lines." By the 1950s, and as a result of the development of computer sciences and applications, the automated processes of manufacturing technology were motivated in advanced areas, such as: Computerized Numerical Control (CNC), Computer-Aided Design (CAD), and Computer-Aided Manufacturing (CAM). As expected, those areas often lead to a gain in Flexible Manufacturing Systems (FMS) and Computer-Integrated Manufacturing (CIM) (Kanawaty, 1992). The development phases in manufacturing technology are outlined in Figure 2-8.

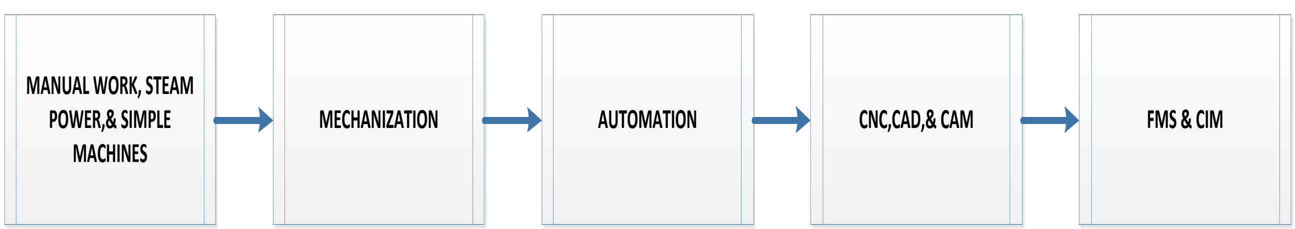


Figure 2-8: Developments in Manufacturing Technology with Regard to Kanawaty's Phases (1992)

To fabricate products, the input of resources is required as is the determination of the methods or the required process. Through a production line or a plant, an output is produced while determining cost, quality, time, productivity, and so forth. A production system can include inputs, such as: human resources (men and women), machines, materials, and methods. However, the outputs could also be determined as productivity, quality, cost, delivery time, safety, environment, or moral (Dennis, 2007).

Based on the construction and manufacturing workforce, each project contains two categories of work: manual/human work and machine work. The use of either type of work is determined based on the chosen methods of fabrication. Machine work is frequently used in manufacturing, while manual work is more commonly used in construction. Typically, a plant implements both processes simultaneously. In other words, replacing one type of process with another one may not result in a successive phase in a consecutive order. Kanawaty stated that, although the cooperation between the manual work, assembly line, and mechanized process may not be consecutive, these three processes can work concurrently through an automated process in the same plant. Kanawaty also affirms that there is a trend towards more amenable production systems (Kanawaty, 1992).

In addition to Kanawaty's studies, Barnes stated that few people support or provide human labour work because machines can do the same work more efficiently and at a lower cost. Barnes predicted that manual work within the construction industry will become negligible in the future. However, machines are not capable of performing all of the same activities as humans. Barnes also states that some activities are performed manually because they are too involved to be mechanized. Additionally, some jobs are performed so rarely that investing in a machine would not be cost-effective. Extraneous factors can affect the extent of use of a machine, including, "quality, yield, material utilization, safety, availability of qualified workers, availability of capital, and the probable life of the product being made" (Barnes, 1968).

2.3.2 A Comparative Study on Construction versus Manufacturing

Performing a comparative study between construction and manufacturing demonstrates the different characteristics of the management of these productivities and their related processes. Sanvido et al. presented many features on the application of computer-integrated manufacturing concepts to construction (Sanvido et al., 1990). Eastman and Sacks compared relative productivity of construction industry sectors for on-site and off-site activities (Eastman and

Sacks, 2008). The comparative studies are summarized based on (Sanvido et al., 1990; Eastman and Sacks, 2008) works, as follows:

- **Products:** Both manufacture and/or construct engineered goods that afford a service (facility) to the user.
- **Building Place:** Manufacturing (off-site); Construction (on-site).
- **Working Environment:** Working environment in manufacturing is well controlled when matched up to the construction's.
- **Working Area:** The position of manufacturing process (equipment, material paths, physical work area, etc.) remains somewhat steady (Constant); where the construction work face is unstable regarding the installation of each.
- **Raw Materials' Processing and Components:** Both contain processing of raw materials and the assembly of many varied components in the final product.
- **Value-Added Content:** Value-added content of the off-site sectors is increasing faster than the on-site sectors.
- **Productivity Growth:** Off-site sectors demonstrate more rapid productivity than on-site sectors, and off-site production of building components has become significantly more labour productive, in contrast to related on-site activities.

As previously mentioned, the focus of this research is on panelized construction, described as a group of factory-built. According to Yu, an extension to the comparative study and points, including differences and similarities between homebuilding and auto-industry, are listed as follows (Yu, 2010):

- The housing market may undergo changes due to various factors, including the economy, land availability, financing, customer's preference, and municipality.
- The majority of the homebuilders' production serves the local market, whether factory-based or traditional stick-built. However, due to market fluctuations, and given the local building codes and permits, added production capacity cannot be contained by demands from markets in other geographical areas.
- The standardization's levels in the automotive industry assembly lines depend on the interchangeability of parts. Standardizing volume production is not the correct approach

for the homebuilding industry as this could result in limitations in the customers' decisions.

- There are similarities between homebuilding and the vehicle manufacturing industry. Typically, both industries sell directly to the final client rather than intermediate customers. The homebuilders' overall production is a high volume of homes every year with different models. Similar to the automotive industry, homebuilding has a similar structure and sequence of operations.
- Automakers and homebuilders apply a comparable strategy plan, wherein the main objective in production strategy planning is to balance the standardization of repetitive production and the flexibility of fulfilling clients' demands (i.e., customization of products). Automakers follow "ship to forecast" or "make to forecast", whereas traditional construction companies allow the customers to identify their desires at the beginning of the information flow by following the "design to order" strategy. Consequently, the construction companies can produce what their customers have requested. To meet the customers' requirements, and to protect themselves from the instabilities in demand, homebuilders abide by a combination of the latter strategies.
- Unlike the manufacturing industry, in order to approach individuals accordingly, lean principles and tools are required to attain a lean enterprise in homebuilding industry. Visual controls are not applied in housing construction as they are in manufacturing.

2.3.3 Comparative Study between Manual and Machine Stations in Off-site Construction

In Landmark Factory, work is performed as manually (labour only), machine work, or both. Processes or activities can add value to the product from a customer standpoint, which is referred to as value-added activities. When no value is added to the product, it is typically categorized as non-value added to assist the value-added processes, which cannot be omitted. Conversely, non-value added does not assist the value-added activities and is deleted. The latter is called "Muda" or "waste".

In the context of this research, machine-based stations are stations that manufacture the products, allowing the machine to work and assist its labour capacity, to maximize productivity. Unless the machines are used for transportations and movements purposes, those stations are used as value-added stations. In panelized construction, the machine-based stations contain automated processes, using and linking technologies such as Computerized Numerical Control (CNC), Computer-Aided Design (CAD), and Computer-Aided Manufacturing (CAM). Manual-based stations depend on labour using simple tools to accomplish their work, which is influenced by human factors, such as: skills, learning curves.

Given that not all construction activities are performed using machines, it is important to consider the manual works. Regardless of the intent to implement automation, certain tasks are still accomplished manually. Moreover, some restrictions may arise when executing the task manually rather than using automation. Those limitations are potentially as a result of plant layout and space, cost issues, production complexity and features, economical concerns.

2.3.4 Factory-Built Housing Industry

Overview

According to the National Institute of Standards and Technology's (NIST) statements, the four main sectors of the construction industry are: residential, commercial/institutional, industrial, and infrastructural. The main differences between the four sectors are the outputs produced, firm size, and the use of technology (Huang et al., 2009). There are two approaches applied towards the production of homes in construction: factory-built (off-site) and on-site built. According to the Canadian Standards Association (CSA), prefabricated wood, closed wall panels systems, and other prefabricated wood buildings are certified by CSA-A277.

Manufactured homes, formerly known as mobile homes, are built and completed at the factory prior to transportation. These homes are certified by the CSA as CSA-Z240, where acceptable (Clayton Research, 2006; CSA, 2008). Based on NAICS industry classification codes, the Canadian government defined Manufactured (Mobile) Home Manufactures with [NAICS 321991], and Prefabricated Wood Building Manufacturing with [NAICS 321992] (Dauphinee & Associates Ltd., 2009).

A factory-built building is defined as, "a modular, manufactured, or panelized building that is built in a manufacturing plant before being transported to its point of installation" (CSA, 2008). The Canadian Manufactured Housing Institute (CMHI) presented an alternate definition of factory-built housing as, "[the] term used to describe houses built far from the site and then assembled in it. These houses vary in size, design, features, and level of completion, regardless of whether they are standardized of customized" (CMHI, 2013).

Prefabrication has a long history in Canada and has run the course for the recent factory-built housing subdivision. Based on the Clayton Research and Canada Mortgage and Housing Corporation (CMHC) study, factory-built housing components are categorized by several major groups including: manufactured homes, modular homes, pre-cut, or pre-engineered homes, log or timber-frame homes, multi-unit residential modular homes, and wood-frame non-residential units (Clayton Research, 2006).

Benefits of a factory-built home

Shafai and the MBI outlined the advantages of industrial home buildings, including: quality and standards, speed, affordability, workers' health and safety, and environmental impact reduction (Shafai, 2012; MBI, 2006, 2010).

The CMHI also summarized the benefits of factory-built homes, as follows:

- **On-time delivery**: because houses are built in factories, delays relevant to traditional site construction no longer exist. Therefore, it is simpler to monitor the schedule.
- **High construction quality**: factory-built housing ensures superior quality and precision because it is done under controlled conditions.
- **Environmental features**: "being green" means using resources that are eco-friendly causing minimum wastage. This is done when houses are built in factories.
- **Firm prices**: given that construction is held in factories, the process is planned and ordered preconstruction. This eliminates unexpected cost increases along the way. When construction begins, the consumer is aware of the housing costs.
- **Outstanding choices**: manufacturers offer a full range of homes and customized services. Factory-designed plans can be personalized to accommodate individual preferences and building sites. There is also a component of offering peace of mind to guarantee high quality and matching standards across the board. CMHI member builders are certified through the CSA.

Chapter 3 : Proposed Methodologies

3.1 Research Processes and Methodology Road Map

As previously mentioned, analyzing productivity and defining a baseline is necessary in any organization. Variability and production features often impact the selection of methodology. Moreover, this presents another challenge in measuring the productivity and influencing factors. For instance, it is difficult to track the production of a manual assembly line due to its complexity of the production of panels. It appears to be easier to track the panels through the machine assembly line. However, each assembly line has different features with several variables. The integrated research process is demonstrated in Figure 3-1 and will be discussed in detail throughout the following paragraphs.

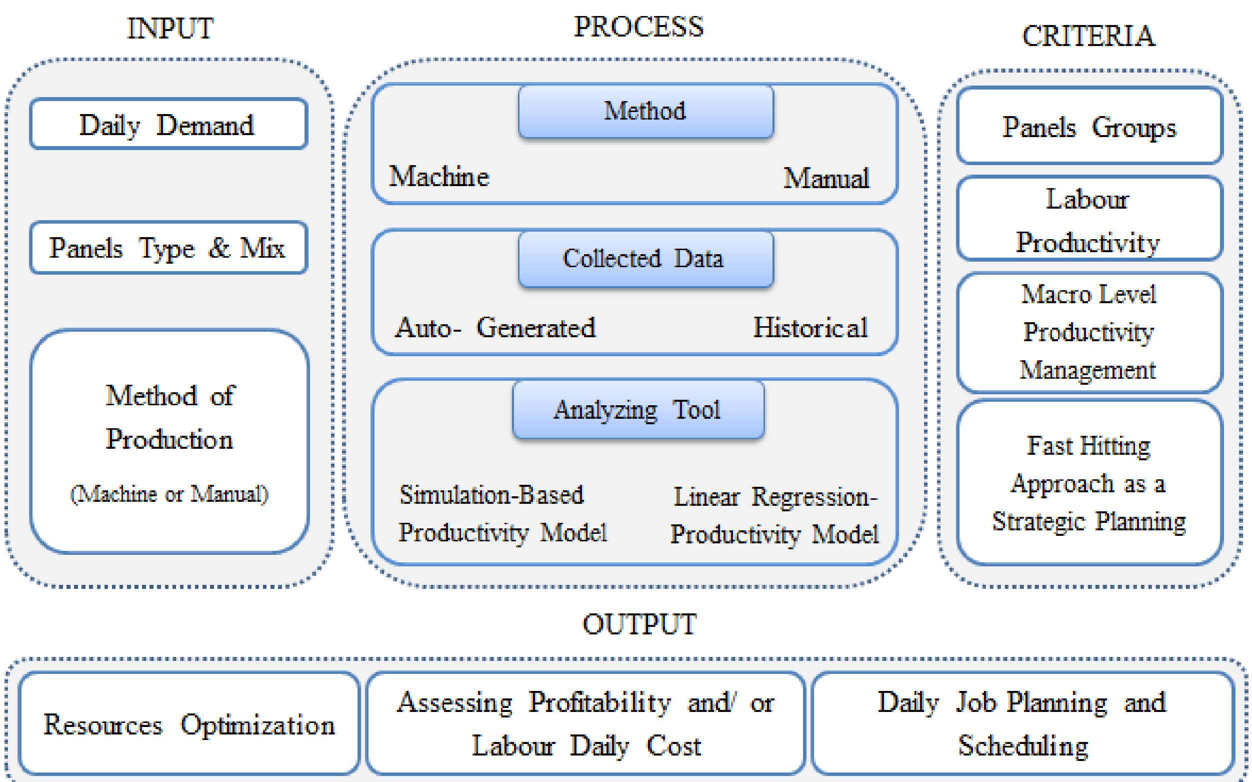


Figure 3-1: Proposed Research Road Map

3.1.1 General Key-factors Impacting Productivity in Panelized Construction

Numerous variables impact the estimation process of panelized construction labour productivity and the associated costs. There are so many variables that it is difficult to consider all of them within one research. The above variables can be classified within three groups, including:

- **Human factors:** skill, gender, age, learning curve, ergonomic, anthropometrics, biomechanics.
- **Production features:** panel geometric and size (length, width, height, and area), panel geometric shape (rectangular, triangular, angled, rake, gable), panel sheathing materials, and insulations.
- **Management and supplying issues:** labour turn-over, change-over, machines setup times, shifts number and time, panels and jobs schedule, absence, safety, inventory level, material supplying, just in time, quality control, quality assurance, training programs, and so forth.

The above groupings influence productivity as a whole, but this research deals with the production features with all the other variables fixed. However, panel features impact the determination of the man-hours spent in different panels through dissimilar assembly lines. Based on specific features, grouping the panels in terms of the machine-assembly line and the manual assembly line was developed, and later presented in detail.

3.1.2 Productivity Models and Parameters-Machine Line Assembly

At Landmark[1], the machine assembly line begins with building panels (walls) using studs and plates at the framing station, followed by the positioning and stapling of the sheathing. Once complete, the panels are sprayed and insulated. As demonstrated in Figure 3-2, at Landmark, the walls are fitted to one long multi-panel batch as multi-panels by optimizing the total length of the group of walls to be close-fitting in one long multi-panel batch up to the maximum capacity of the framing table. Later these multi-panels can be detached to become single panels before being

[1] Landmark Group of Builders is a home building manufacturer in Edmonton and one of Alberta's largest integrated residential building companies. The organization provides high quality products in Alberta's new housing market, building over 1,000 homes per year <http://www.landmarkgroup.ca// >.

loaded to trailers and transported to the site for assembly. Batching the panels in one multi-panel reduces the setup time and results in more efficient handling and savings in terms of materials.

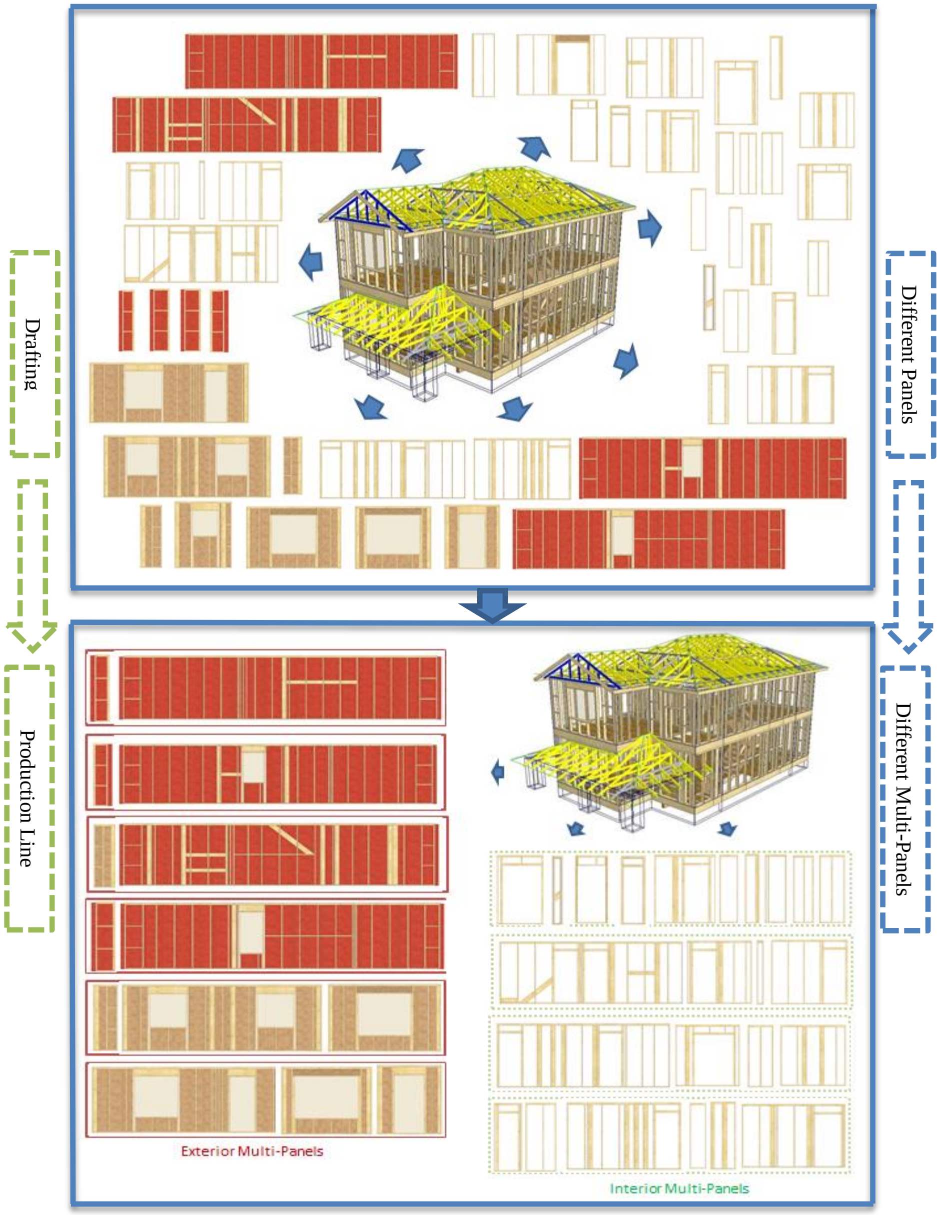


Figure 3-2: Produced Multi-Panels at Landmark

Daily production involves two types of products: exterior walls are produced which require sheathing, and interior panels are produced which do not require sheathing. Landmark produces multi-walls in its machine assembly line. The aim of this research is to not only balance the resources on the wall assembly line, but also to focus on the need to meet daily demand. Those factors affecting labour productivity in the machine assembly line are therefore categorized as follows:

- **Crew size:** may be changed based on absence, sickness, turnover, injuries, or vacations.
- **Shift-hours arrangements:** most working days are considered staggered shifts. Coffee and lunch breaks run in a staggered pattern to maintain production during the breaks.
- **Planned stoppage time:** planned stoppage time is allocated by general meetings and safety meetings. The planned stoppage time occurs in situations of technical or absence reasons. Therefore, the management, with reason, may decide to run non-staggered shifts during breaks or another type of stoppage time.
- **Unplanned stoppage time:** occurs when one of the root causes takes place, such as: machine breakdown, materials quality's issues, dis-organization, program or computer concern, line bottleneck, supplying issues, (labour) operator mistakes, or drafting errors.
- **Exterior multi-walls production:** includes a number of produced exterior multi-panels and total linear footage (LNFT). The exterior multi-walls (panels) contain walls in one long multi-panel by optimizing the total length of group of walls to be fit in one long multi-panel up to the maximum capacity of the framing table. The number and total length of exterior panels vary based on the model and its design. Schedules can impact the number of exterior or interior walls that are built within a specific day.
- **Interior multi-walls production:** similar to exterior multi-walls, Interior multi-walls include number of produced interior multi-panels and total linear footage (LNFT). Also, the interior multi-walls (panels) contain walls in one long multi-panel by optimizing the total length of group of walls to be fit in one long multi-panel up to the maximum capacity of the framing table. The main difference between interior panels and the exterior panels is the sheathing procedure. The interior panels include all the panels and do not require sheathing. The number and total length of interior panels vary based on the model and its design. Also, jobs schedule disturbs the number of interior walls which fabricated in specific day.
- **Multi-panels' sequences and the daily production mix:** based on the production mixture of interiors and exteriors, multi-panels' sequence is considered one of the most

important factors. They play a fundamental role in creating bottlenecks in the production stations and it is potentially the cause of losing efficiency throughout the shift.

Chosen model architecture for machine line panels' assembly: it is important to focus on analyzing the machine assembly line by fitting the data to distributions and considering load levelling (products mix levelling) in terms of manufacturing management. The latter is accomplished within the macro-level of the productivity measurements and based on the cycle time of the produced multi-panels within certain number of resources. As demonstrated in Figure 3-1, the impacted variables are used as a house model' features, multi-panels' sequence, unplanned time, production mix and load levelling.

Model's Inputs: the model's inputs include many components. This research suggests the consideration of the main factors that can influence labour or labour productivity in panelized construction within macro-level management.

- The panel type varies in every case. The products are either interior walls or exterior walls.
- Identifying the product type leads to determining the cycle time based on fitting distributions such as fitting the cycle time to a normal distribution.
- Panels are sequenced through the production line using different patterns. As a result, the production efficiency and utilization is affected by the panels' sequencing.
- The model's design and features, such as total linear footage of each type of walls, determine the number of panels per job, which vary from one house to another. This optimizes the total length to reach the maximum capacity of the framing table length.
- The number of resources differs from day-to-day, as some issues are related to crew size and shift arrangement.
- To assist in measuring the cost analysis and associated profitability, an assumption of the average rate of the crews is considered as one of the model inputs.

Model's outputs: similar to the model's inputs, the model's outputs consider many factors, including:

- Predicting the bottlenecks during the production line based on scheduling the panels and their orders.

- Estimating and tracking the labour cost and stations utilization.
- Allocating daily resources at a predetermined time of the shift.

Model's criteria: as in each study, criteria items assist in the research as to clarify the contents and to give more recommendations for future studies in this area.

- The research deals with two main types of panels, including the exterior and interior panels. The exterior panels require sheathing whereas the interior panels do not.
- The machine line is designed to produce standard walls. Landmark's standard multi-walls deal with multi-panels in a rectangular shape and high standards based on the manufacturing. Landmark's standard walls are 8 or 9 ft high.
- According to this study, to optimize the usage of top and bottom plates, the manufacturing company determines that the multi-panels are built to the maximum capacity of the framing table. This decreases the setup time. Therefore, over 90% of Landmark's total multi-panels are manufactured. They are between 36 and 40 ft. Each wall is optimized to fit within the range of one multi-panel.
- The productivity is estimated as single-factor productivity. That is determined from the spent man-hours in the machine line to fabricate certain amount of multi-panels (units). Therefore, only labour productivity is considered. The latter is used to asset profitability and labour cost.
- While preparing the regression models, unplanned time is accounted for. Dealing with macro-level planning accounts estimating and scheduling during longer days, as well as for minor delays. Major delays and abnormalities, however, were excluded.
- A strategic plan is presented for daily planning considering such constraints as labour availability, products mix, and matching the daily demand. To achieve the desired targets, the planning stage launches goals and anticipated sequences of multi-panels considering Ballard's concepts as Last Planner System (LPS). That helps in transforming what "should" be done into what "can" be done. On the other hand, these strategies can be defined as a fast hitting approach (ready, aim, map) aligning with Taiichi Ohno's philosophy "Just do it".

3.1.3 Productivity Models and Parameters-Manual station

Landmark's manual assembly line begins with building the panels using studs and plates at a manual table station. Following this, the sheathings are positioned and stapled, and then sprayed. Similar to with the machine line, the data is collected based on daily production, where all the data is considered quantitative.

The main focus was on working hours during daily production considering the fabrication of the panels manually, without considering the spray foam or other stations. The latter was considered as this station is isolated and does not affect the machine line. At the manual station, daily production consists of two products. The first products are exterior walls, which require sheathing. The second products are interior panels, which do not require any sheathing sheets and are different heights and shapes compared to exterior panels. Landmark uses a manual table to produce what called manual walls. Typically, these walls cannot be produced using a machine line due to the following reasons:

- Panels cannot be optimized within certain length or capacity of these panels' height in the production line.
- No standard heights of studs or sheathings are available in the market. As such, additional cost is required to cut the components. More space is required for the storage and inventory.
- Panels drafted in different geometrical shapes, such as gable and rake walls, require a great deal of additional manual work, including squaring and adjusting the angled pieces. This generally results in additional time spent on the machine line and can slow the rate of production.
- Given the variety of height, panels can cause safety hazards in the machine line. As a result, panels are generally built manually and all safety concerns are verified to determine what kind of panels cannot be fabricated at the machine.
- Framing station's table capacity and maximum panel's height can be produced.
- Maintaining the utilization of the manual stations when it is idle. The reason for this is to keep the manual line busy so, to avoid the starvation of the station, no manual panels are available. Therefore, some of the standard walls can be completed by machine while others must be done manually.

- For certain house building schedules, the machine line becomes overloaded. In this case, some standard walls are provided to the manual crew to decrease the loading of the machine line if they are not fully utilized.

As many factors can influence productivity in manual station, those considerations can also influence the man-hours spent on the fabrication of the manual walls. In addition to wall types, dimensions and shapes impact the manual line productivity. Further, other human factors and variables can have a similar impact, such as: work, skill, and learning curve. In order to deem the production conditions normal, one must assume that the workers have normal skills.

Chosen model architecture for manual line panels' assembly: based on daily production of many variable walls groups, we must analyze the manual line assembly line using historical data analysis. This is accomplished by considering the macro-level of the productivity measurements, based on the estimated man-hours of the produced multi-panels. As revealed in Figure 3-1, the impacted variables are in the form of a house model, unplanned time, production mix, panel features, and geometric shapes.

Model's Inputs: to achieve the goal of measuring productivity through the manual station, human factors are avoided by gathering and analyzing the data based on normal conditions, normal crew skills, and evading conditions of when a crew has new member or absences. Consequently, more stability in the data and the inputs were achieved. Based on many variables that influence the productivity model in the manual line, the chosen main inputs include:

- The daily manual panels' length and height, whether those panels are interior walls, exterior walls, or angled walls, such as exterior rake and gable walls.
- The daily requirement panels per job, with the notion that the number of panels per job varies from house to another.
- The daily requirement panels can contain walls from the machine line, which are completed manually.

Model's outputs: with regards to the model's outputs in the machine assembly line, the chosen model's outputs consider the following:

- Estimating and tracking the labour man-hours.

- Predicting the required crew size based on daily production.
- Allocating the man power resources during each day within planned time of the shift.

Model's criteria: constraints can arise within the chosen model for tracking the productivity in the manual station. The study considered the following:

- Fabrication difficulties can affect grouping the walls, as some groups consume more efforts and time than others.
- The unplanned time was excluded from the recorded working time during the day. As a result, the net operating time was calculated for the regression model.
- The productivity is estimated as multi- factors productivity. That is determined from the spent man-hours in the manual station to fabricate different amounts of dissimilar panels. Therefore, only labour productivity is considered in a linear regression model with different factors.
- A strategic plan is presented for daily planning considering such constraints as required crew size and labour availability in the manual station, products characters, and matching the daily demand. Accordingly, that helps in converting what "should" be done into what "can" be done. Then again, these strategies can be presented as a fast hitting approach (ready, aim, map) aligning with Taiichi Ohno's philosophy "Just do it".
- The estimated time in the regression model was designed to track linear length of grouped panels. In other words, based on the linear length of each panels, the groups of height, and the walls' types, the model estimates the net operating time of man-hours. This is required to build specific walls during specific days.
- Based on the height, grouping the walls is as a result of observing the work and discussions with the production supervisors at the Landmark plant.
- Based solely on the height and type, the studied groups were determined. Those categories are clustered at Landmark, as follows:
    - Exteriors less than 5 ft in height.
    - Exteriors between 5 and 8 ft in height.
    - Standard Exterior (can also done by the machine) as 8 ft or 9 ft in height.
    - Exteriors between 8 and 9 ft in height.
    - Exteriors between 9 and 10.5 ft in height

- Exteriors more than 10.5 ft in height.
- Exterior gable or rake walls, which contain all types of exterior walls with angled shape regardless the height in this case.
- Interiors less than 5 ft in height.
- Interiors between 5 and 8 ft in height.
- Standard Interiors (can also done by the machine) as 8 ft or 9 ft in height.
- Interiors between 8 and 9 ft in height.
- Interiors between 9 and 10.5 ft in height
- Interiors more than 10.5 ft in height.

It is difficult to include all of the impacting factors within one study. Therefore, the 13 factors listed are presented as the main factors affecting the daily production in the manual station. The impact of the angled interior walls was very slight on the daily spent man-hours. This is as a result of another time study as well as from the discussions with the production manager. There was a large impact on the angled exterior walls and, therefore, it was included as a main factor. The angled interiors walls were analyzed as normal interiors and grouped based on their height.

Chapter 4 : Implementation and Case Study

4.1 General Processes and Activities in Panelized Construction

The thesis is based on eleven months' (September 2012 to August 2013) of research on the Landmark Group of Builders. As one of Alberta's largest integrated residential building companies, Landmark primarily operates in Calgary, Edmonton, and Red Deer. The organization provides high quality products in Alberta's new house market, building over 1,000 houses per year.

There are five stages in the process of panelized construction, as demonstrated in Figure 4-1, including: 1) preparing plans and specifications; 2) estimating jobs and scheduling; 3) off-site manufacturing and on-site construction; 4) on-site lifting; and 5) close-out. Focusing on the off-site manufacturing of Stage 3, data flow begins in the scheduling department through the integration of the drafting department. The drafters supply the files for the machines and/or other users to handle the generated data. During post-scheduling, the last planner or production manager makes the order to produce or manufacture the job. The job then moves to the control centre and production list. This cycle is essential to each job. Subsequently, the job is distributed to the required stations at the plant. The labour (manpower) and CNC machines are required to perform the job, whether the stations are manual-based stations or machine-based stations.

Control centre[2] monitor the flow of production units within the production system as well as influence the production process using defined controls, including book unit–in, book unit–out, and element types. Figure 4-2 presents a detailed data flow chart of the Landmark plant's manufacturing stage. This chart includes the proposed flow to achieve daily engineered productivity reports.

[2] More information regarding the Control Centre is available in Appendix A.

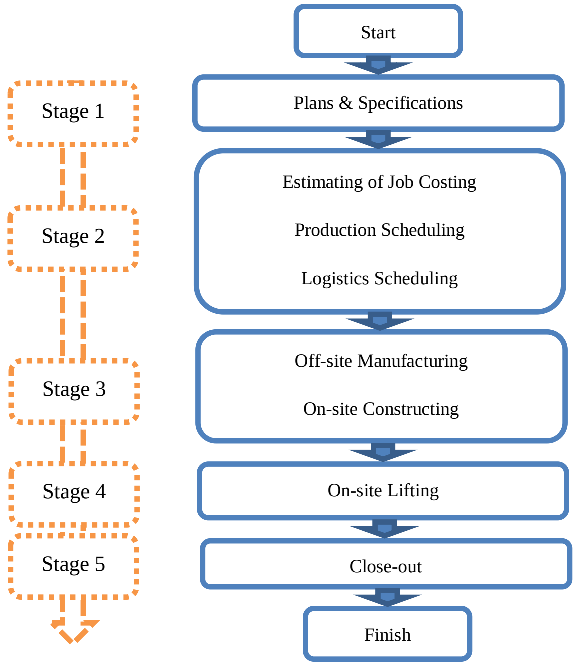


Figure 4-1: Main Stages and Overview of the Core Process

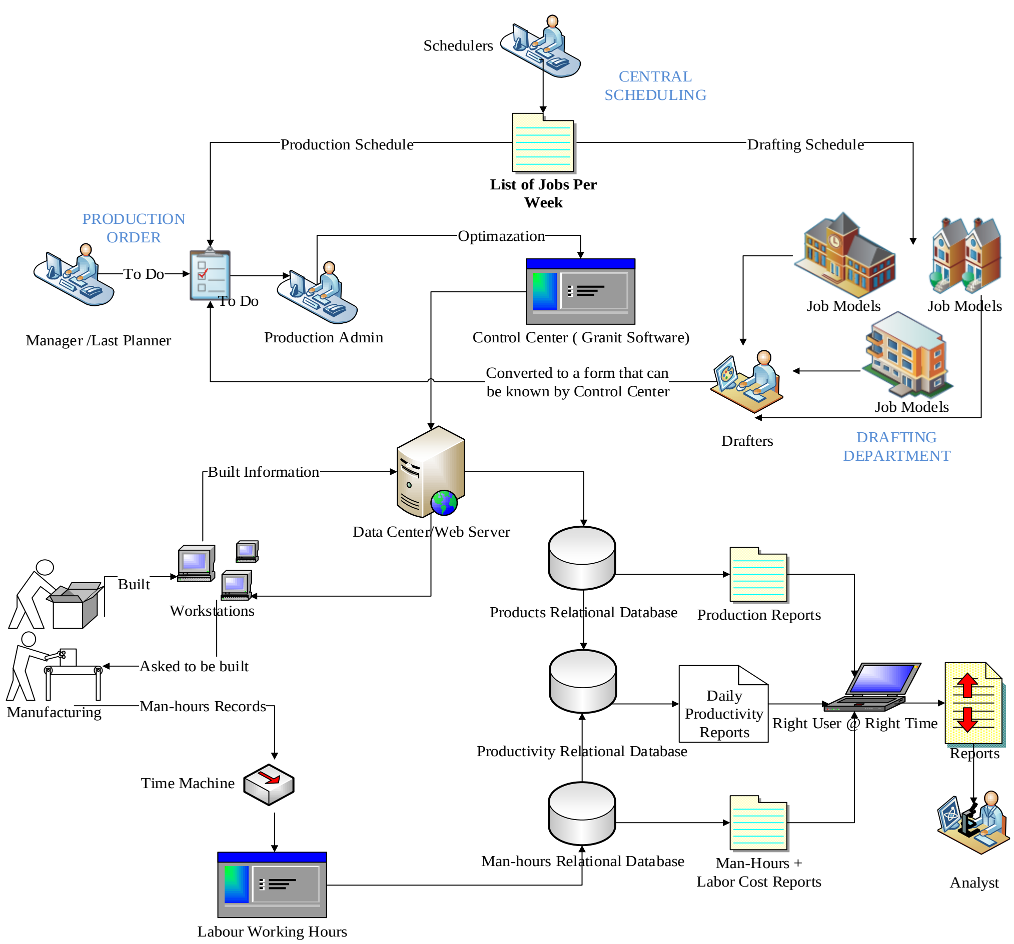


Figure 4-2: Information and Data Flow at Stage 3 Including a Proposed Flow to Get Daily Engineered Productivity Reports

4.2 Detailed Processes in Off-site Walls Fabrication Stage

While establishing the processes in panelized construction, it is equally important to identify the activities that take place at the plant, in terms of wall fabrication and wall assembly lines. Researchers can implement and develop methodologies, as well as propose ideas, based on floor panels, roof panels, and other main components of panelized construction.

At Landmark, arrays of products are manufactured within numerous stations. Given that each station contains a unique description, products flow throughout several stations. Landmark's work descriptions and basic stations for wall assembly are presented in Table 4-1.

Table 4-1: Basic Stations at Landmark Plant

Short	Description	Brief Work Description
HPP	Panel saw	Pre-Cutting of required sheathings which are not 4'x8' or 4'x9', to be supplied to manual station or machine line.
WBS	Part cutting	Pre-Cutting the small parts to be supplied to manual station, component table, and the backing station.
W1	Component table, rough opening	Fabricating of window/door opening, and header of garage openings. In addition to bracing the openings to give the support during the movement of panels through the machine line.
W2	Framing table WEM	Building the multi-panels which contain more than one wall based on optimizing the length up to 40'.
W3	First table after framing table	Labeling walls, placing bolts, and attaching required guard wrap insulation for 2nd-floor panels.
W4	Second table after framing station, normally used for sheeting	Placing, positioning, and fixing sheathings in their positions
W5	Multi-function bridge WMS	Stapling sheathing, and routering openings and wall edges.
W6	Butterfly table	Tilting panel up to vertical (the sender wing), and directing the multi-panels to the butterfly cart (the receiver wing)
W7	Butterfly cart	Receiving the panels from W6 or W16, and then transferring them to W8, W9, or W10.Before transfer them to W9 or W10, the multi-panels should be separated to detached panels.
W7_1	Exit for short exterior walls at butterfly cart	For safety and functionality requirements, small and short walls can't be transferred in the line, so they should be pulled using forklifts.

W8	Spray booth (three rails, W8_1, W8_2, W8_3,W8_4)	Spraying the required thickness of spray foam based on the specifications. Only exterior walls have this procedure.
W9	Transfer line for interior walls	This line contains interior multi-panels on trolleys, backing is installed if required.
W10	Transfer line for exterior walls	This line contains exterior multi-panels on trolleys, backing is installed if required.
W11	Transfer cart	Getting panels from W9, W10, or W16, and then transfer them to the required destination W12, W13, or W14.
W12	Window assembly small windows	Checking framing and stapling guard wrap, then positioning the window/door, and check their opening capability.
W13	Window assembly large windows	
W14	Wall magazine	Receiving Exterior panels which do not have windows or doors, and also long panels over 13 ft.
W15	Loading cart	Receiving panels fromW12,W13,W14, then loading them on the trailers sequenced based on job number and floor number (1st or 2nd floor)
W16	Manual table	Building panels that cannot be built by machine line.
W16_1	Transfer line from manual table to butterfly cart (to spray booth)	Receiving panels from W16, to be routed to W8 (i.e., spray booth).
W16_2	Transfer line from manual table to transfer cart (wall magazine)	Receiving panels from W16, to be routed to W11.

W1: Component table, rough opening

W2: Framing table

W4: Second table after framing table

W5: Multi-function bridge WMS

W6: Butterfly table

W6: Butterfly cart

W8: Spray Foam Booth

W9,W10 : Transfer Lines for Walls

W10: Transfer Cart

W12,13: Windows Assembly Lines

W14: Wall Magazine

W15: Loading Cart

WBS: Pre-Parts Cutting & Preparation

W16: Manual Table

Figure 4-3: Photos from a Numerous Stations Regarding Panels' Assembly and Transforming at Landmark

As demonstrated in Figure 4-4, Landmark has two main assembly lines to produce panels. The machine line begins at the framing station and continues up to the spray booth. At the spray booth, the second assembly line begins at the manual station and ends at the spray booth. The flow of the products is consistent with the transfer line until the loading station.

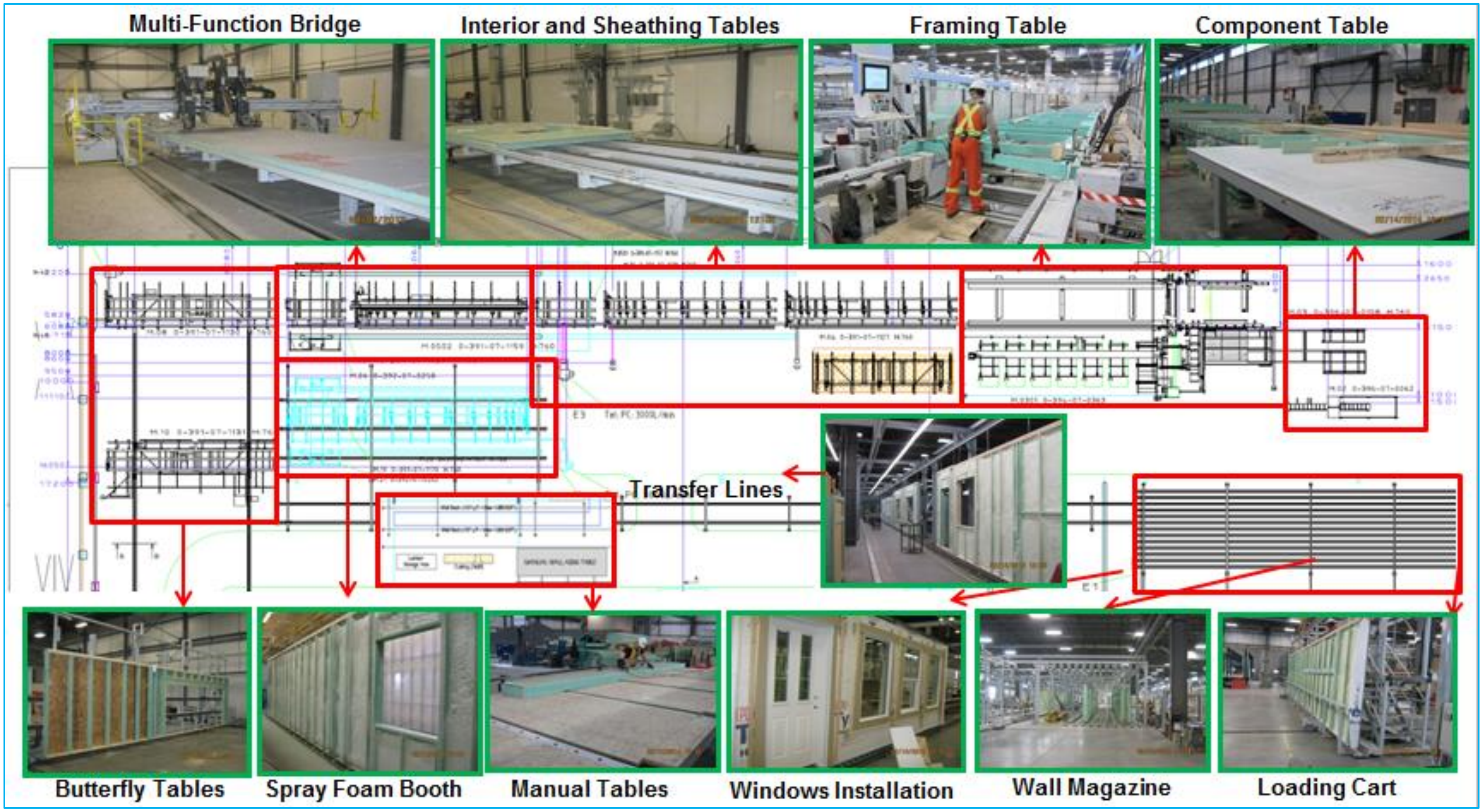


Figure 4-4: Wall Panel Production Line at Landmark

4.3 Application of Proposed Methodologies -- Case Study

4.3.1 **Production Mix and Panel's Families:**

As a result of the assortment of products, the main characteristics of the panels vary based on the production mix and the product's destination. This can assist in identifying the product's family matrix. The considerations of the main product family fluctuate based on the total work content and the similarity of processing steps and equipment that the product goes through. Although the demand for one product within a family can vary, the demand for a whole family is often more stable. Exterior panels require additional attention is given to the sheathing and any other additional work required. Interior panels do not require sheathing. At times, however, the product should go through defined destination based on the plant layout and the path design. This is the reason why there are still interior panels in the sheathing table, even though sheathing is not required for interior panels.

The product is categorized in four groups as follows:

- **Interior walls category**: includes all walls that do not require OSB[3] sheathing during the process of fabricating the panels. It is typically composed of 2 x 4 inch sections.
- **Mechanical walls category**: the mechanical walls category typically function as bearing loads walls. At times, they contain holes at both the top and bottom plates to facilitate the finishing procedure, such as plumbing. Generally, it has 2 x 8 inch sections.
- **Exterior walls category**: includes all the walls that require OSB sheathing and must be insulated with spray foam or other insulation method.
- **Garage walls category**: this category is analogous to the exterior walls category. However, it does not require spraying at the plant during the fabrication stage. Typically these walls are insulated and finished by the home-owner.

The machine assembly line provides standard walls as both interior and mechanical walls as one family. This family is called the "interiors family." The other family consists of the exterior and garage, entitled the "exteriors family." Similarly, the manual assembly line has two major families. The exterior family includes non-standard exterior panels, non-standard garage panels,

[3] OSB sheathing is a type of structurally-engineered board made of compressed wood.

rakes, and gable walls. Conversely, the second family contains non-standard interior panels, non-standard mechanical panels, stairs, and other angled interior panels. Landmark factory uses CAD software called SEMA[4] which drafts and designs the framing based on wall type and function as illustrated in Figure 4-5.

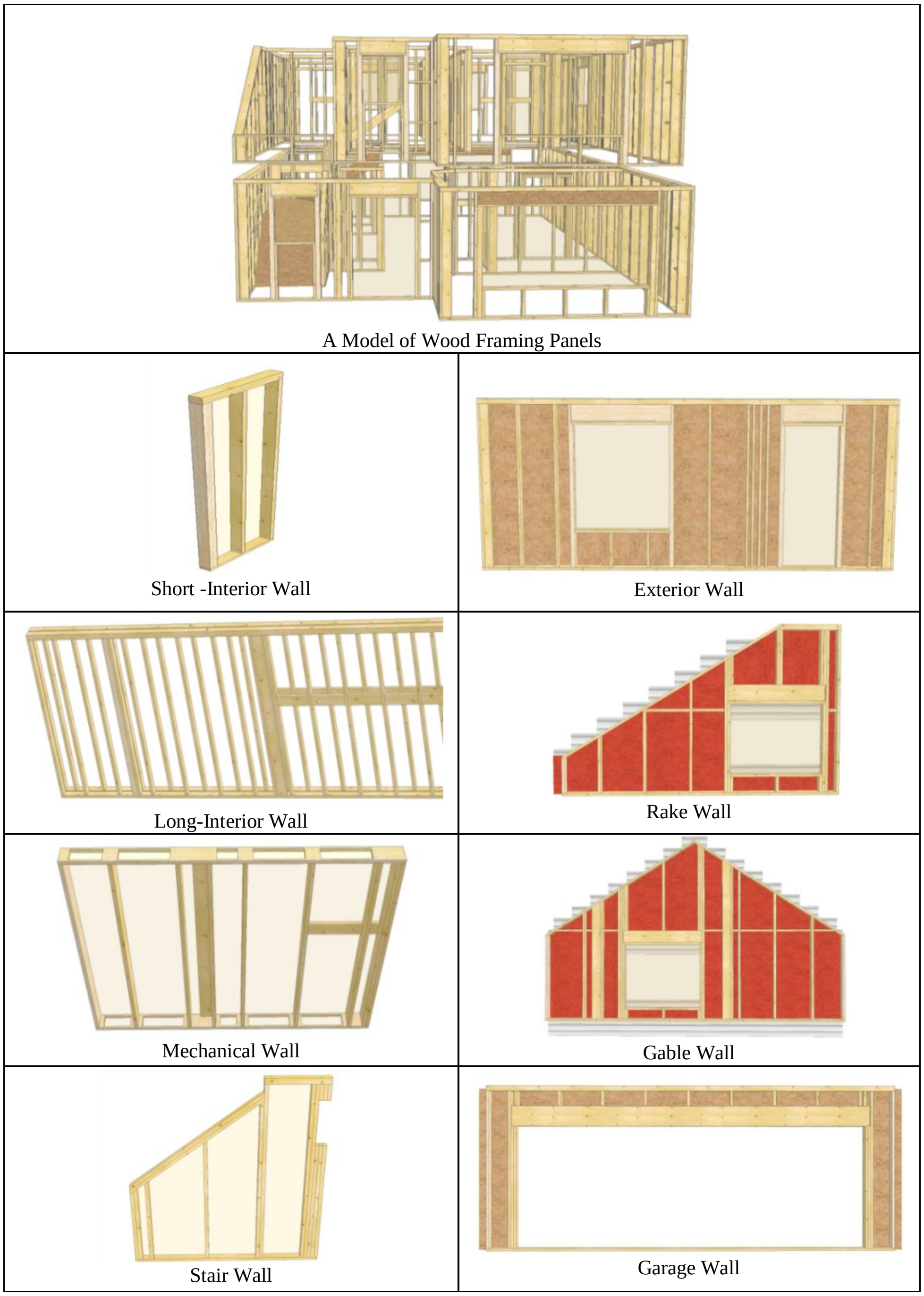


Figure 4-5: A Model of Wood Framing Panels and Some Different Types of Landmark's Panels

[4] More information regarding the SEMA is available in Appendix A.

4.4 Machine line Assembly

With regards to panels' fabrication, this study identifies the machine line assembly, including:

- Station W1 (Component table, rough opening)
- W2 (Framing table)
- W3 (First table after framing station)
- W4 (Second table after framing station, normally used for sheathing)
- W5 (Multi-function bridge)
- W6 (Butterfly table)
- W7 (Butterfly cart)
- W8 (Spray Insulations)

To simplify the work and considering the resources' allocations, stations are formed through the consideration of product family, close cycle time, plant layout, and product flow. The stations are shaped as follows:

- **Framing station**: contains W1 (component table, rough opening) and W2 (framing table).
- **Sheathing station**: contains W3 (first table after framing station), W4 (Second table after framing station, normally used for sheathing), W5 (multi-function bridge), and W6 (butterfly table).
- **Spray booth station**: contains W7 (butterfly cart), and W8 (spray insulations).
- **Transfer line station**: contains W9 (transfer line for interiors), W10 (transfer line for exteriors), and W11 (wall transfer cart). Backing is occasionally required for both. However, this station is a kind of safety-buffer supermarket, so they do not affect the manufacturing stage of the panels.
- **Windows station and loading station**: windows and loading stations are isolated stations (islands) and they have a buffer as a finish goods (FG) supermarket. The latter is to ensure that they do not affect the fabrication of the panels. Therefore, this study does not include these stations.

Creating a buffer and safety inventories is important to maintain a smooth flow of products. The buffer inventory is required to cover the variations in the ordering pattern and the takt time.

Safety inventory is necessary to assist in dealing with the variation in cycle time and inefficiencies throughout the processes and the flow.

The main focus of this study is the assembly lines. As such, this thesis will cover the critical stations with regards to the panels' assembly. The critical stations consist of the framing station, the sheathing station, and the spray booth station. These stations form the machine assembly line at the fabrication stage. However, an overview of all of the stations may ensue through other studies.

4.4.1 Data Collection in the Studied Stations

Data was collected for three stations in the machine assembly line. This data combines the time spent on each multi-panel and resources required through the assembly line and the allocation of the resources alongside with the number of resources in each station which is documented daily. The studied stations include framing, sheathing, and spray foam stations.

Framing and sheathing stations data:

In the case of produced panels, the control centre and CNC machines collect the data based on recording automatically the time which the machine starts fabricating the multi-panels till the machines finishes assembling this multi-panels in the associated station. The CNC machines reports were developed to give information related to the produced panels as presented in Table 4-2. This research deals with the process time to fabricate multi-panels in numerous stations. As presented in Table 4-2, column (A) offers the identification number of each multi-panels and shows the load sequence of those multi-panels, where (EW) means exterior walls, and (IW) means interior walls. Column (B) presents total length of each multi-panel in feet. Column (C) presents total width (height) of each multi-panel in feet. Column (D) presents the time that the CNC machine starts fabricating the multi-panels in the correlated station. Column (E) presents the time that the CNC machine finishes fabricating the multi-panels in the related station. Therefore, the process time was calculated based on the difference between the beginning date and the ending date of fabricating multi-panels in the associated station, as in column (F). By collecting and analyzing the data, all the instructions presented in Appendix B are followed concerning the inputs, outputs, constrains, and filtrations.

Table 4-2: Data Collected "Reports Sample" Indicates the Collected Cycle Time for Framing Station

A	B	C	D	E	F=E-D
produnit	Pulength (ft)	Puwidth (ft)	begindate	enddate	Processtime (minutes)
EW003540	39.1	8	5/30/2013 7:58	5/30/2013 8:10	12.45
IW003550	40.0	8	5/30/2013 8:10	5/30/2013 8:20	10.25
EW003541	37.5	8	5/30/2013 8:20	5/30/2013 8:30	9.95
IW003551	40.0	8	5/30/2013 8:30	5/30/2013 8:41	11.05
EW003542	40.0	8	5/30/2013 8:41	5/30/2013 8:53	11.5
IW003552	38.4	8	5/30/2013 8:53	5/30/2013 9:06	13.37
EW003543	40.0	8	5/30/2013 9:06	5/30/2013 9:20	13.42
IW003553	38.7	8	5/30/2013 9:20	5/30/2013 9:32	12.55
EW003544	39.4	8	5/30/2013 9:32	5/30/2013 9:45	12.93

Spray booth station data:

Similar to the framing and sheathing stations, the data is collected at the spray booth station. The time spent on spraying the multi-panel is recorded manually. It considers the number of sprayers used on the multi-panels and all associated time. The total process time is calculated based on the number of sprayers and the spent time. Consequently, the total process time (man-hours spent) equals spent time on spraying each multi-panel multiplied by the number of sprayers as shown in Table 4-3.

Table 4-3: Sample of the Collected Data for the Sprayed Multi-walls

A	B	C	D	E	F	G=Ex F
Date	produnit	Pulength (ft)	Puwidth (ft)	Spent Time (minutes)	NO # Sprayers	Total Process =Time *NO #Sprayers (minutes)
22-May	EW003162	40.0	8	59	1	59
22-May	EW003163	39.2	8	30	2	60
22-May	EW003164	37.5	8	20	3	60
23-May	EW003165	40.0	8	30	2	60
23-May	EW003167	39.4	8	24	2	48
23-May	EW003168	37.0	8	25	2	50
4-Jun	EW004049	36.1	8	35	2	70
4-Jun	EW004050	34.5	8	33	2	66
4-Jun	EW004067	36.9	8	30	2	60
4-Jun	EW004068	40.0	8	34	2	68
4-Jun	EW004069	36.6	8	32	2	64
4-Jun	EW004070	39.6	8	48	1	48
4-Jun	EW004071	39.1	8	26	2	52

4.4.2 **Applying Product Quantity Analysis**

Product Quantity Analysis (PQA) calculates and visualizes the volume and variety of different products in the plant. It also manages the data that was collected over several months. To apply PQA, the products are classed into main products. Subsequently, these main products are analyzed based on a variety of product mixes and volumes, whether they are high or low.

Analyzing volume and variety of different products

Through analyzing over 100 house models and in matching them with the daily production at both the manual and machine lines, it is determined that the manual build does not exceed 16% of the total production in average. The impact of the total production and the house model are driven by the machine line. Within the perspective of manufacturing and automation, and pertaining to quality and safety, the more machine builds there are in the model, the faster the houses are built. Typically, over 80% of the production is accomplished through machine builds. This leads to a focus on mapping and operating the machine line for current state in value stream mapping. In this case, all manual build types do not exceed 20% of the total panels' length in a model. Landmark's goal was to reduce the manual built walls by 3% by the end of 2013. After finishing this research, by the end of 2013, the goal was accomplished through redesigning houses and adding more dynamic clamps to the machines to allow building a variety of panel sizes. This emphasizes the need to focus on the mapping of the machine line.

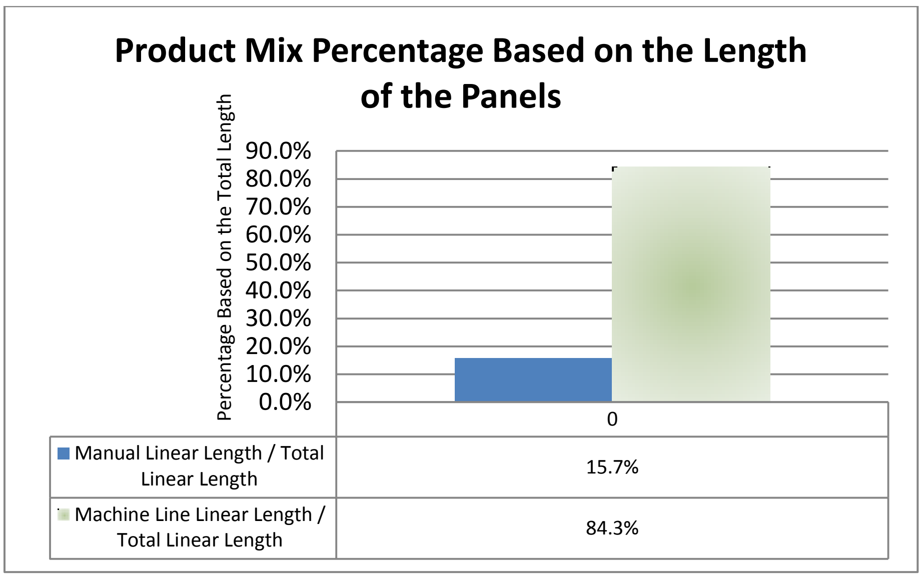


Figure 4-6: Manual versus Machine Production Based on the Total Length of the Produced Panels

Through the use of the machine assembly line, and to track the data during a three-month span, over 500 multi-panels were filtered based on major delays that do not typically occur in normal condition. The percentages of various products are demonstrated in Figure 4-7. This figure indicates the production family as high volume with low variety product mix. Also, Figure 4-7, clearly shows that the exterior and interior multi-walls are the main family. These walls impact the daily production lead and cycle time, in which they can vary in cycle time and can be influenced by multi-panels' sequence and the pre-defined routings. Described in the product process analysis, the runners (produced multi-panels) will subsequently be combined in classes depending on the similarity in processes.

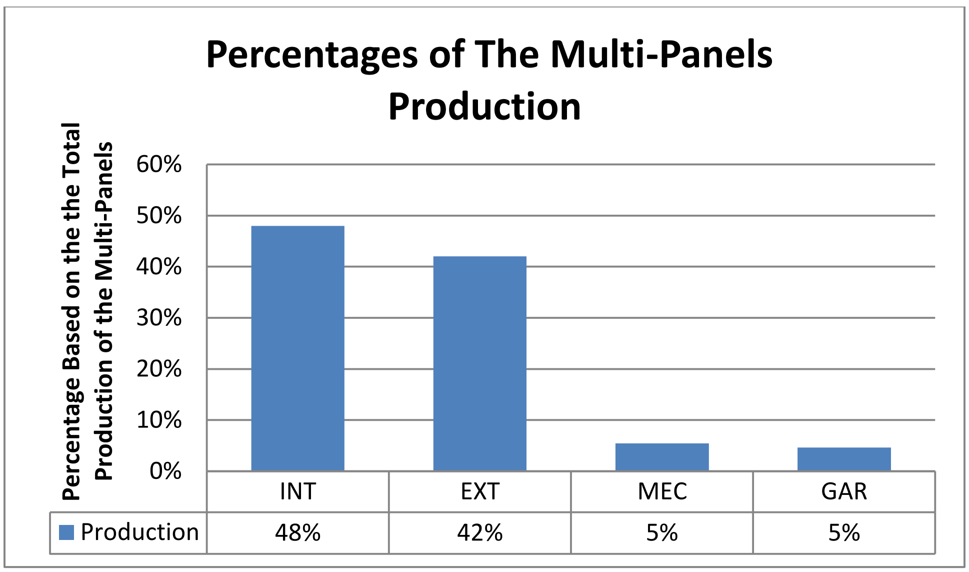


Figure 4-7: Volume and Variety of the Product Mix in the Machine Line

Given that the fabrication of houses varies from day-to-day, optimizing the walls in one multi-panel leads to a difference between the produced multi-panel's lengths. Therefore, research was conducted to study the variation of the main products based on the length of each multi-panel as presented in Figure 4-8. With a ratio of 80:20, the production family contains high volume with a low variety product mix. The percentage for multi-panels falls between 36 and 40 ft with a length of 80%, as demonstrated in Figure 4-8. Mapping the product family matrix and the runners (products), routing analysis is done to estimate the cycle time and processes for each family.

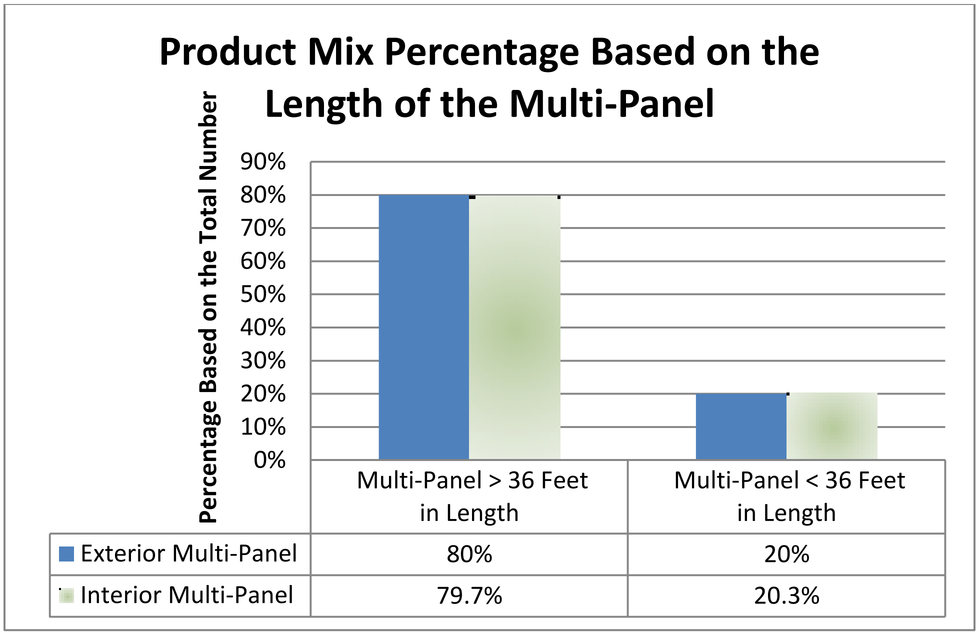


Figure 4-8: Volume and Variety of the Product Mix in the Machine Line Based on Multi-panels' Lengths

Product process analysis

Product routing analysis is summarized in Table 4-4, where (X) indicates that the product will be modified at the station by adding value to the product. Also in Table 4-4, (T) indicates that the product will pass through the station without being modified as non-value added time or transportation time. The diagram also demonstrates that the interior walls and mechanical walls have similar process steps. As previously mentioned, both the exterior walls and garage walls have similar steps yet dissimilar to those of the interior walls process. This leads to classifying the products in three, rather than four, main groupings. The latter classifications contribute mainly to balancing the line in each station and identifying possible bottlenecks through defined product's sequences. The three classifications are:

- Interior panels' class, which contains mechanical and normal interior walls.
- Exterior panels' class, which only has exterior walls.
- Garage panels' class, which has a similar process to the exterior panels 'class, with the exception of having another insulation procedure and can be finished later by the home-owner.

Table 4-4: Product Routing Analysis at Landmark for Standard Multi-panels

PRODUCT	PERCENTAGES OUT THE TOTAL	FRAMING STATION	SHEATHING STATION	SPRAY BOOTH STATION	TRANSFER LINE STATION	INTERIOR PACKAGING STATION
INTERIOR WALLS	48%	X	T	T	X	X
MECHANICAL WALLS	5%	X	T	T	X	X
EXTERIOR WALLS	42%	X	X	X	X	T
GARAGE WALLS	5%	X	X	T	X	T
Where (X) indicates that the product will be modified at the station, and (T) indicates that product will pass through the station without being modified.						

4.4.3 Cycle Time for Each Product Family

In this study, it was identified that each defined station was fabricated for panels longer than 36 ft in length. The collated and analyzed data fit a distribution that considered the following distribution rules: Chi-Squared, Kolmogorov-Smirnov, and Anderson Darling. By using Minitab 16 and EasyFit[5], the former rules were applied for the purposes of filtering and fitting distributions[6].

Table 4-5: Fitting Distributions of the Process Time (in minutes) in the Studied Stations

Station	Exteriors Multi-Panels	Interiors Multi-Panels
Framing Station	Normal (13.97,2.9)	Normal (13.37,2.6)
Sheathing Station	Normal (19.88,5.0)	Triangular (2.2,6.0,3.1)
Spray Booth Station	Normal (55.72,9.7)	Triangular (1.8,2.5,2.0)

When the curve was fit to normal, it offered good performance in fitting with regards to Chi-Squared, Kolmogorov-Smirnov, and Anderson Darling. The process time values were also tested to make sure that no negative values had been generated. Given that interior multi-panels pass by sheathing stations without modification, the transportation time is similar for both interior and garage multi-panels since they pass by the spray booth station without being sprayed. The transportation depends on the speed at which the machine moves the product. The product in the machine line assembly is moved and pushed along using the machines rather than labour power. In this case, the labour only operates the machine, and the machine moves the product.

[5] More information regarding Minitab and EasyFit is available in Appendix A.
[6] More information regarding the collected data and fitting distribution rules is available in Appendix B.

To determine the cycle time for each station, the number of resources impacts the cycle time. While there is an intention to increase the machine’s uptime and availability, adding individuals to work on one machine does not necessarily signify that the productivity will increase or that the product will be delivered faster. The effect of resources is feasible when the station contains an abundance of manual work and when spraying the multi-panels is done manually—in this case the spray booth. In other words, the CNC machines determine the speed or production rate (output) of the product through the line, while in other places the production rate (output) can be determined by the number of resources or man-power.

This study was performed using more than 500 multi-panels. The PQA is applied when working with multi-panels longer than 36 ft in length. Subsequently, the results, as presented in Table 4-5, Table 4-6, and Table 4-7, were fitted to convenient distributions based on Chi-Squared, Kolmogorov-Smirnov, and Anderson Darling tests.

Table 4-6: Fitting to Normal Distribution for Multi-panels with more than 36 ft in Length, Including Unplanned Time

<table>
<tr><th rowspan="2">Station</th><th rowspan="2">Family Type</th><th rowspan="2">Number of Resources / Constraints</th><th rowspan="2">Time Constraints</th><th colspan="2">Fitting To Normal</th></tr>
<tr><th>μ</th><th>σ</th></tr>
<tr><td>Framing</td><td>Exteriors, Garage Multi-Panels</td><td>3 people</td><td rowspan="2">Process Time is based on certain (fixed) number of resources</td><td>13.97</td><td>2.92</td></tr>
<tr><td>Framing</td><td>Interiors Multi-Panels</td><td>3 people</td><td>13.37</td><td>2.59</td></tr>
<tr><td rowspan="3">Sheathing</td><td rowspan="3">Exteriors, Garage Multi-Panels</td><td rowspan="3">3 people + Multifunction Bridge, where results show that almost 60 % of the work done manually and 40 % done using the machine (the bridge) in average.</td><td>Manual Work</td><td>11.93</td><td>2.98</td></tr>
<tr><td>Bridge Work</td><td>7.95</td><td>2.02</td></tr>
<tr><td>Total</td><td>19.88</td><td>5.00</td></tr>
</table>

Over 50 exterior wall multi-panels were tracked and fitted in the distribution within the spray booth station. As was shown in table 4-7, the total process time is calculated using the total man-hours (minutes) required for spraying one multi-panel. The presented results in in Table 4-5, Table 4-6, and Table 4-7 were used later as inputs in the simulation model.

Table 4-7: **Fitting to Normal Distribution for Sprayed Multi-panels with more than 36 ft in Length, Including Unplanned Time**

Station	Family Type	Number of Resources	Time Constraints	Fitting To Normal	
				μ	σ
Spray Booth	Exteriors, Multi-Panels	Variable	Total Process Time equals spent time on spraying each multi-panel times the number of sprayers	55.72	9.65

4.4.4 Exploring Implementation Strategies and Scenarios at Machine - Assembly Line

Based on the daily demand, the production mix can include exterior, garage, and interior multi-panels. Therefore, both the multi-panels' sequences and the daily production mix are factors in determining the following:

- Line balance
- Station utilization
- Production rate, lead time, and takt time
- Possible bottlenecks
- Resources' numbers and allocation

A number of scenarios are provided to determine the mixture of the exteriors and interiors as main families. These families influence the production of the first two stations, whereas there is no significant difference between the garage walls and the exterior walls. Subsequently, the influence of garage walls appears in the balancing process of the spray booth station. The most common mixes are based on three main scenarios, as shown in Table 4-8 and Figure 4-9.

Table 4-8 allows for the determination of the takt and cycle time in the framing and sheathing station. The garage panels, on the other hand, impact the spray booth stations in terms of the multi-panels' sequences. When dealing with garage walls as exterior walls, although they do not go through a spray booth, at the same interval of those garage walls, manual exterior walls can go through the booth. This is a similar process to Landmark's. However, while studying the total length of the exterior manual walls and the garage walls on a daily basis, they were almost the same, as in 5% of the total production.

Table 4-8: Basic Scenarios Affecting the First Three Stations in the Machine-line

Scenario Number	Exterior Multi-panels Percentage out of (Exterior + Interior)	Interior Multi-panels Percentage out of (Exterior + Interior)	Repeated Pattern (Load Level)
#1	50 %	50 %	Exterior-Interior
#2	33 %	67 %	Exterior-Interior-Interior
#3	67 %	33 %	Exterior-Exterior-Interior

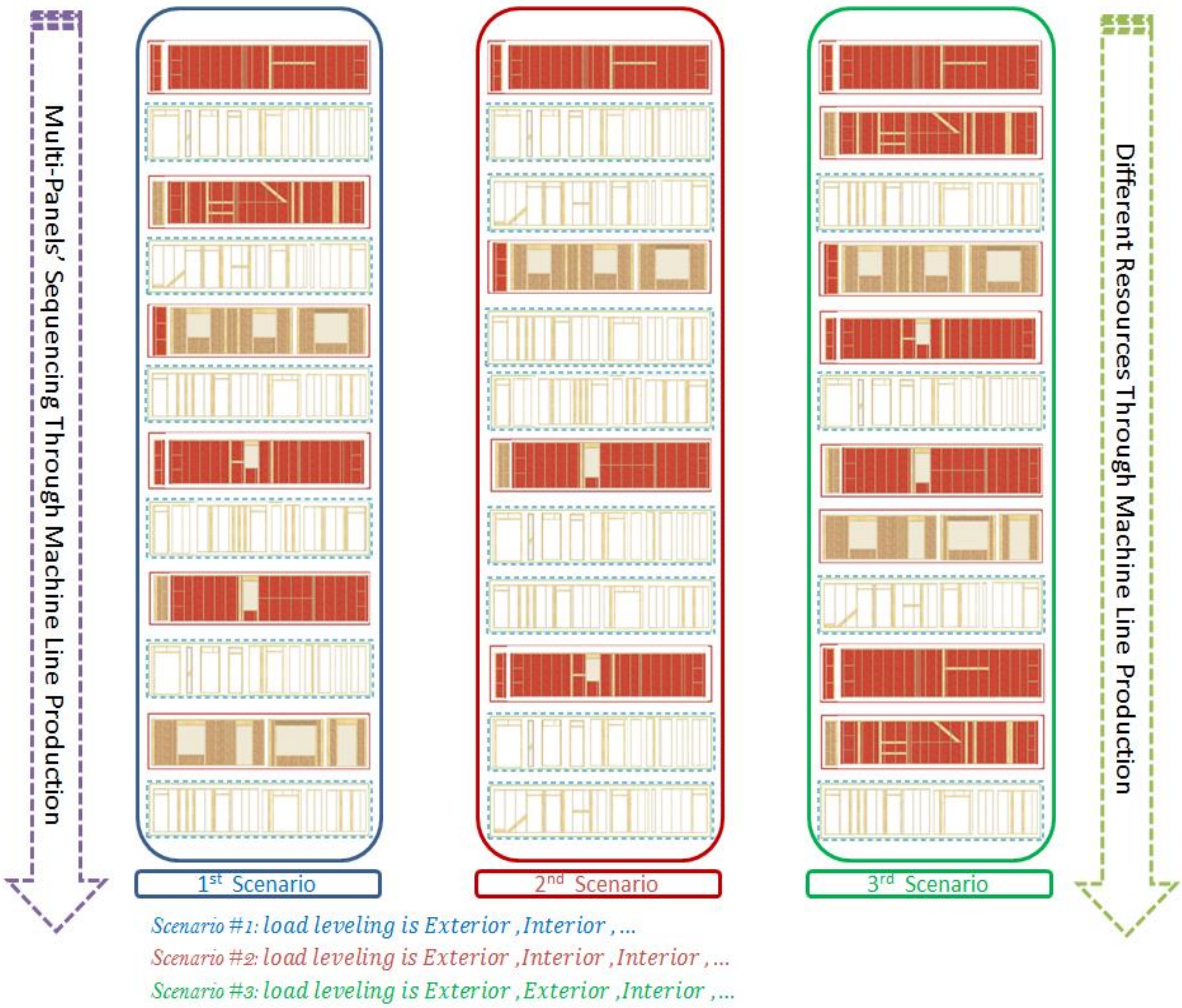


Figure 4-9: Studied Multi-Panels Sequencing in Machine Line

Determining the objective or the target can vary based on the company. Subsequently, everything begins at the brainstorming stage to identify the priorities. As in any measurement system, the first step is to list the objectives. Therefore, after some discussions with Landmark managers, the main objectives that a panelized company hopes to achieve in the machine assembly line are listed below in the order of priority:

- Meeting the customer's demands within a predefined time frame, without any defects and within safety procedures.
- Producing to takt time, where takt time equals the available working time per day, divided by the customer's daily demand. In this kind of construction, takt time is generally measured in minutes. As such, a takt equals (x minutes), signifying during (x minutes), a complete product is manufactured off the assembly line. To meet the customer's demand, the actual takt time should be less than the designed takt time.
- Creating a pull system and appropriate continuous flow with respect to LOB and LPS concepts. This allows for the drum (pace maker) to begin the process, with all of the subsequent stations to follow the same takt of the drum. In other words, the bottleneck is located in the upstream, in which no other bottlenecks should be created after the pace maker.
- Optimizing and allocating resources through a number of proposed scenarios to minimize the labour direct cost.
- Seeking perfection and seeking continuous improvements (CI).

These objectives contribute to the use of a specific number of resources in a station. The above intents also present the guidelines to attain the optimal number of required resources. To accomplish this, a fast-hitting approach is required to best enhancing the triple-*p* (productivity, profitability, and performance) models. It also helps in making daily decisions. Research on this topic advises using post- simulation as a tool. However, other constraints might occur based on other criteria or strategies. To achieve the objectives above, this research defined strategies and criteria to get the resources' optimization in the machine assembly line, as presented in Figure 4-10.

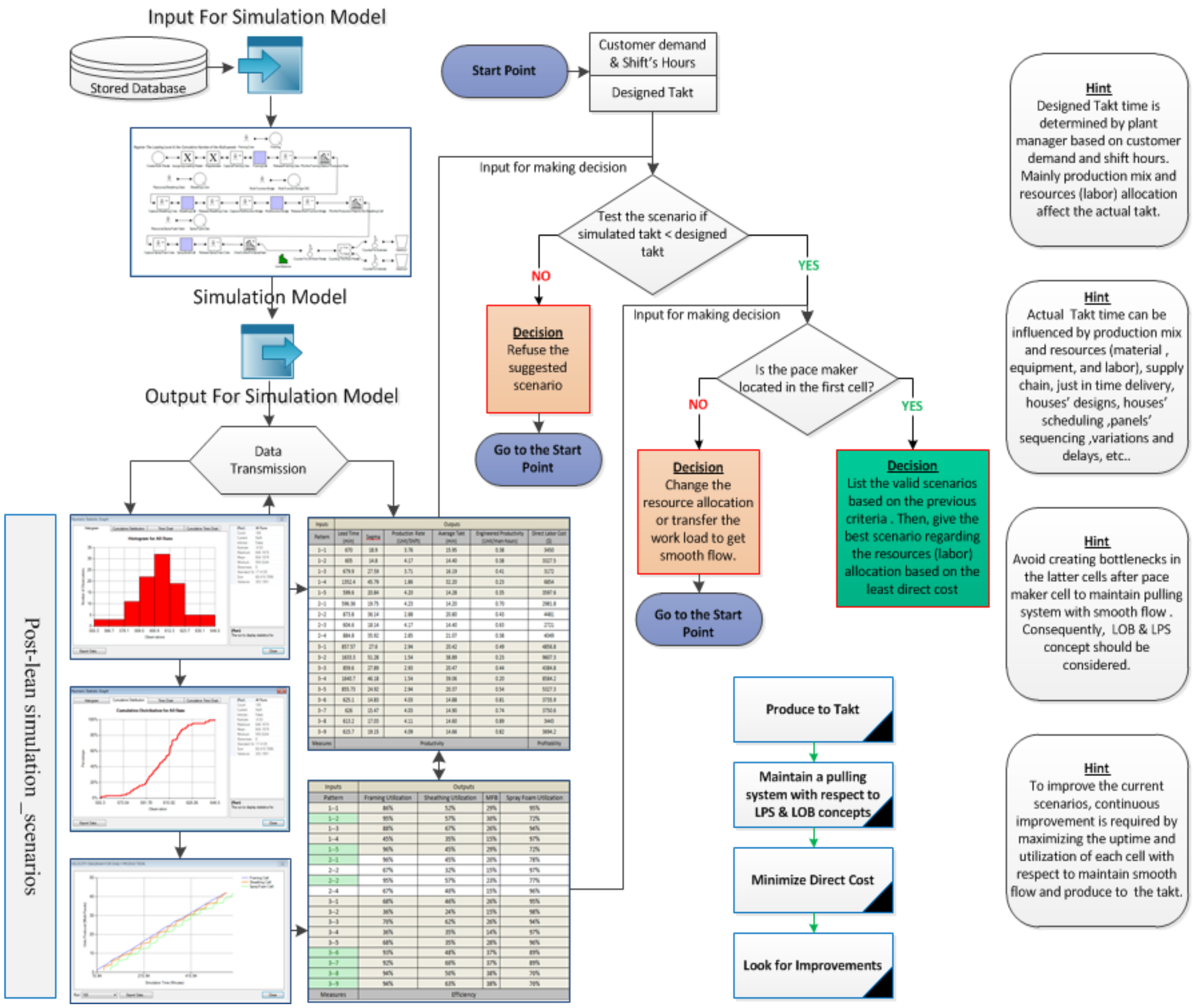


Figure 4-10: Defined Strategies and Criteria to Get the Resources' Optimization / Allocation in the Proposed Scenarios

4.4.5 Implementation of Simulation Model

Post-simulation can be used in construction management and decision support systems. It is such a noteworthy tool in automated project planning and control. Development of manufacturing technologies pushes construction industry to get advantages from afforded technologies to increase the efficiency of the work procedures. Simulation model can be used to test the effectiveness and the results of the anticipated changes. It can be employed to test different scenarios prior to implement improvement plans and to assess productivity, profitability, and performance models.

Based on lean concepts, upon exploring the basic scenarios, the simulation model focuses on mapping the current state after identifying the main factors affecting productivity and performance, such as multi-panels' sequences and product family matrixes. Therefore, that model contributes in assessing the productivity, profitability, and performance models and offers recommendations, based on the changing sequences of the multi-panel and product family matrixes. That should be affiliated also with different scenarios of human resources allocation in the production line. In this research, the simulation[7] is performed using Simphony.NET 4.0[8].

4.4.6 Mapping Different Scenarios of the Current State

In this research, the VSM includes three basic scenarios. The first scenario consists of multi-panels with half exteriors and half interiors as a mix. The second scenario is composed of multi-panels with a double ratio of interiors to exterior as a mix. The third scenario contains multi-panels with a double ratio of exteriors to interiors as a mix.

Each process in each station has two major cycle times. There is a cycle time is for exteriors and a different one for interiors. The main constraints in the case study are presented as the maximum and minimum number of resources in each station and having a designed achievable takt time. Adding more resources may not increase productivity and could potentially become a waste.

Another issue is presented in the event that people are added to a machine. Given that the speed of the machine is not associated with manpower, the addition of people does not necessarily result in increased output. Rather, when more people supervise the machine as it works, it could lead to potential manufacturing setbacks. Therefore, some stations have a fixed number of people, particularly when using CNC machines. At the stations that rely solely on manual labour, the production rate fluctuates based on the crew sizes. In this case, assigning more resources impacts the linear production rate should the resources work in a parallel manner. Resources constraints in the studied stations are presented in Table 4-9.

[7] More information regarding the used simulation model is available in Appendix C
[8] More information regarding Simphony.NET is available in Appendix A.

Table 4-9: Resources Constraints in the Studied Stations

Station	Minimum Number of people	Maximum Number of people	Characteristics
Framing Station	3	3	Machine Based Station
Sheathing Manual Work	2	4	Manual Based Station
Sheathing Multi-Function Bridge	NA	NA	Machine Based Station
Spray Foam Station	3	6	Manual Based Station

To obtain effective production performance, and through the understanding of the lean, LPS, and LOB concepts, proper integration and communication between scheduling and the production departments is necessary. To assist the productivity, profitability, and performance models, using simulation is proficient when lean concepts, LPS, LOB, and simulation technologies are integrated.

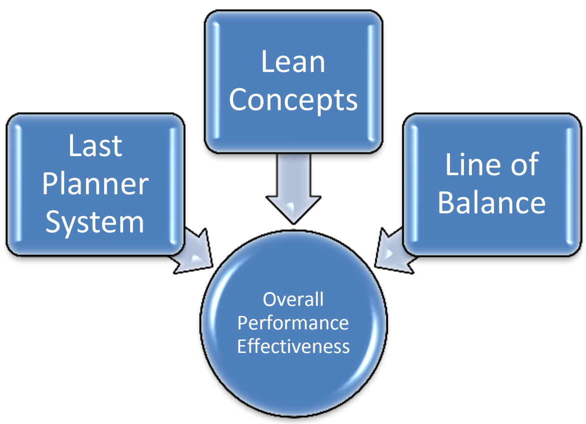


Figure 4-11: Overall Performance Effectiveness Concept

4.4.7 Verification of the Simulation Model

Zayed and Halpin present their recommendations using the validation factor (VF) where

$$VF = \frac{PMR}{CP} \qquad [3]$$

Within this formula, **PMR** represents Productivity Model Results and **CP** signifies the Collected Productivity. In the simulation model, VF is the simulation output divided by the actual output. The results were based on tracking the actual total lead time for numerous days at different times, and then comparing those results with simulated scenarios, as demonstrated in Table 4-10.

The simulated scenarios considered the same resource allocation, same panel sequencing, and same quantities as produced throughout the observed days.

Table 4-10: Comparing the Results between the Actual and Simulated Outputs

Test ID	A Simulation (minutes)	B Actual (minutes)	C=A-B Residual (minutes)	(B-A)/B Difference %	A/B FV	Resources Allocation in Stations [Framing, Sheathing, Spray foam]	Output (Multi-Panels)
1	613	605	8	-1%	1.01	[3,3,5]	43
2	93	100	-7	7%	0.93	[3,4,5]	5
3	663	635	28	-4%	1.04	[3,4,5]	46
4	266	253	13	-5%	1.05	[3,3,5]	17
5	322	311	11	-4%	1.04	[3,3,5]	22
6	652	625	27	-4%	1.04	[3,3,5]	46
7	156	151	5	-3%	1.03	[3,4,6]	10

In addition to FV, this thesis deals with a significance level (α= 0.05) as a (p-value < α= 0.05) for the regression models. If we consider the difference between the actual data and the simulated data as residual, then the null hypothesis (H_0) should be:

$$H_0: \Delta_{(Residual)} = 0 \leftrightarrow \mu_{(Simulation)} = \mu_{(Actual)}$$

$$H_1: \Delta_{(Residual)} \neq 0 \leftrightarrow \mu_{(Simulation)} \neq \mu_{(Actual)}$$

To verify the model, and by applying a paired two-sample *t*-test for means, the *P*-value was given as *P* (T<=t) two-tail = 0.04 < 0.05 with a Pearson Correlation of 99.9%. Therefore, the simulated model is acceptable.

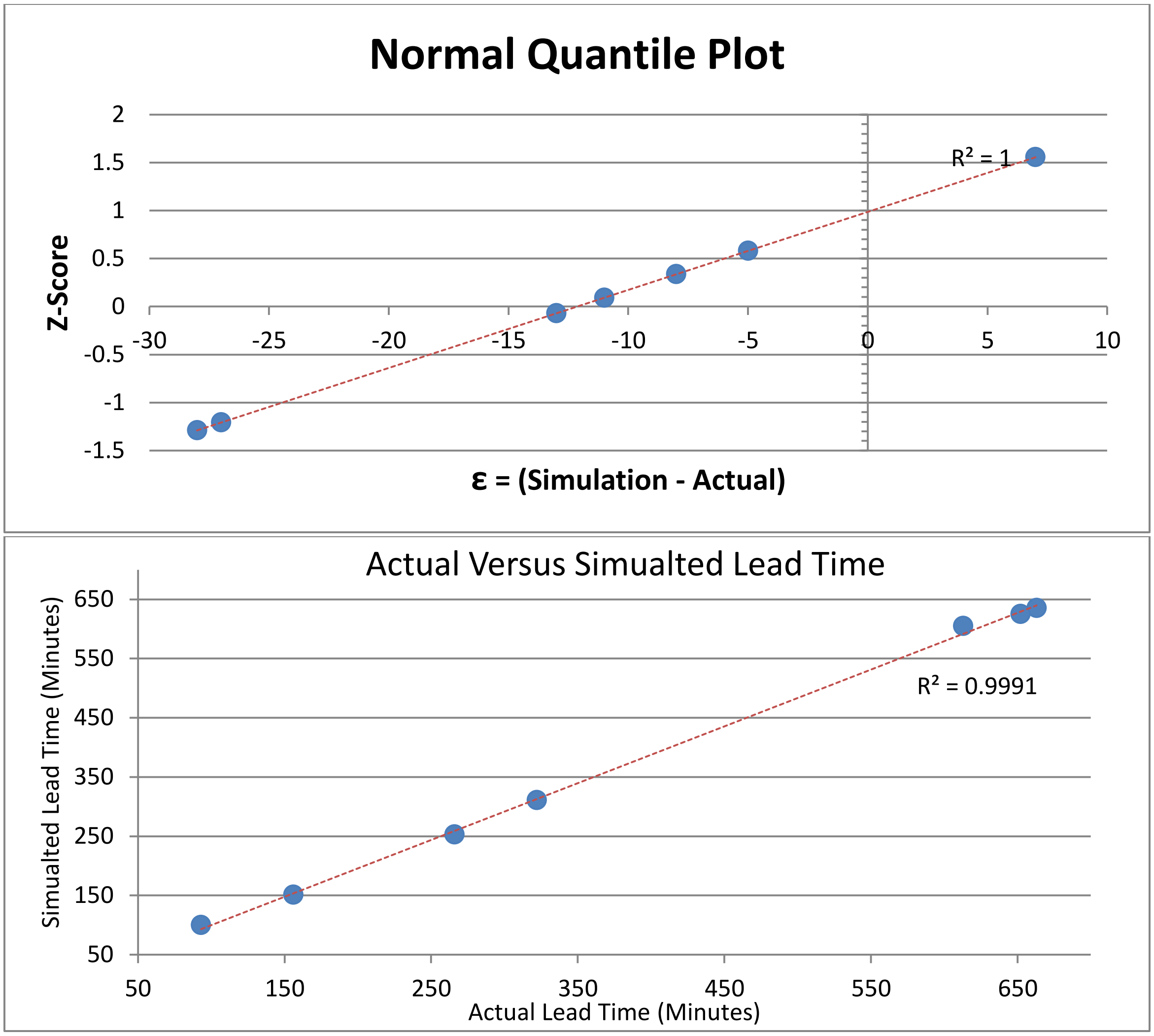


Figure 4-12: Comparing the Simulation Data versus Actual Data

4.4.8 Analyzing the Model Results

Three main scenarios of load levelling of the multi-panels and numerous patterns of resource allocation were used in the simulation model. A hierarchical process to determine the preferable scenario with associated patterns is used after that which is outlined in Figure 4-13.

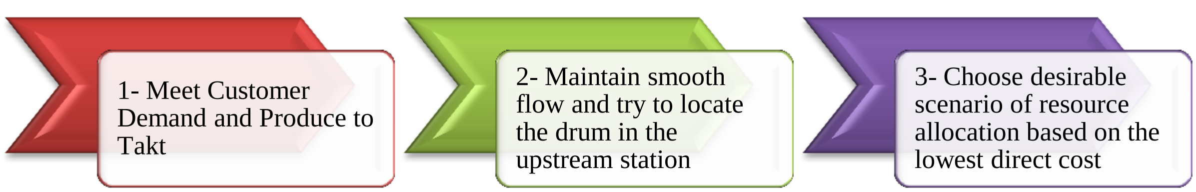


Figure 4-13: Chosen Techniques to Nominate the Best Scenario of Allocating Manpower in the Studied Stations

To simplify the work, the patterns were presented as pattern (I, J), where I represents the load levelling, and J signifies the studied case with different resources' allocation as presented in Table 4-11.

$I = 1, then\ load\ levelling\ is\ Exterior, Interior, \ldots$

$I = 2, then\ load\ levelling\ is\ Exterior, Interior, Interior, \ldots$

$I = 3, then\ load\ levelling\ is\ Exterior, Exterior, Interior, \ldots$

The analysis was performed through the comparing different patterns in each suggested scenario. The combination is driven from meeting the designed takt, then assessing the allocation of the possible bottleneck in the upstream. This is accomplished by seeking the least direct cost while achieving profitability in the same conditions.

Used Equations in the Model

In this research, the designed takt time was derived from monthly planning, and then converted to daily planning. Therefore, the takt time equals to the available working time per day, divided by the customer's daily demand as in Equation 4.

$$\boldsymbol{T_{Takt} = \frac{T_{Shift}}{N}} \qquad [\mathbf{4}]$$

$\boldsymbol{Where\ \ T_{Takt}}$: $\boldsymbol{Takt\ Time\ (minutes)}$**or what can represent the** $\boldsymbol{designed\ takt\ time\ in\ the\ model}$

T_{Shift}: $Available\ working\ time\ per\ day\ (Shift\ time)(minutes)$

N: $Customer's\ daily\ demand\ (Total\ Required\ Number\ of\ Multi - Panels)$

As an input for the model, the required quantities of multi-panels, which are more than 36 ft in length, are calculated based on the daily designed takt and shift duration. Each unit in the model is equivalent to multi-panels.

$$P_{Units} = \frac{AT_{Shift}}{T_{Takt}} \qquad [5]$$

$\boldsymbol{Where\ \ P_{Units}}$:
$\boldsymbol{Produced\ Quantities\ (units), which\ represents\ the\ calculated\ quantities\ in\ the\ model}$

AT_{Shift}: $Actual\ Daily\ Shift\ Duration\ (minutes)\ excluding\ planned\ stopage\ time$

T_{Takt} : $Takt\ Time\ (minutes)$or what can represent the $designed\ takt\ time\ in\ the\ model$

With regard to the lead time, it is presented as results of cumulative lead times in each station.

$$T_{Lead\ time} = \sum Lt(i) \quad [6]$$

$\boldsymbol{Where\ \ Lt(i): the\ leadtime\ for\ cell\ (i),}$

$\boldsymbol{T_{Lead\ time}\ (minutes)\ represents\ the\ calculated\ total\ lead\ time\ in\ the\ model}$

$$AT_{Takt} = \frac{T_{Lead\ time}}{P_{Units}} \quad [7]$$

$\boldsymbol{Where\ \ AT_{Takt}: the\ calculated\ average\ takt\ time\ in\ the\ model\ (minutes)}$

$T_{Lead\ time}: the\ calculated\ total\ lead\ time\ in\ the\ model\ (minutes)$

$P_{Units}: the\ calculated\ quantities\ (units), which\ represents\ the\ number\ of\ produced\ units\ in\ the\ shift$

Consequently, the average production rate is calculated based on the total number of the produced units divided by the total lead time as presented in Equation 8.

$$PR = \frac{P_{Units}}{T_{Lead\ time}} * 60 \quad [8]$$

$\boldsymbol{Where\ \ PR: the\ calculated\ production\ rate\ \ \ in\ the\ model\ \left(\frac{Unit}{Hour}\right)}$

$P_{Units}: the\ calculated\ quantities\ (units), which\ represents\ the\ number\ of\ produced\ units\ in\ the\ shift$

$T_{Lead\ time}: the\ calculated\ total\ lead\ time\ in\ the\ model\ (minutes)$

To maintain a smooth flow, the pacemaker should be allocated in the upstream station. Therefore, bottleneck should be avoided for being created in the stations after pacemaker. To identify the bottleneck or the drum, the measure is obtained from the station with the highest utilization.

$$Ut(i) = \left(\frac{Pt(i)}{Lt(i)}\right) \quad [9]$$

$\boldsymbol{Where\ \ Ut(i): the\ calculated\ utilization\ (\%)\ of\ the\ station(i)\ in\ the\ model}$

$Pt(i): the\ calculated\ processing\ time\ (minutes)\ in\ station\ (i)$

$Lt(i): the\ leadtime\ (minutes)\ for\ station\ (i) = Pt(i) + Wt(i)$

$Wt(i): idle\ time\ or\ waiting\ time\ in\ station\ (i)$

The obtained labour (engineered) productivity is calculated based on the total spent man-hours as inputs and the total produced units during the shift as demonstrated in Equation 10.

$$L(prod) = \left(\frac{P_{Units}}{T_{Lead\ time} * TR}\right) * 60 \quad [10]$$

$$\textbf{Where } L(prod)\textbf{: the calculated labour productivity in the model} \left(\frac{\textbf{units}}{\textbf{manhours}}\right)$$

P_{Units}: *the calculated quantities (units), which represents the number of produced units in the shift*

$T_{Lead\ time}$: *the calculated total lead time in the model (minutes)*

TR: *the total resources'(labour)numbers, which used to fabricate the produced units in the shift*

After getting the engineered productivity of the labour, direct labour cost will be available, based the average hourly rate and the spent man-hours as revealed in Equation 11.

$$DLC = \begin{cases} TR \times \left(\frac{T_{Lead\ time}}{60}\right) \times RHR, & if\ T_{Lead\ time} < T_{Shift} \\ TR \times \left(\frac{T_{Shift}}{60}\right) \times RHR + TR \times \left(\frac{T_{Lead\ time} - T_{Shift}}{60}\right) \times OHR, & if\ T_{Lead\ time} > T_{Shift} \end{cases} \quad [11]$$

$$\textbf{Where } DLC\textbf{: the calculated Direct Labour Cost } (\$) \textbf{ in the model}$$

TR: *the total resources'(labour)numbers, which used to fabricate the produced units in the shift*

$T_{Lead\ time}$: *the calculated total lead time in the model (minutes)*

T_{Shift}: *Available working time per day (shift time)(minutes)*

RHR: *the Regular Average Hourly Rate* $\left(\frac{\$}{hour}\right)$

OHR: *the Over Average Hourly Rate* $\left(\frac{\$}{hour}\right)$

In Table 4-12, the Lead time was calculated based on the sample mean (average), where the standard deviation (STDV) of the total lead time was calculated as presented in Equation 12, 13.

$$Lead\ time\ (mean) = \frac{\sum_{i=1}^{n} T_{Lead\ time}(i)}{n} \quad [12]$$

where n is the number of runs in the simualtion model

$T_{Lead\ time}(i)$ *represnts the vlaue of the* $T_{Lead\ time}$ *(minutes) in each run*

$$Standard\ Deviation\ (STDV) = \sqrt{\frac{\sum_{i=1}^{n}(T_{Lead\ time}(i) - \mu)^2}{n-1}} \quad [13]$$

where (μ) *is the mean*
= Lead time (mean) in this case, n is the number of runs in the simualtion model

$T_{Lead\ time}(i)$ $represnts\ the\ vlaue\ of\ the\ T_{Lead\ time}\ (minutes)\ in\ each\ run.$

$$Y = \bar{y} \pm t_{(n-1),(1-\frac{\alpha}{2})} \frac{S}{\sqrt{n}} \quad [14]$$

Where: Y = confidence interval of mean value with a 95% confidence level; $\bar{y}$ = mean value of production rate, average takt, labour productivity, and direct labour cost; t = value of t-distribution with the corresponding confidence interval and simulation running times; S = standard deviation of production rate, average takt, labour productivity, and direct labour cost based on the simulation results; n = simulation running times.

Simulation Results and Outcomes

The simulation model results in assessing the criteria, inputs, and outputs, including possible productivity, profitability, and performance measures, as presented in Tables 4-11, 4-12, and 4-13. Table 4-14 offers a proportional evaluation between two patterns, using the same scenario and inputs. It demonstrates that resource allocation is a factor in determining the location of bottleneck, the labour (engineered) productivity, and associated probability.

Table 4-11: Criteria, and Inputs of the Simulated Scenarios

Scenario #	Criteria		Inputs					
	Shift Duration [T_{Shift}]	Designed Daily Takt [T_{Takt}]	Quantity [P_{Units}]	Pattern ID	Framing Crew	Sheathing Crew	Spray Foam Crew	Total Resources [TR]
1	630 min	15 min	42 Multi-Panels	1--1	3	2	3	8
	630 min	15 min	42 Multi-Panels	1--2	3	2	4	9
	630 min	15 min	42 Multi-Panels	1--3	3	3	4	10
	630 min	15 min	42 Multi-Panels	1--4	3	2	5	10
	630 min	15 min	42 Multi-Panels	1--5	3	3	5	11
	630 min	15 min	42 Multi-Panels	1--6	3	4	5	12
2	630 min	15 min	42 Multi-Panels	2--1	3	2	3	8
	630 min	15 min	42 Multi-Panels	2--2	3	3	3	9
	630 min	15 min	42 Multi-Panels	2--3	3	2	4	9
	630 min	15 min	42 Multi-Panels	2--4	3	3	4	10
	630 min	15 min	42 Multi-Panels	2--5	3	2	5	10
3	630 min	15 min	42 Multi-Panels	3--1	3	2	3	8
	630 min	15 min	42 Multi-Panels	3--2	3	3	3	9
	630 min	15 min	42 Multi-Panels	3--3	3	2	4	9
	630 min	15 min	42 Multi-Panels	3--4	3	3	4	10
	630 min	15 min	42 Multi-Panels	3--5	3	2	5	10
	630 min	15 min	42 Multi-Panels	3--6	3	4	4	11
	630 min	15 min	42 Multi-Panels	3--7	3	3	5	11
	630 min	15 min	42 Multi-Panels	3--8	3	4	5	12
	630 min	15 min	42 Multi-Panels	3--9	3	3	6	12
	630 min	15 min	42 Multi-Panels	3--10	3	4	6	13

Table 4-12: Outputs of the Simulated Scenarios based on 95% Confidence Level

Inputs	Outputs					
Pattern ID	Lead Time (mean)	Sigma [STDV]	Production Rate (Unit/Shift) [PR]	Average Takt $[AT_{Takt}]$	Engineered Labour Productivity (Unit/man-hours) $[L(prod)]$	Direct Labour Cost ($) $[DLC]$
Scenario #1: load levelling is Exterior, Interior, Exterior, Interior, etc …						
1--1	1352.4	45.79	[1.85 – 1.88]	[32.41 – 31.99]	[0.231 – 0.234]	[$6,908 - $6,801]
1--2	679.9	27.59	[3.68 – 3.74]	[16.32 – 16.06]	[0.409 – 0.415]	[$3,208 - $3,135]
1--3	670	18.9	[3.74 – 3.78]	[16.04 – 15.86]	[0.374 – 0.378]	[$3,478 - $3,422]
1--4	610.5	18.9	[4.10 – 4.15]	[14.64 – 14.45]	[0.410 – 0.415]	[$3,071 - $3,034]
1--5	605	14.8	[4.15 – 4.19]	[14.47 – 14.34]	[0.377 – 0.380]	[$3,343 - $3,312]
1--6	599.6	20.84	[4.17 – 4.23]	[14.37 – 14.18]	[0.348 – 0.353]	[$3,622 - $3,573]
Scenario #2: *load levelling is Exterior, Interior, Interior, Exterior, Interior, Interior, etc …*						
2--1	884.8	35.92	[2.83 – 2.87]	[21.23 – 20.90]	[0.353 – 0.359]	[$4,091 - $4,007]
2--2	873.8	36.14	[2.86 – 2.91]	[20.97 – 20.64]	[0.318 – 0.323]	[$4,528 - $4,433]
2--3	604.6	18.14	[4.14 – 4.19]	[14.48 – 14.31]	[0.460 – 0.466]	[$2,737 - $2,705]
2--4	596.36	19.75	[4.20 – 4.25]	[14.29 – 14.11]	[0.420 – 0.425]	[$3,001 - $2,962]
2--5	587.8	20.2	[4.26 – 4.32]	[14.09 – 13.90]	[0.426 – 0.432]	[$2,959 - $2,919]
Scenario #3: *load levelling is Exterior, Exterior, Interior, Exterior, Exterior, Interior, etc …*						
3--1	1640.7	46.18	[1.53 – 1.54]	[39.28 – 38.85]	[0.191 – 0.193]	[$8,936 - $8,530]
3--2	1633.3	51.28	[1.53 – 1.55]	[39.13 – 38.65]	[0.170 – 0.172]	[$9,675 - $9,539]
3--3	859.6	27.89	[2.91 – 2.95]	[20.60 – 20.34]	[0.324 – 0.328]	[$4,422 - $4,348]
3--4	857.57	27.6	[2.92 – 2.96]	[20.55 – 20.29]	[0.292 – 0.296]	[$4,897 - $4,816]
3--5	645.8	16.7	[3.88 – 3.92]	[15.45 – 15.30]	[0.388 – 0.392]	[$3,293 - $3,244]
3--6	855.73	24.92	[2.93 – 2.96]	[20.49 – 20.26]	[0.266 – 0.269]	[$5,368 - $5,287]
3--7	626	15.47	[4.01 – 4.05]	[14.98 – 14.83]	[0.364 - 0.368]	[$3,460 - $3,426]
3--8	625.1	14.83	[4.01 – 4.05]	[14.95 – 14.81]	[0.334 – 0.338]	[$3,768 - $3,733]
3--9	615.7	19.15	[4.07 – 4.12]	[14.75 – 14.57]	[0.339 – 0.343]	[$3,717 - $3,672]
3--10	613.2	17.03	[4.09 – 4.13]	[14.68 – 14.52]	[0.314 – 0.318]	[$4,007 - $3,964]
Assessing	Productivity					Profitability

Table 4-13: Presenting the Average Utilization of the Studied Stations

Inputs	Outputs			
Pattern	Framing Utilization [Ut(%)]	Sheathing Utilization [Ut(%)]	MFB	Spray Foam Utilization [Ut(%)]
Scenario #1: $load\ levelling\ is\ Exterior, Interior, Exterior, Interior, etc\ \ldots$				
1--1	45%	35%	15%	97%
1--2	88%	67%	26%	94%
1--3	86%	52%	29%	95%
1--4	94%	42%	30%	70%
1--5	95%	57%	30%	72%
1--6	96%	45%	29%	72%
Scenario #2: $load\ levelling\ is\ Exterior, Interior, Interior, Exterior, Interior, Interior, etc\ \ldots$				
2--1	67%	40%	15%	96%
2--2	67%	32%	15%	97%
2--3	95%	57%	23%	77%
2--4	96%	45%	20%	78%
2--5	96%	60%	22%	57%
Scenario #3: $load\ levelling\ is\ Exterior, Exterior, Interior, Exterior, Exterior, Interior, etc\ \ldots$				
3--1	36%	35%	14%	97%
3--2	36%	24%	15%	98%
3--3	70%	62%	26%	94%
3--4	68%	46%	26%	95%
3--5	90%	90%	37%	88%
3--6	68%	35%	28%	96%
3--7	92%	60%	37%	89%
3--8	93%	48%	37%	89%
3--9	94%	63%	38%	70%
3--10	94%	50%	38%	70%
Assessing	Efficiency			

Table 4-14: A comparative Study between Two Patterns with Same Inputs but Different Resources 'Allocation

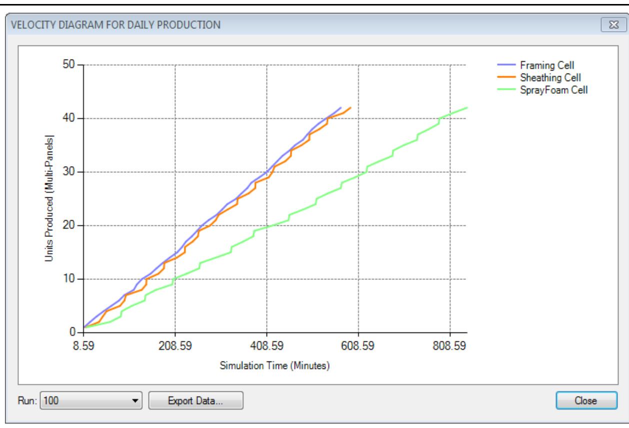
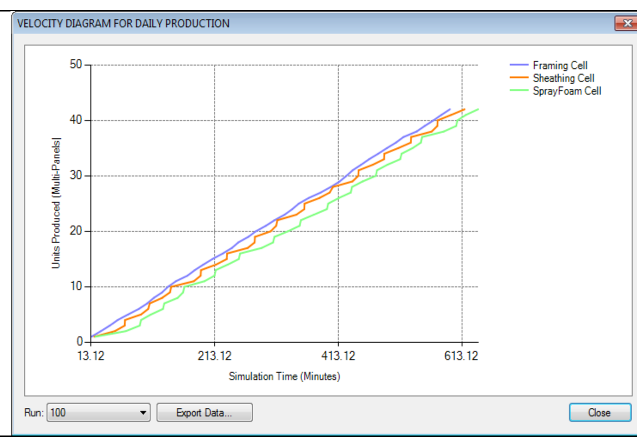
Pattern	3--6	3--7
Quantity /Outputs	42 Units	42 Units
Total Number of Resources	11	11
Resources Allocation	(3) Framing, (4) Sheathing, (4) Spray Foam,	(3) Framing, (3) Sheathing, (5) Spray Foam,
Lead Time	[851 – 860] minutes; within 95% confidence level	[623 – 629] minutes ; within 95% confidence level
Average Takt	[20.26 - 20.49] minutes; within 95% confidence level	[14.83 - 14.98] minutes; within 95% confidence level
Engineered Labour Productivity	[0.266 - 0.269] unit / man-hours; within 95% confidence level	[0.36 - 0.37] unit / man-hours; within 95% confidence level
Daily labour Direct Cost	[$5,287 - $5,368] ; within 95% confidence level	[$3,426 - $3,460] ; within 95% confidence level
Utilization of the Upstream station	68 %	92 %
Utilization of the Downstream station	96 %	89%
Bottleneck Is Driven By	Downstream station	Upstream station
Is The Pace Maker Located In Upstream?	NO	YES
LOB [Velocity Diagram]		

Table 4-15: Analyzed Results for the Proposed Scenarios and Ranking the Outputs Based on the Defined Strategies

Inputs	Outputs As Mean Values						
Pattern ID	Average Takt $[AT_{Takt}]$	Meeting the Designed Takt	Pace Maker is Allocated in	Production Rate (Unit/Shift) [PR]	Engineered Labour Productivity (Unit/man-hours) $[L(prod)]$	Direct Labour Cost ($) [DLC]	Overall Performance Ranking
1--1	32.20	NO	Downstream	1.86	0.23	$6,854	NA
1--2	16.19	NO	Downstream	3.71	0.41	$3,172	NA
1--3	15.95	NO	Downstream	3.76	0.38	$3,450	NA
1--4	14.54	YES	Upstream	4.13	**0.41**	**$3,053**	**1**
1--5	14.40	YES	Upstream	4.17	0.38	$3,328	2
1--6	14.28	YES	Upstream	4.20	0.35	$3,598	3
2--1	21.07	NO	Downstream	2.85	0.36	$4,049	NA
2--2	20.80	NO	Downstream	2.88	0.32	$4,481	NA
2--3	14.40	YES	Upstream	4.17	**0.46**	**$2,721**	**1**
2--4	14.20	YES	Upstream	4.23	0.42	$2,982	3
2--5	14.00	YES	Upstream	4.29	0.43	$2,939	2
3--1	39.06	NO	Downstream	1.54	0.19	$8,584	NA
3--2	38.89	NO	Downstream	1.54	0.17	$9,607	NA
3--3	20.47	NO	Downstream	2.93	0.33	$4,385	NA
3--4	20.42	NO	Downstream	2.94	0.29	$4,857	NA
3--5	15.38	NO	Upstream	3.90	0.39	$3,269	NA
3--6	20.37	NO	Downstream	2.94	0.27	$5,327	NA
3--7	14.90	YES	Upstream	4.03	**0.37**	**$3,443**	**1**
3--8	14.88	YES	Upstream	4.03	0.34	$3,751	3
3--9	14.66	YES	Upstream	4.09	0.34	$3,694	2
3--10	14.60	YES	Upstream	4.11	0.32	$3,986	4
Assessing	Meeting the Designed Takt		Flow	Productivity		Profitability	Performance

Upon presenting the analyzed results, it is crucial in project management that the best scenarios and patterns are ranked based on the defined strategies and goals which have been presented in Figure 4-10, and Figure 4-13. As demonstrated in Table 4-15, Figure 4-14, and Figure 4-15, it appears that less takt time results in a high production rate, but does not necessarily result in higher engineered productivity or less direct costs. Also, as demonstrated in Table 4-15, Figure 4-14 and Figure 4-15, the higher the engineered labour productivity, the lower the associated direct labour cost will be. It appears also from the results that load levelling has a strong effect, especially when there are a limited number of resources. Therefore, the three scenarios conclude approximately with the same results regarding the takt time, labour cost, engineered labour productivity, and production rate if there is over-usage of resources. Accordingly, using too many resources in the production line eliminates the effect of load levelling and results in less engineered labour productivity and more associated direct cost.

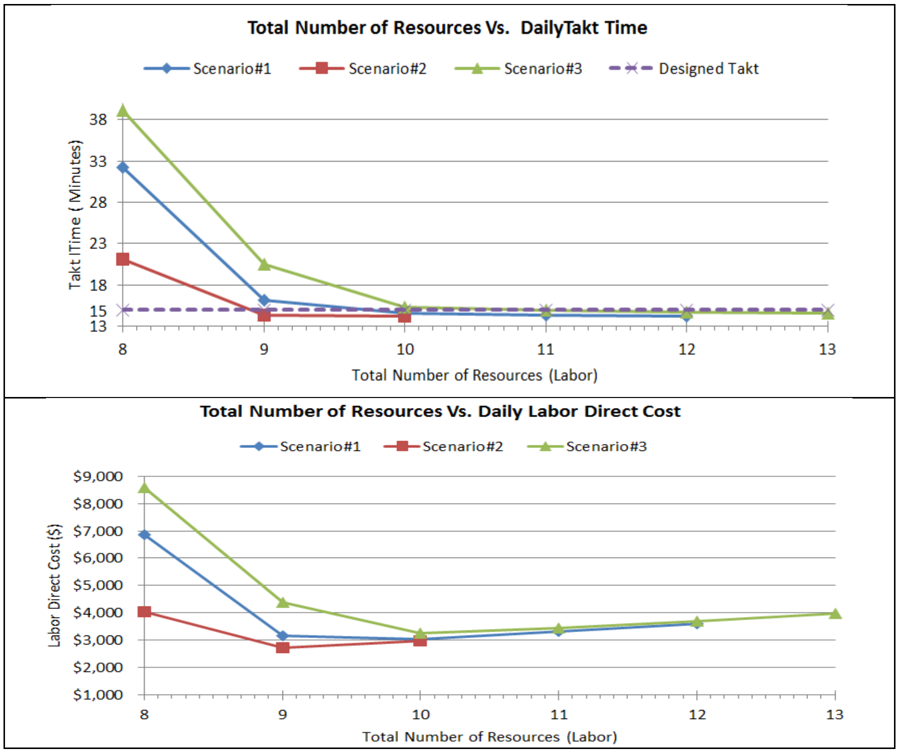


Figure 4-14: Total Number of Resources Effect on Daily Average Takt and Associated Direct Labour Cost

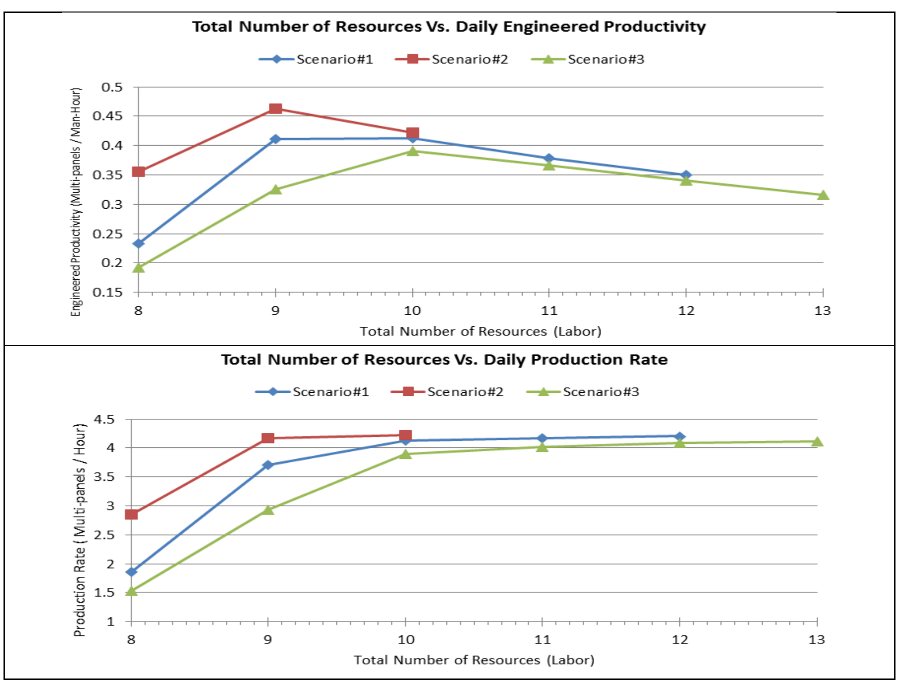


Figure 4-15: Total Number of Resources Effect on Daily Engineered Labour Productivity and Production Rate

Consequently, simulating different scenarios based on load levelling and resource allocation guides the schedulers and managers to estimate a daily takt time and planning ahead. This estimation is contingent on the pace maker cycle time (takt) and the limitations in resources throughout the working days. This leads to ranking scenarios using defined patterns and load levelling cases, which are maintained throughout production days to achieve enhanced performance. In this case, the LPS and LOB concepts are followed to achieve a higher performance for each scenario, based on limited resources and daily demands. Enhancing all the triple-*p* (productivity, profitability, and performance) models in general and profitability in specific can be easily done through ranking the scenarios based on overall performance ranking. That aids in speeding up the flow of products down the chain and within the production constrains such as resources numbers and allocation, load levelling, daily production, and designed takt time. Considering the previous logic and balancing the resources among the production line lead basically to improve the operational efficiency of production line and increase the profitability, as has been demonstrated in this thesis.

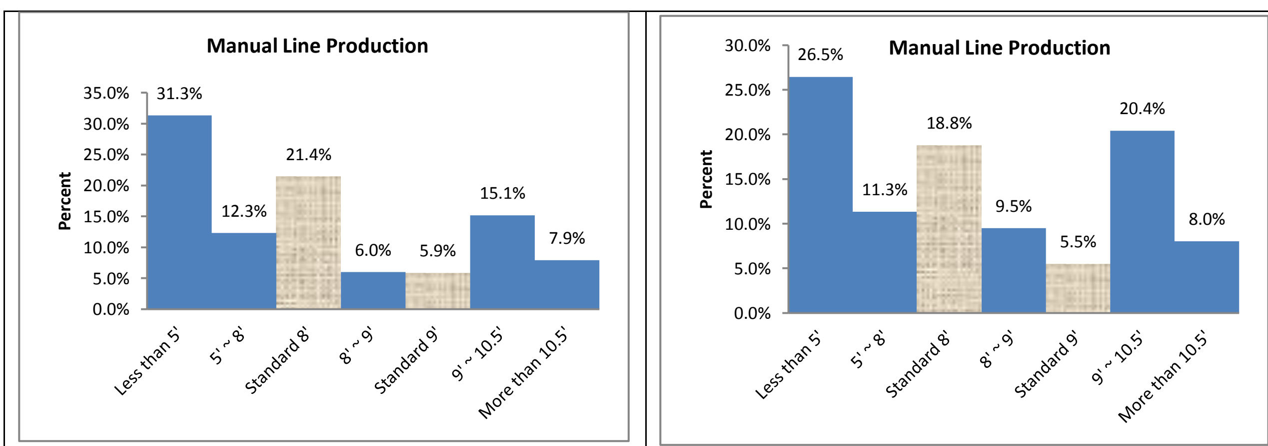
4.5 Manual Station Assembly

The manual station has unique characteristics. Numerous products with different sizes, dimensions, and types go through this station. This station is separated from others stations because it has a buffer and safety inventories. Therefore, this station is studied as a stand-alone station without considering the effect of other stations. As a result, the panels’ sequence is not as significant. In studying this station, the crew builds the panels based on the houses’ daily scheduling requirements wherein the manual production is changeable and the crew size is unstable. The latter can differ daily.

4.5.1 Production Family Matrix in the Manual Station

As previously outlined, based on the production analysis of the volume and the variety of products of over 100 houses, the total manual production is around 16% of the total production at the Landmark plant. This 16 % also contains high production of standard walls with 8 ft and 9 ft in height. This demonstrates that the majority of production is driven by the machine assembly line.

As shown in Figure 4-16, as a result of the wide variety of manual production, clustering the manual products is necessary to analyze the productivity throughout different groups. This thesis supports the efforts of modelling the manual station production features to achieve the required man-hours using linear regression. In this case, the key factors are the manual production features and groups. The estimated required man-hours are determined by multiplying a factor with the linear length of each produced component within a specific group.



Variation Between Manual Production Products Based on Total Number of Each Group

Variation Between Manual Production Products Based on Total Linear Length of Each Group

Figure 4-16: Variations between Manual Station's Productions

As discussed in Chapter 3, the studied groups were determined based on the height of each panel at Landmark, as follows:

- Exteriors less than 5 ft in height.
- Exteriors between 5 and 8 ft in height.
- Standard Exterior (can also done by the machine) as 8 ft or 9 ft in height.
- Exteriors between 8 and 9 ft in height.
- Exteriors between 9 and 10.5 ft in height
- Exteriors more than 10.5 ft in height.
- Exterior Gable or rake walls, which contain various exterior walls with an angled shape regardless of the height, in this case.
- Interiors less than 5 ft in height.
- Interiors between 5 and 8 ft in height.
- Standard Interiors (can also done by the machine) as 8 ft or 9 ft in height.
- Interiors between 8 and 9 ft in height.
- Interiors between 9 and 10.5 ft in height.
- Interiors more than 10.5 ft in height.

Machine assembly line and the manual line contain distinct differences. The manual line must not send garage walls to the spray booth. As such, the product family is often divided into two classifications, including the garage and exteriors as the first class, and the interior and mechanical as the second class. In reviewing the studied groups, they are either exteriors or interiors. The exteriors are garage walls or normal exterior. The interiors are either mechanical or normal interior.

4.5.2 Data Collection in the Manual Station

The purpose of the collection of integrated data is to gain useful inputs and outputs in terms of the users' expectations and study perspectives. Data was collected manually for over five months (September 2012 to January 2013) based on the CAD drawings to build the regression model. The crew leaders immediately reported the delays in production, and the reports were then analyzed. The days that experienced major and/or minor delays were excluded and, subsequently, the data was analyzed during normal work conditions. This means that only operating man-hours were used in the productivity regression model.

Similar to the machine line that collected and analyzed data, all of the instructions presented in previous chapters and Appendix B were followed, in terms of inputs, outputs, constraints, and filtrations. The number of resources in manual station was documented daily and the working hours. Daily man-hours were calculated based on total man-hours spent in the manual station, provided by the production manager. The production manager at landmark uses Avanti[9] which generates and records man-hours for each employee. In this research, the production manager provides the daily man-hours in the manual station and the crew size without getting any access neither to the names nor the hourly rates of the crew.

4.5.3 Building Regression Model

After gathering the historical data, building the productivity model looks more complicated because of the numbers of the inputs factors. 75% of the data was used for building the model, with the remaining 25% applied towards the verification and/or validation of the models.

Choosing the type of regression

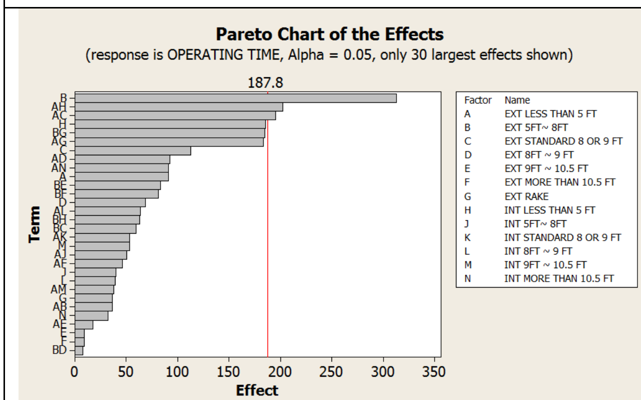
Minitab 16[10] was used to build, analyze, test, and validate the model. While the chosen factors appeared enormous, a tangible challenge was gained regarding the complexity of the model's factors. Therefore, linear regression appeared to be the simplest way to handle the various factors. It also demonstrated an opportune way of dealing with many factors rather than a quadratic, cubic, or other non-linear regressions—especially in Minitab.

The main effects are determined by the production features with 13 groups of heights and categories. However, the interactions between the factors are a parameter in determining their coefficients. In using Minitab 16 to analyze the data, and based on two-way interactions (two layers), a Design of Experiments (DOE) was developed. DOE was developed by defining custom factorial design, followed by the analysis of factorial design within interactions between factors.

[9] More information regarding Avanti software is available in Aappendix A.
[10] More information regarding Minitab 16 is available in Appendix A.

The Pareto Chart of Effects and the normal plot of the effects were presented in two-way interactions, outlining the 30 largest effects on net operating time (man-hours). Upon testing the *P*-value factors, the majority of the combined factors demonstrated a large *P*-value (most *P*-values were larger than 0.1) even though it demonstrated high R-square values. This results in a lack of evidence to reject the null hypnosis. In other words, this indicates that the main factors within one layer are explanatory and independent variables. Therefore, this research will focus on only one layer of the main factors as independent factors without interactions.

Pareto Chart of the Effects	Normal Plot of the Effects



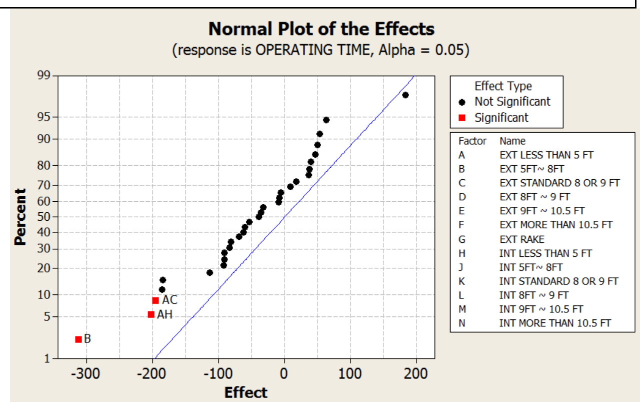


Figure 4-17: Pareto Chart and Normal Plot of the Effects Based on Two Ways Interactions between the Impacted Factors

Developing the regression model

Through analysis, the main 13 factors exposed independent behaviours. Given the high *P*-values of the integrated factors, the behaviours were based on two layers of interactions. Developing the model and filtering the factors to reach an estimation formula of operating time (man-hours) is easier to accomplish when using independent factors.

To better understand those factors affect the man-hours calculation, the criterion of the *P*-value is used to reject the null hypothesis. As presented in Figure 4-18, the input data is entered as the total length of each group of panels that are built on specific days. Once again, input data excludes all delay factors. The initial evaluation of the regression model immediately excluded four factors due to high *P*-value numbers, as presented in Figure 4-19.

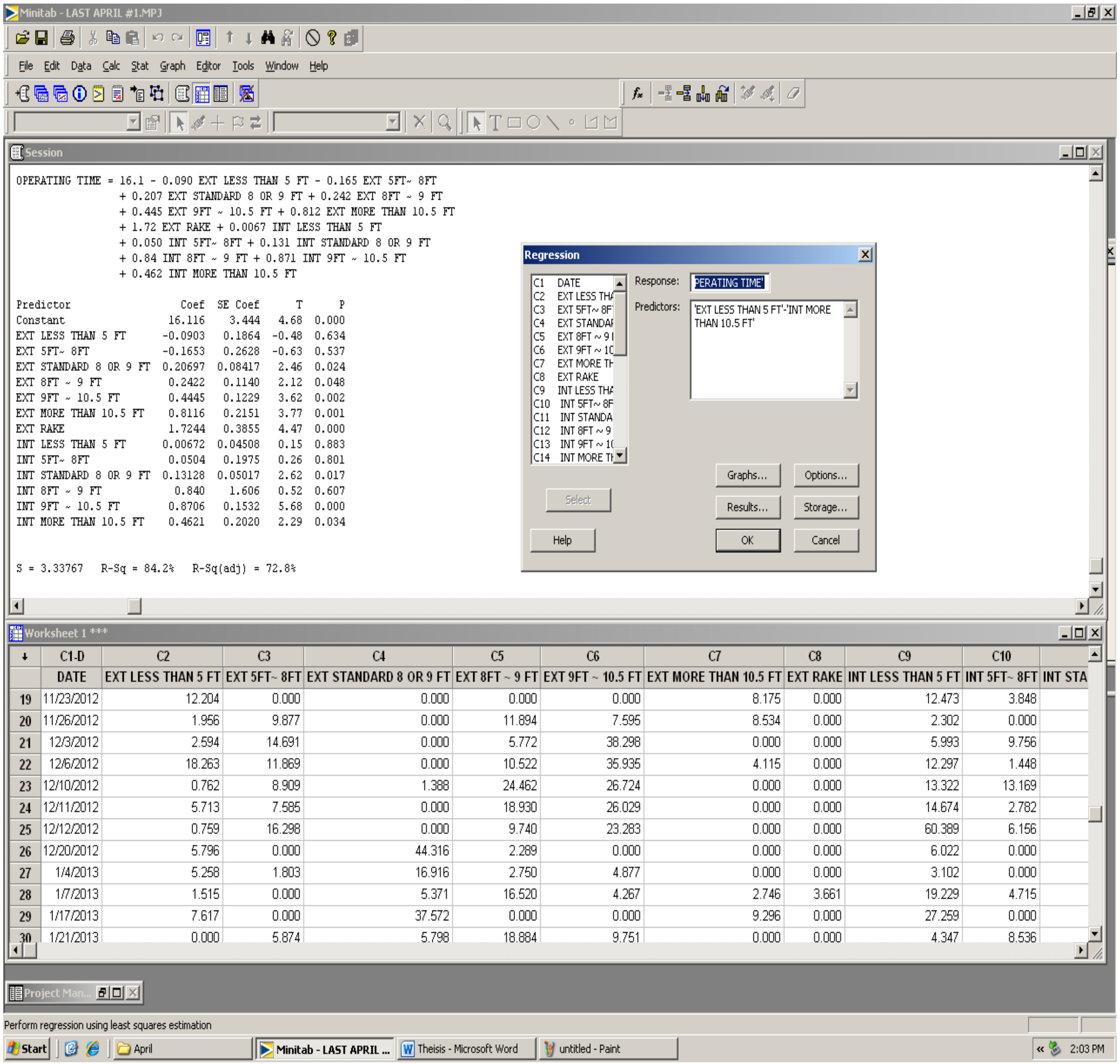


Figure 4-18 : Main User Interface Using Minitab with the Data Entry

Upon removing and editing the predictors, the conclusive findings are presented in Figure 4-21. It appears that all of the *P*-values for the predictors are less than 0.05, which rejects the null hypothesis for those factors as inputs. There were 13 initials factors, resulting in eight final predictors. The predictors represent the linear length of each group as inputs for the regression model measured by metres.

```
OPERATING TIME = 16.1 - 0.090 EXT LESS THAN 5 FT - 0.165 EXT 5FT~ 8FT
                 + 0.207 EXT STANDARD 8 OR 9 FT + 0.242 EXT 8FT ~ 9 FT
                 + 0.445 EXT 9FT ~ 10.5 FT + 0.812 EXT MORE THAN 10.5 FT
                 + 1.72 EXT RAKE + 0.0067 INT LESS THAN 5 FT
                 + 0.050 INT 5FT~ 8FT + 0.131 INT STANDARD 8 OR 9 FT
                 + 0.84 INT 8FT ~ 9 FT + 0.871 INT 9FT ~ 10.5 FT
                 + 0.462 INT MORE THAN 10.5 FT

Predictor                    Coef   SE Coef      T      P
Constant                   16.116     3.444   4.68  0.000
EXT LESS THAN 5 FT        -0.0903    0.1864  -0.48  0.634
EXT 5FT~ 8FT              -0.1653    0.2628  -0.63  0.537
EXT STANDARD 8 OR 9 FT    0.20697   0.08417   2.46  0.024
EXT 8FT ~ 9 FT             0.2422    0.1140   2.12  0.048
EXT 9FT ~ 10.5 FT          0.4445    0.1229   3.62  0.002
EXT MORE THAN 10.5 FT      0.8116    0.2151   3.77  0.001
EXT RAKE                   1.7244    0.3855   4.47  0.000
INT LESS THAN 5 FT        0.00672   0.04508   0.15  0.883
INT 5FT~ 8FT               0.0504    0.1975   0.26  0.801
INT STANDARD 8 OR 9 FT    0.13128   0.05017   2.62  0.017
INT 8FT ~ 9 FT              0.840     1.606   0.52  0.607
INT 9FT ~ 10.5 FT          0.8706    0.1532   5.68  0.000
INT MORE THAN 10.5 FT      0.4621    0.2020   2.29  0.034


S = 3.33767   R-Sq = 84.2%   R-Sq(adj) = 72.8%
```

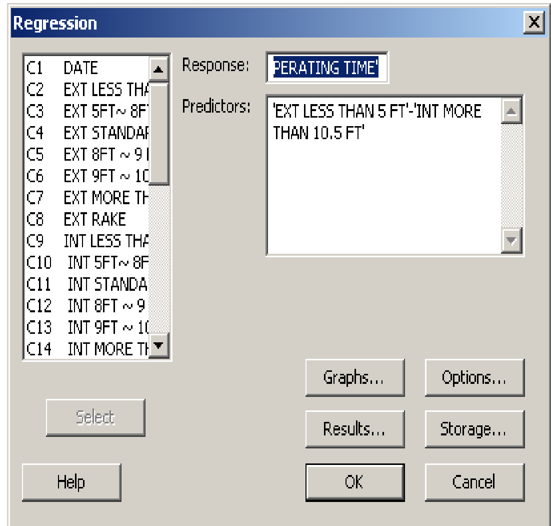


Figure 4-19: Initial Evaluating of the Regression Model

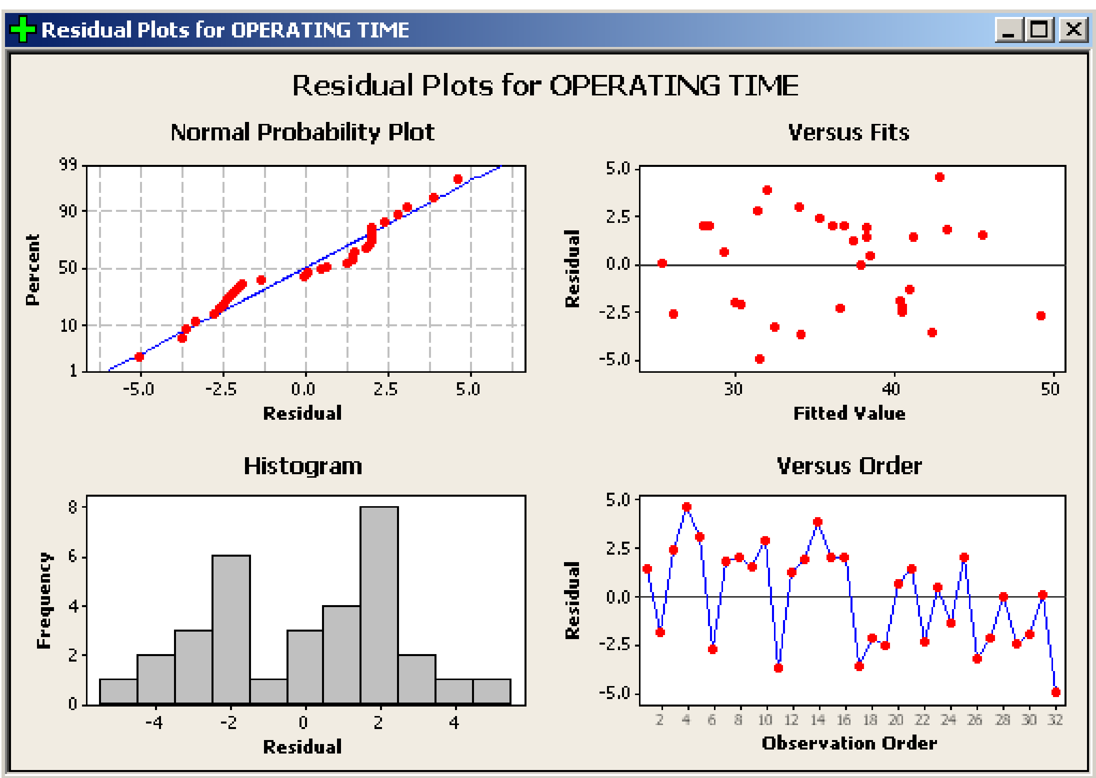


Figure 4-20: Initial Residual Plots for Operating Time of the Regression Model

```
The regression equation is
OPERATING TIME = 15.8 + 0.198 EXT STANDARD 8 OR 9 FT + 0.266 EXT 8FT ~ 9 FT
               + 0.376 EXT 9FT ~ 10.5 FT + 0.749 EXT MORE THAN 10.5 FT
               + 1.76 EXT RAKE + 0.903 INT 8~10.5 FT Excluding ST
               + 0.142 INT STANDARD 8 OR 9 FT + 0.449 INT MORE THAN 10.5 FT
```

Predictor	Coef	SE Coef	T	P
Constant	15.773	2.214	7.12	0.000
EXT STANDARD 8 OR 9 FT	0.19812	0.06393	3.10	0.005
EXT 8FT ~ 9 FT	0.26636	0.08882	3.00	0.006
EXT 9FT ~ 10.5 FT	0.37622	0.05702	6.60	0.000
EXT MORE THAN 10.5 FT	0.7492	0.1376	5.44	0.000
EXT RAKE	1.7608	0.3157	5.58	0.000
INT 8~10.5 FT Excluding ST	0.9029	0.1262	7.16	0.000
INT STANDARD 8 OR 9 FT	0.14185	0.03771	3.76	0.001
INT MORE THAN 10.5 FT	0.4492	0.1509	2.98	0.007

S = 2.99904   R-Sq = 83.7%   R-Sq(adj) = 78.0%

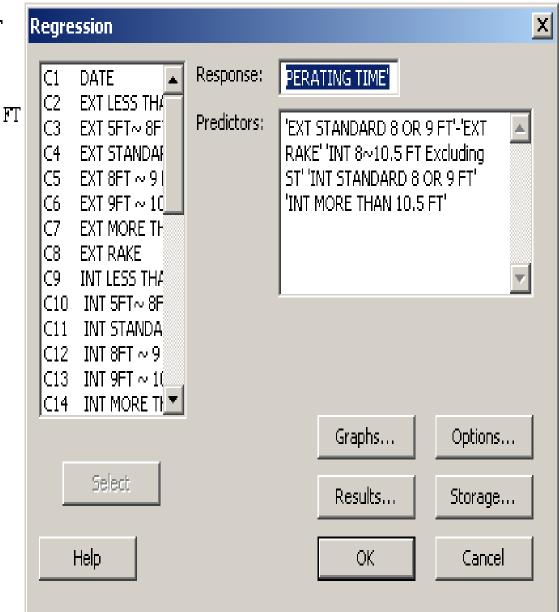


Figure 4-21: The Final Evaluating of the Regression Model

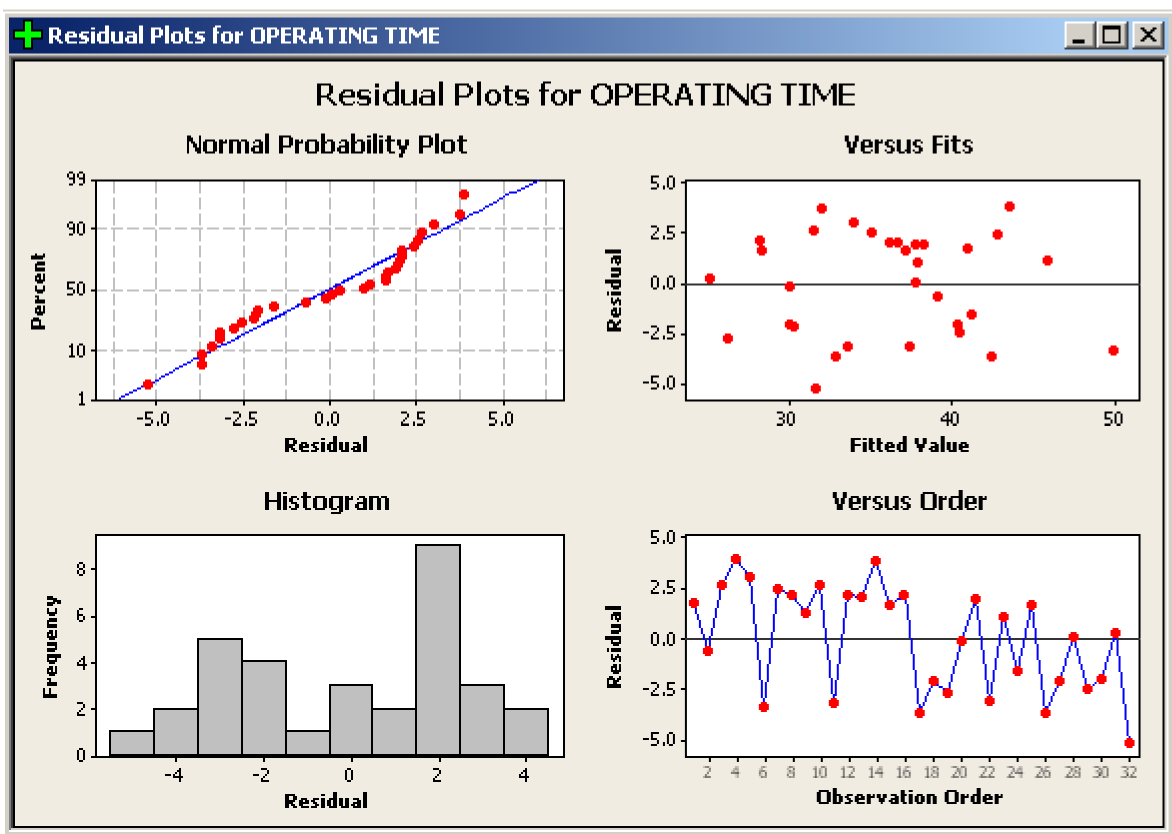


Figure 4-22: Final Residual Plots for Operating Time of the Regression Model

According the regression model, the equation of estimated man-hours will be as following:

$$Total\ man - Hours\ =$$

$$15.773 + 0.19812 \times A + 0.26636 \times B + 0.37622 \times C + 0.7492 \times D + 1.7608 \times E + 0.14185 \times F + 0.9029 \times G + 0.4492 \times H \qquad [\mathbf{15}]$$

Where:

A is the total linear length (in metres) of all the produced exterior walls during the day with a height of 8 ft (2. 44 m) or 9 ft (2.74 m).

B is the total linear length (in metres) of all the produced exterior walls during the day with a height between 8 ft (2.44 m) and 9 ft (2.74 m).

C is the total linear length (in metres) of all the produced exterior walls during the day with a height between 9 ft (2.74 m) and 10.5 ft (3.05 m).

D is the total linear length (in metres) of all the produced exterior walls during the day with a height larger than 10.5 ft (3.05 m).

E is the total linear length (in metres) of all the produced exterior rake walls only during the day.

F is the total linear length (in metres) of all the produced interior walls during the day with a height of 8 ft (2. 44 m) or 9 ft (2.74 m).

G is the total linear length (in metres) of all the produced interior walls during the day with a height between 8 ft (2.44 m) and 10.5 ft (3.05 m) excluding the 9 ft (2.74 m) walls in height.

H is the total linear length (in metres) of all the produced interior walls during the day with a height larger than 10.5 ft (3.05 m).

4.5.4 **Verification of the Regression Model**

Upon excluding all planned and unplanned stoppage time, the validation of the model is done by tracking the actual collected man-hours. The data is then compared with the predicted outputs developed in the linear regression model.

Using Equation 3, Validation factor was calculated and plotted as in Figure 4-23. The productivity model results in estimating the total daily required man-hours to fabricate and assemble panels based on various daily demands and the house design.

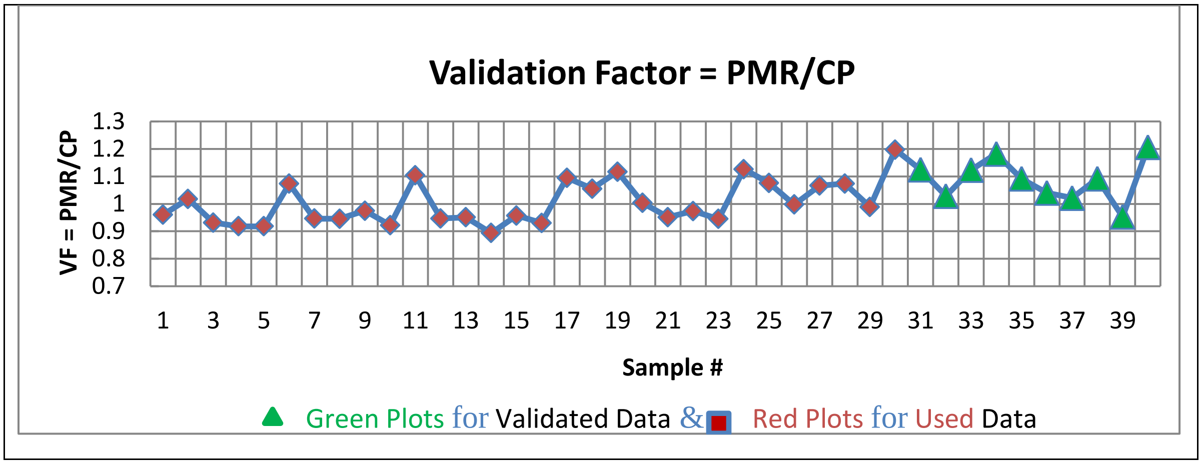


Figure 4-23: VF Factor Based on the Predicted and the Collected Daily man-hours Spent in the Manual Table

Table 4-16: Comparing the Results between the Actual and Predicted Man-Hours as Outputs

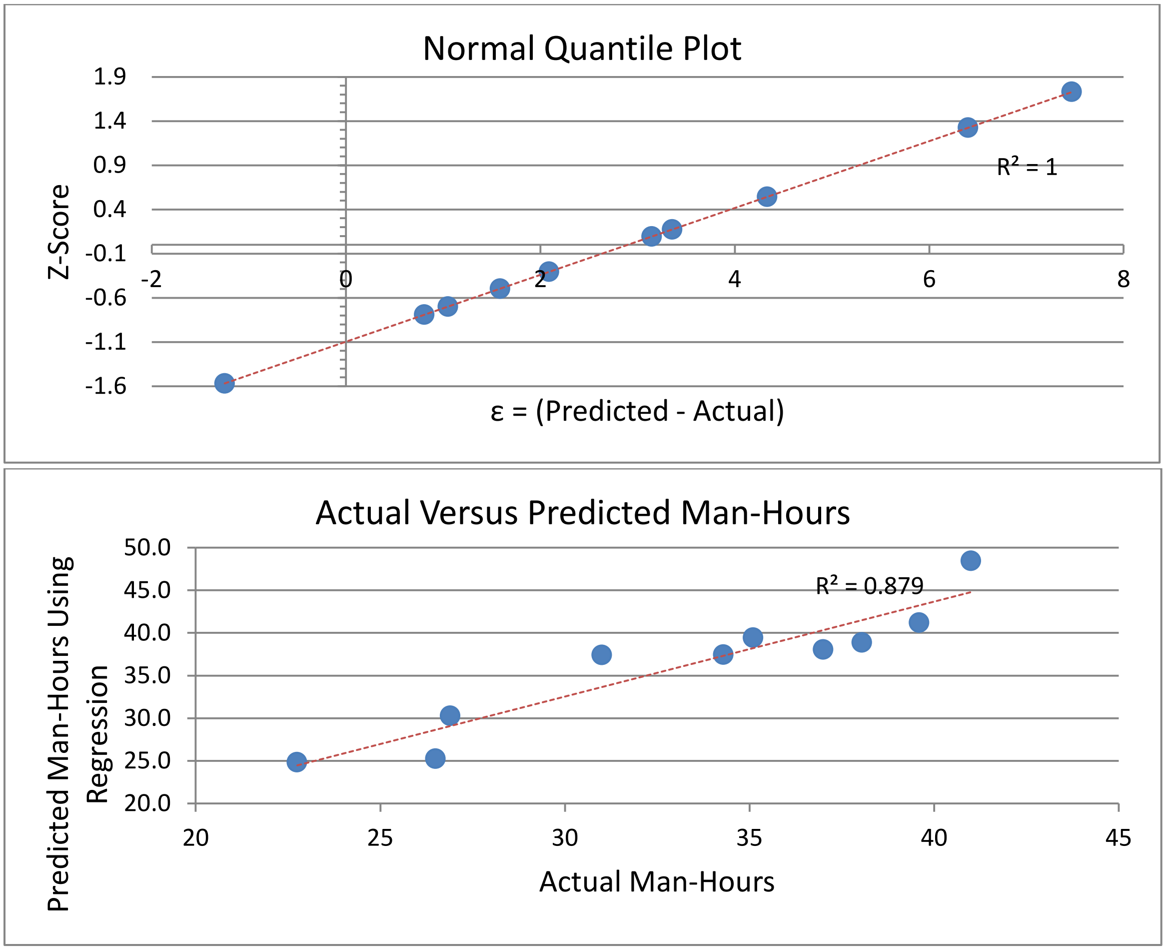
Tested ID	Actual Man-Hours	Predicted Man-Hours Using Regression	FV=PMR/CP
1	**26.9**	**30.3**	**1.12**
2	**37**	**38.0**	**1.03**
3	**35.1**	**39.4**	**1.12**
4	**41**	**48.5**	**1.18**
5	**34.3**	**37.4**	**1.09**
6	**39.6**	**41.2**	**1.04**
7	**38.05**	**38.9**	**1.02**
8	**22.75**	**24.8**	**1.09**
9	**26.5**	**25.3**	**0.95**
10	**31**	**37.4**	**1.21**

In addition to FV, the validated data was tested using a paired two-sample *t*-test for means. As mentioned before, 75% of the data was used for building the model, with the remaining 25% applied towards the verification and/or validation of the models. If we consider the difference between the actual data and the simulated data as residual, then the null hypothesis (H_0) should be:

$$H_0: \Delta_{(Residual)} = 0 \leftrightarrow Total\ ManHours_{(Regression\ Model)} = \ Total\ ManHours_{(Actual)}$$

$$H_1: \Delta_{(Residual)} \neq 0 \leftrightarrow Total\ ManHours_{(Regression\ Model)} \neq \ Total\ ManHours_{(Actual)}$$

To verify the model, and by applying a paired two-sample *t*-test for means, the P-value was given as P (T<=t) two-tail = 0.007 < 0.05 with a Pearson Correlation of 93.7%. Therefore, the regression model is acceptable.



4-24: Comparing the Regression Model's Man-Hours as Output versus Actual Man-Hours

4.5.5 Analyzing the Model Results and Outcomes

As stated in the final evaluation of the regression, the factors contribute to the determination of the total man-hours required to build demand throughout a specific day. This is contingent on a specific mix of each group length in metres. The top weight is the rake/gable exterior walls, which correlates to the complexity of these walls and intensifies the work required to build the rake and gable walls. Crew balancing is accomplished through estimating the required total man-hours based on the daily production of the manual station. By dividing the total man-hours by the net shift hours, the crew size is determined. The latter influences the profitability and associated labour cost based on daily basis.

Chapter 5 : Conclusion and Recommendations for future research

5.1 General Conclusion

To successfully schedule production's units, a proper sequencing of activities and a comprehensive understanding of interdependent activities is included, in addition to flexible, simultaneous service linkages. Therefore, any resource limitations, time dependency, designed takt time, production mix, load levelling, and the product flow procedure are observed as they may change the analyzing course and associated outputs.

Every organization aims to improve productivity, profitability, and performance with the intent of reducing resource waste by obtaining the same outputs from fewer inputs, more outputs from the same inputs, or more outputs from fewer inputs. This is all accomplished while maintaining a high standard of safety and quality.

This research presents strategies to decrease resource wastage as well as improve the overall performance of the company under study. It also aims to increase the efficiency of panelized construction production procedures in general. This thesis introduces and describes numerous industrial concepts and many items related to productivity in construction, and offers comparative studies between conventional construction and manufacturing methods as well as between manual and machine-based stations, in order to maximize productivity.

In developing a productivity model, a panelized company defines an appropriate baseline of the performance. Defining the proper performance baseline results in a later application of improvement tools, including lean principles, line of balance, and last planner. Knowing that benchmark allows a company to reuse the data as a decision-making tool for estimating and allocating resources, arranging shifts, tracking productivity and throughputs, assessing profitability, producing to the takt, maintaining a flexible and smooth flow, identifying possible bottlenecks, implementing improvements, and scheduling jobs.

Two assembly lines of panels' fabrication were studied. The study identified processes in off-site walls fabrication stage, applying product quantity analysis (PQA) and product routing analysis in Landmark Group of Builders. In the machine assembly line, a productivity model was developed based on cycle time of each product mainly based on linear feet measurement, number of multi-panels, load levelling, multi-panels (products) mix, resources constraints, and product flow. In analyzing the simulation model, integration of lean concepts, last planner system (LPS), and line of balance (LOB) was presented in detail.

Three main scenarios of load levelling were presented, along with patterns of resource allocation. The analyzed results were discussed to achieve a number of objectives and to assess productivity, profitability, and performance models. In doing so, production scheduling and managing the resources allocation can be performed with ease, throughout the daily production, planning stages, and control phases. Similarly, the manual assembly line as a manual station was presented as another productivity model. The productivity model to track the man-hours in the manual station was developed based on historical data. It considers the variability and complexity of the product through the analysis of related quantitative and qualitative data. This was accomplished by grouping the manual product and analyzing each group based on the produced linear feet and the daily spent man-hours. The productivity model developed into a linear regression to estimate the required man-hours in the manual station based on daily demand. Consequently, determining the required crew size and shift hours is more efficient.

5.2 Research Contributions

The contributions of this research to academia and industry are outlined as follows:

- Offering comparative studies between conventional construction and manufacturing methods, and, within the manufacturing method, between manual and machine-based stations.
- Developing benchmarking for productivity measurements in panelized wood frame construction.
- Identifying factors affecting productivity in manual and machine-based assembly lines in panelized construction.
- Providing a framework to decrease resource waste in manual and machine-based assembly lines through crew and resource balancing.
- Estimating the required man-hours in the manual station in order to meet the daily demand. This contribution is particularly relevant to industry.
- Designing the fabrication of walls based on the multi-panel system. This contribution is particularly relevant to industry.

5.3 Limitations

The following limitations are also identified with respect to this research:

- The research presented in this thesis deals primarily with the macro level of managing resources through the production line, rather than on micro-level tasks.
- The research focuses on the main stations impacting production but not on all processes and stations.
- During the PQA, the cycle time was calculated and simulated for the main families, but it only considered the multi-panels between 36-40 ft in length produced using the machine assembly line.
- The cycle time estimation was based on station cycle time, not the time required to complete each task.
- The load levelling only considered three main scenarios and observed the minimum and maximum number of labour in the studied stations as labour availability constraints.
- The linear regression model was provided to estimate the man-hours spent at the manual assembly line based on specific factors and groups. However, other alternate distributions and groupings could be considered in future studies.

5.4 Recommendations for Future Studies

In addition to those recommended in the list of research limitations, the following recommendations for future study are outlined below:

- Performing further research on the micro-level and the time required to complete each task, rather than station cycle time. This approach could potentially replace the PQA by assigning the cycle time for each task based on the product family and product routing analysis. This could be studied by further investigating the activities in the stations and seeking to identify hidden factors and possible improvements.
- Developing a dynamic model to estimate productivity, profitability, and performance.
- Optimizing the load levelling and scheduling.
- Applying Knapsack algorithm and combinatorial analysis to optimize the sequencing of panels based on the total resources and different types of panels.
- Estimating man-hours and assessing productivity, profitability, and performance in both the fabrication and on-site assembly stages, as well as studying the influence of supply

chain, just in time, and production flow on productivity, profitability, and performance models in panelized construction.

- Prior to the fabrication phase, developing a dynamic model to read from a database in order to estimate productivity, profitability, and performance models as baselines, then using the content to match it with the available man-hours required for each studied station. This could contribute to visual management and compare the results for “projected” and “built”.
- Developing a model to identify the most effective method by which to group the walls built manually. For instance, further research can be conducted to identify the main factors based on the grouping, the range of square footage for each panel, and the type. The research presented in this thesis has dealt with a measurement system in order to achieve estimating and scheduling. The measurements are based on linear length. However, both can be measured in square units per produced panel, where the output units are based on the same measuring type.
- Studying the effects of labour skills and learning curve on labour productivity related to wood framing and panelized construction.

References

AbouRizk, S., Halpin, D., Mohamed, Y. & Hermann,U. (2011). “Research in Modeling and Simulation for Improving Construction Engineering Operations.” *ASCE, Journal of Construction Engineering and Management,* Vol. 137, No. 10, 843-852.

AbouRizk, S., Knowles, P. & Hermann,U. (2001). “Estimating Labour Production Rates for Industrial Construction Activities.” *ASCE, Journal of Construction Engineering and Management,* Vol. 127, No. 6, 502-511.

Al-Sudairi, A.A., Diekmann, J.E., Songer, A.D. and Brown, H.M. (1999). “Simulation of Construction Processes: Traditional Practices Versus Lean Principles.” *Proceedings, Seventh Annual Conference of the International Group for Lean Construction,* IGLC-7, Berkeley, CA, July, 39-50.

Ammar, M. (2013). “LOB and CPM Integrated Method for Scheduling Repetitive Projects.” *ASCE, Journal of Construction Engineering and Management,* Vol. 139, No. 1, 44-50.

Arditi, D., Tokdemir, O.,& Suh, K. (2002). “Challenges in Line-of-Balance Scheduling.” *ASCE, Journal of Construction Engineering and Management,* Vol. 128, No. 6, 545-556.

Armentrout,D.(1986). “Engineering Productivity Management and Performance Measurement.” *ASCE, Journal of Management in Engineering,* Vol. 2, No. 3,141-147.

Ballard, H. (2000). “The Last Planner System of Production Control.” PhD thesis, School of Civil Engineering, Faculty of Engineering, University of Birmingham.

Barnes,R.M.(1968). “Motion and time study, Design and Measurement of Work.” 6th edition, John Wiley & Sons, Inc., New York, USA.

Bernold, L., E., Abraham, M., D. & Reinhart, D., B. (1990). “FMS Approach to Construction Automation.” *ASCE, Journal of Aero Space Engineering,* Vol.3, No.2, 108-121.

Canada Mortgage and Housing Corporation (CMHC), (2013)." Housing And Marketing Information< http://www.cmhc-schl.gc.ca/odpub/esub/64685/64685_2013_A01.pdf?fr=1393913701337 > (Accessed March 3rd, 2014).

Canadian Manufactured Housing Institute (CMHI), (2013)." The Advantages of a Factory-Built Home." <http://www.cmhi.ca/buying-home/advantages> (Accessed January 5, 2013).

Canadian Manufactured Housing Institute (CMHI), (2013)." What is Factory-Built Housing." <http://www.cmhi.ca/buying-home/what-factory-built-housing> (Accessed January 5, 2013).

Construction Industry Institute (CII): Benchmarking & Metrics <https://www.construction-institute.org/scriptcontent/index.cfm> (Accessed May 21, 2013).

Canadian Standards Association (CSA). (2008). "Procedure for Factory Certification of Buildings." Canadian Standards Association, Mississauga, ON, Canada.

Chao, L. & Skibniewski, M. (1994). "Estimating Construction Productivity: Neural-Network-Based Approach." *ASCE, Journal of Computing in Civil Engineering*, Vol. 8, No. 2, 234-251.

Cho, S., Sorensen, K., Fisher, M., & Dickey, A. (2009). "ERP Application of Real-Time VDC-Enabled Last Planner System for Planning Reliability Improvement." *ASCE, Journal of Computing in Civil Engineering*, 156-165.

Choi, J. & Russell, S., J. (2005). "Long-term Entropy and Profitability Change of United States Public Construction Firms." *ASCE, Journal of Management in Engineering*, Vol. 21, No. 1, 17-26.

Clayton Research Associates Limited. (2006). “Profile and Prospects of the Factory-Built Housing Industry in Canada.” Canada Mortgage and Housing Corp., Canada.

Damci, A. & Arditi, D., & Polat, G. (2013). “Multiresource Leveling In Line-of-Balance Scheduling.” *ASCE, Journal of Construction Engineering and Management*, 139, 1108-1116.

Dauphinee, P, & Associates Ltd. (2009). “European Closed Wall panel Systemsfor Pre-built Homes.” BC Wood Specialties Group Association, Vancouver, BC, Canada.

Davenport,T.,H., Harris,J.,G.,& Morison,R. (2010). “Analytics At Work: Smarter decisions, Better Results.” Harvard Business Press, Boston, Massachusetts, USA.

Dennis, P. (2007). “Lean Production Simplified: A Plain Language Guide to the World’s Most Powerful Production System.” 2nd edition with a Forward by John Shook, Productivity Press, New York, USA.

Dissanayake, M., Fayek, A., Russel, A. & Pedrycz, W. (2005). “A Hybrid Neural Network for Predicting Construction Labour Productivity.” *Proceedings, International Conference on Computing in Civil Engineering*, Cancun. Mexico, Jul. 12-15.

Eastman, C. & Sacks, R. (2008). “Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities.” *ASCE, Journal of Construction Engineering and Management*, Vol. 134, No. 11, 517-526.

Ebrahimy, Y. & Rokni, S. (2010). “Validity of Industry Benchmarks and Metrics for Engineering Productivity.” *ASCE, Construction Research Congress*, 1057-1063.

Ericson,W.,W.(2011). “Performance dashboards: measuring, monitoring, and managing your business.” 2nd edition, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Fischer,G., Lárusson,L.,H., & Jönsson,J. (2009). “Prefabricated Floor and Roof Panel with Engineered Cementitious Composites (ECC).” *ASCE, Journal of Structures*, 2199-2208.

Gao,T., Ergan,S.,Akinci,B.,Garrett,J.H.& Soibelman,L.(2012). “Development of a Framework for Identifying Information Bottlenecks and Evaluating Different Data Capture Technologies to Support Proactive Productivity Management.” Construction Research Congress, USA, 356-365.

Huang, A., L., Chapman, R., E., & Butry, D., T. (2009). “Metrics and Tools for Measuring Construction Productivity: Technical and Empirical Considerations.” National Institute of Standards and Technology (NIST), and Building and Fire Research, Maryland, USA.

Hubbard, D., W. (2010). “How To Measure Anything: Finding The Value Of ‘Intangibles’ in Business.” 2nd revised, expanded & simplified edition, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Johnson, B. & Christensen, L. (2008). “Educational Research: Quantitative, Qualitative, and Mixed Approaches.” 3rd edition, Sage Publications, Inc., USA.

Kaplan, R. & Norton, D. (1992), “The Balanced Scorecard-Measures that Drive Performance.” Harvard Business Review, January-February, 71-79.

Kanawaty, G. (1992). “Introduction to time study.” 4th revised edition, International labour organization, Geneva.

Kim, I. (2007). “Development and implementation of an engineering productivity measurement system (EPMS) for benchmarking.” Ph.D. dissertation, Univ. of Texas at Austin, Austin, TX.

Kim,Y., & Ballard, G.(2010). “Management Thinking in the Earned Value Method System and the Last Planner System.” *ASCE, Journal of Management in Engineering,* Vol. 26, No. 4, 233-228.

Lean Enterprise Institute <http://www.lean.org/> (Accessed August 17, 2013).

Liao, P., Thomas, S., R., O'brien, W., J., Mulva, S., P., & Dai, J. (2009). "Development of Project Level Engineering Productivity Benchmarking Index." *ASCE, Building A sustainable Future, Construction Research Congress,* 1087-1095.

Liao, P., Thomas, S., R., O'brien, W., J., Mulva, S., P., & Dai, J. (2011). "Factors Affecting Engineering Productivity." *ASCE, Journal of Management in Engineering,* Vol. 27, No. 4, 229-235.

Liu, M., Ballard, G., & Ibbs, W. (2011). "Work Flow Variation and Labour Productivity: Case Study." *ASCE, Journal of Management in Engineering,* Vol. 27, No. 4, 236-242.

Lu, M.(2001). "Productivity Studies Using Advanced ANN Models." PhD thesis, Construction Engineering and Management, University of Alberta, Edmonton, Canada.

Mathematical & Statistical Sciences, University of Alberta." What is a P-Value?" <http://www.stat.ualberta.ca/~hooper/teaching/misc/Pvalue.pdf> (Accessed April 1, 2013).

Mayer, Z. & Kazakidis, V. (2007). "Decision Making in Flexible Mine Production System: Design Using Real Options." *ASCE, Journal of Construction Engineering and Management, Vol.133,* No.2, 169-180.

McCabe, B., AbouRizk, S. & Goebel, R. (1998). "Belief Networks for Construction Performance Diagnostics." *ASCE, Journal of Computing in Civil Engineering*, Vol. 12, No. 2, 93-100.

Mewis, R. W., Babbit, C., Baker, T., Balboni, B., Bastoni, R. A., Chiang, J. H., Christensen, G. W., et al. (2007). *Contractor's Pricing Guide: Residential Detailed Costs 2008*. Reed Construction Data Inc., Kingston, MA, USA.

Mewis, R. W., Babbit, C., Baker, T., Balboni, B., Bastoni, R. A., Chiang, J. H., Christensen, G. W., et al. (2007). *Contractor's Pricing Guide: Residential Square Foot Costs 2008*. Reed Construction Data Inc., Kingston, MA, USA.

Minitab tip Sheet 13: Multiple Regression and Model Checking, Department of Mathematics and Statistics, University of Reading (2011) <http://www.reading.ac.uk/web/FILES/maths/MINITAB_Tip_sheet_13.pdf> (Accessed May 31, 2013).

Modular Building Institute (MBI), (2006)." Growing Green: One MBI Member is a Catalyst for Environmentally Friendly Modular Construction." <http://www.modular.org/marketing/documents/sustain.html> (Accessed January 5, 2013).

Modular Building Institute (MBI), (2010)." Improving Construction Efficiency & Productivity with Modular Construction." <http://www.modular.org/marketing/documents/Whitepaper_ImprovingConstructionEfficiency.pdf> (Accessed January 5, 2013).

Multiple Regression Analysis in Minitab, <http://case.truman.edu/Documents/Minitab%20Multiple%20Regression%20Analysis.pdf> Accessed May 31, 2013).

Mundel,E.,M. (1985). "Motion and Time Study: Improving Productivity." 6th edition, Prentice-Hall, Inc., Englewood, New Jersey, USA.

National Association of Homebuilders (NAHB) (2014); "Cost of Constructing a Home; January2104 Special Study Report for Housing Economics by Heather Taylor." < http://www.nahb.org/fileUpload_details.aspx?contentTypeID=3&contentID=221388&subContentID=554381&channelID=311 > Accessed January 6th, 2014).

Nash, M., & Poling, S. (2008). “Mapping the Total Value Stream: A Comprehensive Guide for Production and Transactional Processes.” CRC Press, Productivity Press, Taylor & Francis Group, New York, USA.

Oglesby, C., Parker, H. & Howell, G. (1989). “Productivity improvement in construction.” McGraw-Hill, New York.

Ohno, T. (1998). “Toyota Production System.” Productivity Press, New York, USA.

Park, H. Thomas,S.& Tucker,R.(2005). “Benchmarking of Construction Productivity.” *ASCE, Journal of Construction Engineering and Management*, Vol. 131, No. 7, 772–778.

Rivas, R., A., Borcherding, J., D., Gonzalez, V., & Alarcon, L., F. (2011). “Analysis of Factors Influencing Productivity Using Craftsmen Questionnaires: Case Study in a Chilean Construction Company.” *ASCE, Journal of Construction and Management*, Vol. 137, No. 4, 312-320.

Rivas, R., A., Borcherding, J., D., Gonzalez, V., & Alarcon, L., F. (2011). “Analysis of Factors Influencing Productivity Using Craftsmen Questionnaires: Case Study in a Chilean Construction Company.” *ASCE, Journal of Construction and Management*, Vol. 137, No. 4, 312-320.

Rother, M., & Shook, J. (2003). “Learning to See: Value Stream Mapping to Create Value and Eliminate Muda.” Version 1.3, Lean Enterprise Institute < http://www.lean.org/ >, Brookline, Massachusetts, USA.

Shafai, L. (2012). “Simulation Based Process Flow Improvement for Wood Framing Home Building Production Lines.” MSc thesis, Construction Engineering and Management, University of Alberta, Edmonton, Canada.

Shewchuk,P,& Guo,C.(2012). “Panel Stacking, Panel Sequencing, and Stack Locating in Residential Construction: Lean Approach.” *ASCE, Journal of Construction Engineering and Management*, Vol. 138, No. 9.

Slack, N., Chambers, S., & Johnston, R. (2010). “Operations Management.” 6th edition, Pearson Education Limited, UK, ISBN 978-0-273-73046-0.

Song, L. & AbouRizk, S. (2008). “Measuring and Modeling Labour Productivity Using Historical Data.” *ASCE, Journal of Construction Engineering and Management*, Vol. 134, No. 10,786-794.

Sonmez, R. & Rowings, J. (1998). “Construction Labour Productivity Modeling With Neural Networks.” *ASCE, Journal of Construction Engineering and Management*, Vol. 124, No. 6,498-504.

Stainer, A. (1997). “Capital input and total productivity management.” *Journal of Management Decision*, Vol. 35, No. 3,224-232.

Starchuk, N. (2011). “On the Performance of a Manufacturing process with Employee Learning and Turnover.” MSc thesis in Engineering Management, Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

Tamer, Z., Yoon, Y. & Hastak, M. (2012). “Protocol for Profitability Analysis using Internal Entities in Organizational Structure of Construction Companies.” *ASCE, Journal of Construction Engineering and Management*, Vol. 138, No. 12, 1394-1402.

Tangen, S.(2005). “Professional Practice: Demystifying productivity and performance.” *International Journal of Productivity and Performance Management*, Vol. 54, No. 1, 34-46.
Tangen, S.(2004). “Evaluation and Revision of Performance Measurement Systems.” PhD thesis, WoxénCentrum, Department of Production Engineering, Royal Institute of Technology, Stockholm, Sweden.

The Construction users Roundtable (CURT). (2005). “Construction Measures: Key Performance Indicators.” <http://www.curt.org/login.aspx?ReturnUrl=%2fFileDetails.aspx%3fid%3d56%26title%3dConstruction%2bMeasures%253a%2bKey%2bPerformance%2bIndicators%2b(UP-101)&id=56&title=Construction+Measures%3a+Key+Performance+Indicators+(UP-101)>

Thomas, H., R. (2012). “Benchmarking Construction Labour Productivity.” *ASCE, Practice Periodical on Structural Design and Construction*, 1-35.

Thomas, H., R. (2000). “Schedule Acceleration, Work Flow, and Labour Productivity.” *Journal of Construction Engineering and Management*, Vol. 126, No. 4,261-267.

Wambeke, B., Liu, M., & Hsiang, S. (2012). “using last Planner and a Risk Assessment Matrix to Reduce Variation in Mechanical Related Construction Tasks.” *Journal of Construction Engineering and Management*, Vol. 138, No. 4,491-498.

Womack, J. P. and Jones, D. T. (1996). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Simon and Schuster, New York, NY, USA.

Younes, B., Bouferguène, A., Al-Hussein, M., Yu, H. & Ajweh, Z. (2013). “Aged-invoice management: a lean and post-lean simulation approach.” *4th Construction Specialty Conference*, Montréal, QC, Canada.

Yu, H., Al-Hussein, M., Al-Jibouri, S., & Telyas, A. (2013). “Lean Transformation in a Modular Building Company: A Case for Implementation.” *ASCE, Journal of Management in Engineering*, Vol. 29, No. 1,103-111.

Yu, H. (2010). “An Integrated Approach toward Lean for Production Homebuilders.” PhD thesis, Construction Engineering and Management, University of Alberta, Edmonton, Canada.

Zayed, T. & Halpin, D. (2005). “Productivity and Cost Regression Models for Pile Construction.” *ASCE, Journal of Construction Engineering and Management*, Vol. 131, No. 7, 779-789.

Appendix A : Software Definitions

- **Avanti software:** mainly used to acquire the working times and attendances applied by payroll, human resources, and accountants.
    - Visit: <https://www.avanti.ca/>
- **Control Centre**: A software used at Landmark. Control Centre was developed by programmers, including Hubert Hopf and his team, to monitor the flow of production units within the production system. It also influences the production process using defined controls, including: book unit–in, book unit–out, and element types. The software was developed in Germany by a company called GranIT Software (Graphical and Numerical Information Technologies Software). I was a member of the GranIT team, in which I was responsible for planning, designing, and implementing this control centre system at Landmark.
    - Visit: << http://granit.de/en/ >
- **EasyFit Statistical Software:** allows the automatic or manual fit of a large number of distributions specific to data. The program selects the optimal model within seconds. It can be used as a stand-alone application or by using Microsoft Excel. This allows for a wide range of business-oriented problem-solving approaches with only a basic understanding of statistics.
    - Visit: <http://www.mathwave.com/products/easyfit.html>

- **Minitab:** powerful statistical software that initiates the analysis and the interpretation of the results with a high level of confidence. It is also considered one of the leading statistical software programs worldwide, in terms of quality improvement.
    - Visit: <http://www.minitab.com/en-US/products/minitab/>
- **SEMA:** a CAD program for timber construction and manufacturing of pre-fabricated houses. It is mainly used for 2D/3D CAD planning, visualization, production data, modernization, and structural analysis.
    - Visit: <http://www.sema-soft.com/en/start.htm>
- **Simphony.NET 4.0**: a discrete-event-based simulation tool developed by the University of Alberta's Construction Engineering and Management Group.
    - Visit: <http://129.128.253.76/simphony40/>

Appendix B : More Information Regarding the Collected and Tested Data

Production Database

This thesis applies two methods in approaching assemblies in panel fabrication. Panels can be assembled by manual station or machine line. The production data is dependent upon the daily based scheduled models and their design, in which each house has different panels, specifications, dimensions, features, and numbers. The data collected for each assembly line depends on the produced panels. CAD files, drawings, and production lists are used to determine inputs for mapping the current state for manual based stations, analyzing data, and identifying main KPIs. The machine-based stations retrieve data from CNC machines through the control centre[11] to map the current state, analyze the data, and identify the main KPIs. The data considers product characteristics, variability of products, workers, and daily allocations. However, this data was used as historical data for preparing the regressions. At a later time, the control centre is used to validate the regression models. The generated data and plotted charts are used as dashboards for tracking productivity, profitability, and performance. This aims to provide the management team with information within the macro-level of daily production.

On the other hand, collecting of the integrated data aims to gain useful inputs and outputs regarding the users' expectations and study perspectives. Data collection, filtrations, data constrains, and formulation models of productivity models were presented later in details. In existing studies (Kanawaty, 1962; Kim, 2007; Song & AbouRizk, 2008), many recommendations have been made related to collecting the relevant data, useful information, and the output measurement, as presented:

- Relevant information should be gained from direct observation.
- Information should assist the research to be identified quickly such as date of study, study number, and the person who did the study.
- Information must contribute to the processes to be recognized quickly such as the location where the operation is taking place, and description of the operation.
- Information should distinguish hastily the products which processed such as the name of the product, drawing number, and material.

[11] More information regarding the control centre is available in Appendix A.

- Information might enable the operative to be identified such as operative’s name.
- Duration of the study and recoded time besides the working condition should be considered.
- The number of metrics categories must be doable (five to eight).
- Collected data must be clear, admirable, and quotable.
- A high correlation should be existed between a quantifiable output measurement and labour hours.
- The output measurement should be separated from productivity –influencing factors such as labour skills.
- The output measurement should be easily tractable, and cost effective to execute.

Recorded Time Database

Beyond using recorded time machine-based stations through the implementation of a control centre for booking-in and booking-out, employees used scanning time machines to record time, based on man hours. Team leaders manually reported unplanned time. Man-hours spent were calculated based on resources allocations throughout the day.

Output Data

Song & AbouRizk and Kim have stated some criteria to shape a proper output measurement method. Those criteria are stated in Table B-1 (Song & AbouRizk, 2008; Kim, 2007).

Table B-1: Followed Criteria for Shaping the Outputs' Measurements

Criteria for the Outputs’ Measurements	Reference
A high correlation should be existed between a quantifiable output measurement and labour hours.	(Song & AbouRizk, 2008)
The output measurement should be separated from productivity –influencing factors such as labour skills.	(Song & AbouRizk, 2008)
The output measurement should be easily tractable, and cost effective to execute.	(Song & AbouRizk, 2008) and (Kim, 2007)

To obtain engineered or labour productivity in panelized construction, integrated data was prepared by using the produced panels as an input. The produced panels are then matched with the time spent or by allocating time required to finish one product using a number of resources.

Quantitative and Qualitative Data

Quantitative research is measurable and deals with numbers and statistics. It handles specific variables, identifies statistical relationships, and is randomly selected. Qualitative research is not related to numbers but, rather, with words, images, and objects. Qualitative research does not study variables but, rather, detects features (Johnson & Christensen, 2008).

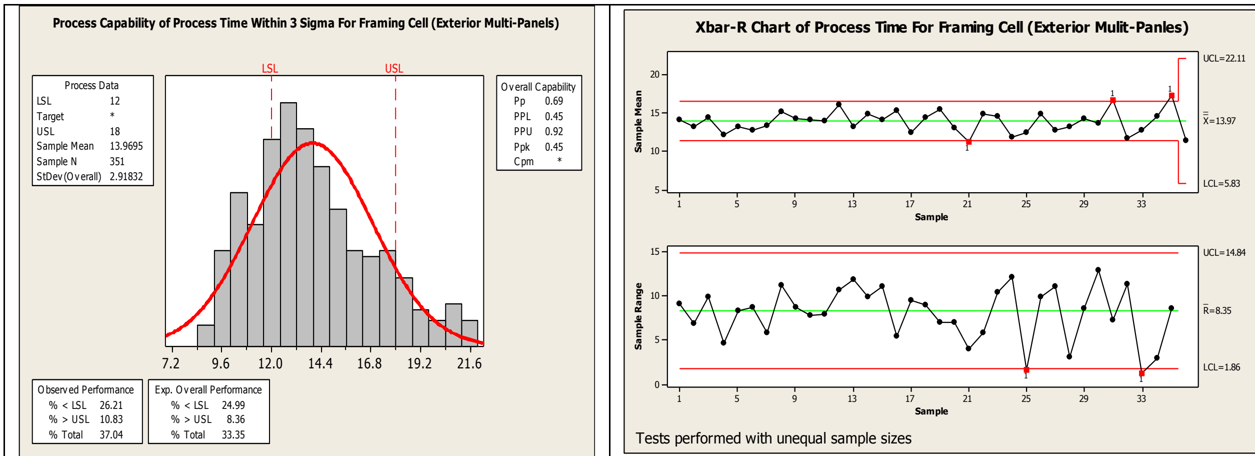
This research will focus on quantitative data, including: panel's numbers, length, height, area, produced time, cost, and spent man-hours. At times, qualitative data is required in order to add a description to the variables. In this research, grouping the interior and exterior panels, classifying the skill levels of the crew, and adding descriptions to the main factors are all considered qualitative data.

Data Filtrations and Constrains

Although the data was collected for the machine assembly line and the manual assembly line, data filtering was based on few criteria. Given that records were documented and verified, the main objective is to establish a baseline prior to exploring scenarios for improvements.

As previously mentioned, there are two ways to retrieve records. The first method is to establish a baseline established by records, excluding delays through the use of net operating time, working in normal conditions, medium skills, and without abnormalities in the process or products.

The second approach is to create a baseline based on recording delays, working in normal conditions, medium skills, and without abnormalities in the process or products. The latter technique results in minor and repetitive delays as part of the processes, in which there is an opportunity to reduce the process time by decreasing delays and looking for kaizen improvements throughout the processes. Through the implementation of the second method, data was collected and analyzed for enormous samples, while considering process stability. They were then fitted to a distribution and measured based on process capability. Process stability indicates that special causes of variance were removed. Capability measurement designates the ability of the station or the station to produce within specific limits, as part of control charts. The latter is based on six sigma concepts and histogram charts, as shown in Figure B-1.



Process Capability

Process Stability

Figure B-1: Control and Quality charts for processing time of exterior-panels in the framing station

Through Kanawaty, Tangen, Kim, Song & AbouRizk's research, and due to the variability of production at the manual station, the required man hours in a manual line were estimated using the first method (Kanawaty, 1962; Tangen, 2004; Kim, 2007; Song & AbouRizk, 2008). The machine line demonstrated stability based on the daily production. Human factors were insignificant. The data and records conclude that the focus is mainly on factors related to production features that influence engineered labour productivity in the machine line. With this, the recorded data was filtered by minimizing the effect of inconstant human factors and diminishing occurred mistakes and delays. The data was also filtered based on supplying issues as often as possible to create a reliable baseline in normal conditions. To recognize the productivity factors, a great deal of work is required to document and observe the production features, labour man-hours, and delays.

Formulation Models of Productivity Measurement and Productivity Models' Design

Lu described productivity models, as follows: work study techniques, expectancy model, action-response model, regression model, expert systems, and Artificial Neural Networks (ANN).This research will focus on the regression models and factors influencing the engineered productivity (Lu, 2001).

Based on the above criteria, productivity models focus on determining the inputs and outputs. Therefore, a regression model was presented on the manual assembly line within the process stability. To estimate engineered labour productivity, the linear regression model was used in the manual line assembly. After applying a Product Quantity Analysis (PQA), the cycle time of each product in the machine assembly line production was provided, based on fitting to a distribution and other criteria throughout the process. The latter was done to study the variability of the products and man-hours. When examining specific load levelling, the Value Stream Map (VSM) was used to observe how the cycle time related to man-power and product types. This leads to estimating the engineered labour productivity, followed by the exploration of decision-making tools for estimating and allocating resources based on using post- simulation outcomes.

Building and analyzing of Regression Model in Panelized Construction

Regression models are either linear or nonlinear. They signify the relationship between variable(s) and independent variable(s). In panelized construction, the dependent variable is regarded as productivity, or man-hours, spent to produce panels. Independent variables often include: panel height, panel length, panel type, and panel construction method (manually or by machine).

If the data is collected without considering the process behind the data, using regression models as an alternative data oriented technique is an appropriate practice (Zayed & Halpin, 2005).

Testing and Verification of Linear Regression Model

Upon collecting the data, validating the data is required to minimize or eradicate ambiguous or missing data. The statistical features can be used to check the robustness of the regression model.

In general:

Data = Fit + Residual,

Therefore, most multiple linear regression models have the following formula:

$$Y = \beta 0 + \beta 1 X1 + \beta 2 X2 + \beta 3 X3 + \cdots . + \varepsilon$$

The Y is the variable in response. The X's are the explanatory and independent variables. The error term is demonstrated as ε. To verify the model validity, the following criteria can be applied:

- The R square for the model (coefficient of determination) signifies the amount of variations in the response, which is explained in the model. The high R square value is the better correlation for the model. Similarly, there is the adjusted R square, which compares the explanatory strength of regression models that contain dissimilar numbers of predictors.
- The SE coefficient is the standard error for estimated coefficients.
- The *P* value of t-test for the coefficients of regression models [P (t)] are where T-statistics are tested to determine whether βi equals zero and whether it matches up to P-values, as discussed later.
- The *P* value of F test compares to 2 and 22 degrees of freedom using statistics tables.
- The fitted line plot is used as a regression plot.
- The residual plot is found where the residual represents the difference between the corresponding value (from the observation) and the predicted value (from the regression equation).
- The determinations of the Least-Squares Regression Line and Population Regression Line.
- The Analysis of Variance (ANOVA): unlike the T-tests, ANOVA is the top-level test to understand whether or not the variables are significant. T-tests typically focus on the consequence of individual variables. To avoid unnecessary increases in variability in the likelihoods arising from the model, it is sound to remove variables in the model and the model fitted again. Unless there is a useful reason to keep a variable in the calculations of the model, it is best to exclude it from the model (Minitab Tip Sheet, 2013).

Overview of Some Criteria Regarding Fitting Distributions

Extracting information from numerical data requires finding the relations between the parameters affecting this data. This can be done through fitting the data into a certain distribution. To ensure that a distribution thoroughly suits the case, statisticians determine approaches that allow researchers to verify the goodness of fitting. Among the many techniques, three methods are used in this thesis, including: the Kolmogorov–Smirnov test (K–S test), the Anderson–Darling test, and Chi-square—the most dependable technique.

P value

The P-value is typically stated in terms of a fixed level α test, where α is a number selected autonomously of the data, often 0.05 or 0.01, and more rarely 0.1. Using fixed level α tests is a useful concept when planning the study. In interrupting the P-value for a test of regression coefficient, if the P-value is less than α, the test will be significant at the α % level. As such, there will be a strong sign to reject the null hypotheses. The null hypothesis signifies the coefficient's value for the variable(s) is zero. Conversely, if the P-value is greater than 0.1, there is no evidence to reject the null hypothesis. Based on the University of Alberta's Mathematical and Statistical Department, Table B-2 provides an overview of many concerns about the relationship between the P-value and null hypothesis' rejection:

Table B-2: The relations between P-value and the Null Hypothesis's Rejection, Mathematical & Statistical Sciences (University of Alberta)

$P > 0.10$	No evidence against the null hypothesis. The data appear to be consistent with the null hypothesis.
$0.05 < P < 0.10$	Weak evidence against the null hypothesis in favor of the alternative
$0.01 < P < 0.05$	Moderate evidence against the null hypothesis in favor of the alternative.
$0.001 < P < 0.01$	Strong evidence against the null hypothesis in favor of the alternative.
$P < 0.001$	Very strong evidence against the null hypothesis in favor of the alternative.

Appendix C : Information Regarding the Simulation Models

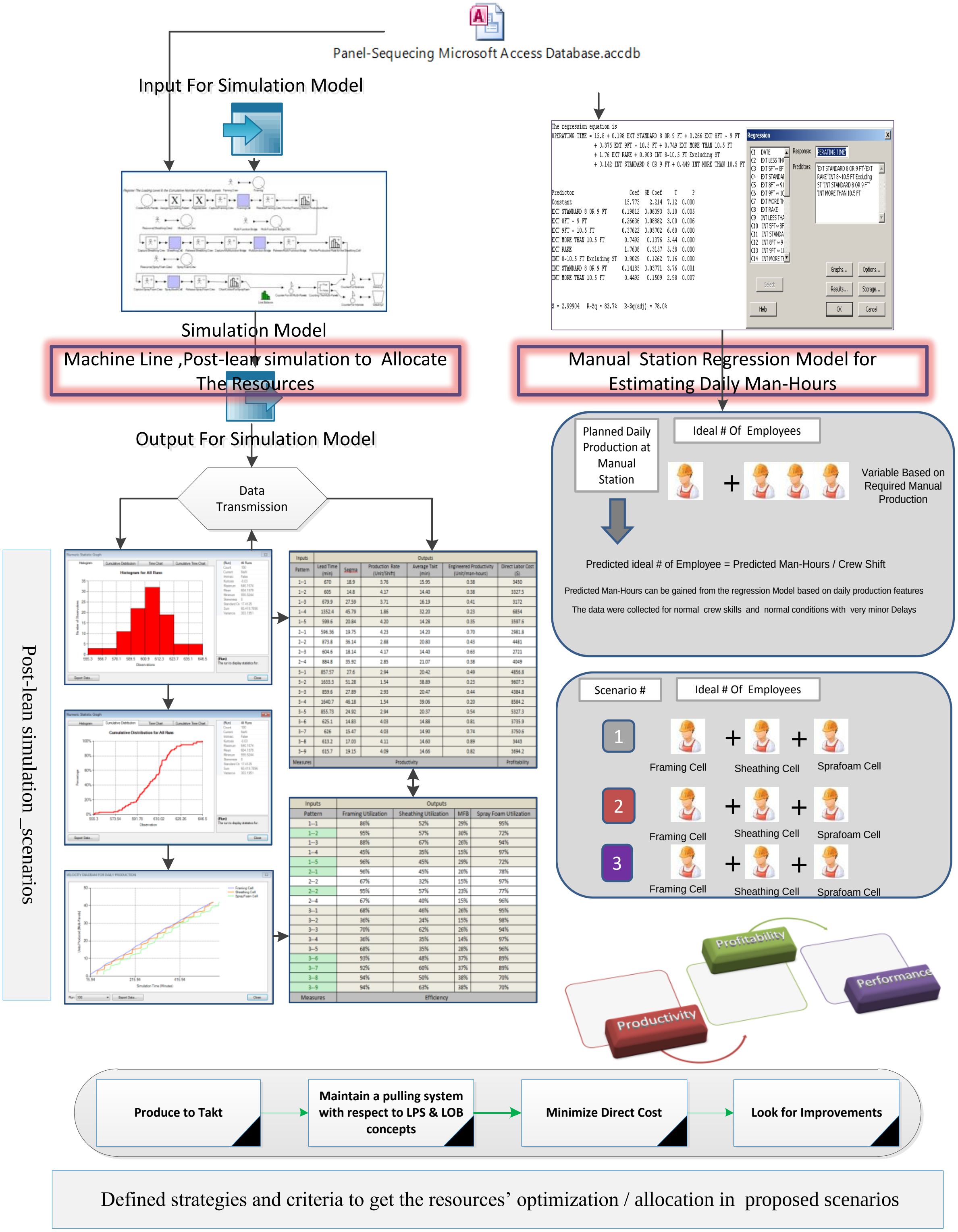


Figure C- 1: Advised System to determine the daily resources and their allocations

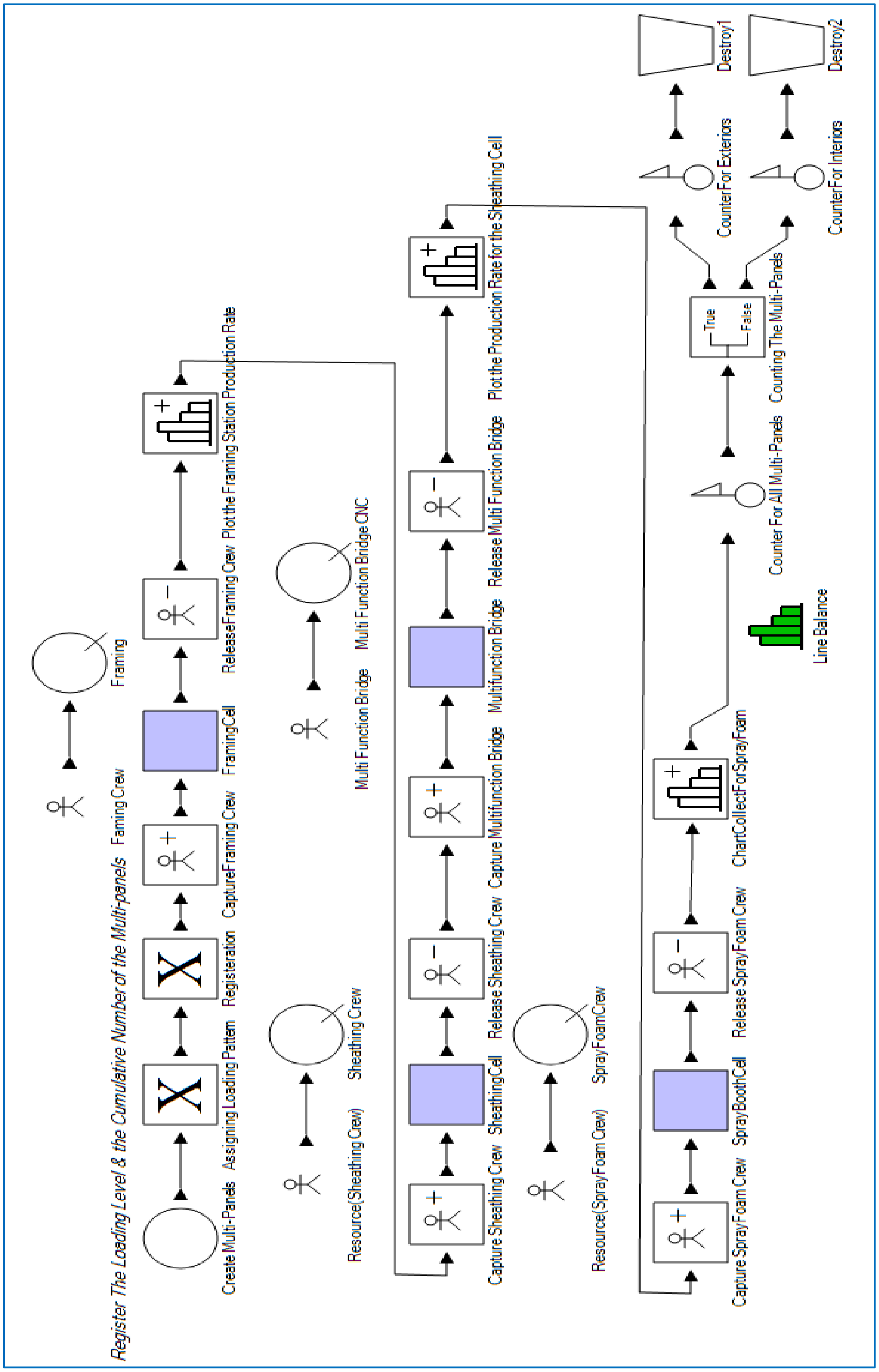


Figure C- 2: A simplified simulation model using Simphony.NET 4.0, which is implemented in this research