Application of Lean in High-Mix Low-Volume Production Systems: A Case Study in the Architectural Lighting Industry

Karuna Dhananjai Kadam

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By: Karuna Dhananjai Kadam

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Signed by the final examining committee:

Chair
Dr. Onur Kuzgunkaya

Examiner
Dr. Onur Kuzgunkaya

Examiner
Dr. Ali Akgunduz

Thesis Supervisor(s)
Dr. Kudret Demirli

Approved by:
Dr. Sivakumar Narayanswamy, Graduate Program Director

Dr. Mourad Debbabi, Dean

Abstract

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Karuna Dhananjai Kadam

With Small to Medium-sized Enterprises (SMEs) in North America offering customized products to compete with low-cost offerings of off-shore manufacturers, their production systems often produce a high mix of products in low volumes. With an objective to improve competitiveness of such SMEs, this thesis develops a framework for lean application in High-Mix Low-Volume (HMLV) production systems and demonstrates its application in a real-life case study. In the developed framework, routing and demand forecasts are first used to select a product family that delivers the highest value. Value stream mapping is then utilized to map process cell data, information flow and material flow. Takt time is measured prior to process and flow kaizen led waste elimination. Next, a continuous flow cell is designed and a pacemaker is selected. A weighted average of total work content is used to define resource requirements, a 'schedule to capacity' concept is developed to enable mix scheduling and a concept of 'dynamic pitch' is introduced to ensure adherence to schedule. Finally, flow based FIFO lanes and pull based supermarkets are assigned to institute inventory leveling and therefrom construct, the future value stream. This thesis also uses linear programming to construct an optimized preventive maintenance schedule that improves uptime and an optimized 'revenue-leveled' schedule that institutes a 'daily financial pitch'. A real-life case study of a HMLV manufacturer in the Architectural Lighting Industry is presented. Lead time improvements of 33% to 60% and processing time improvements of 58% to 79% are achieved in addition to changeover, uptime and yield improvements.

Keywords: Value Stream Mapping, High-Mix Low-Volume, Mix Model, Engineer-to-order, Make-to-order

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List of Abbreviations

ATO	Assemble-To-Order
C/O	Changeover
CBM	Condition-based maintenance
CFC	Continuous Flow Cell
CRI	Colour Rendering Index
CSM	Current State Map
DBR	Drum Buffer Rope
EPEi	Every Part Every interval
ERP	Enterprise Resource Planning
ETO	Engineer-To-Order
FCFS	First-Come First-Served
FIFO	First In First Out
FSM	Future State Map
HMLV	High-Mix Low-Volume
LED	Light Emitting Diode
LMHV	Low-Mix High-Volume
MC	Mass Customization
MTO	Make-To-Order
NVAs	Non-Value-added Activities
POLCA	Paired cell-Overlapping-Loops of Cards-with Authorization
QRM	Quick Response Manufacturing
SCARE	Simplify, Combine, Add/Automate, Rearrange, Eliminate
SKU	Stock Keeping Unit
SME	Small and Medium-sized Enterprise
SIPOC	Supplier, Inputs, Process, Outputs and Customers
TOC	Theory Of Constraints
TPM	Total Productive Maintenance
TPS	Toyota Production System
UNV	Universal
VSM	Value Stream Mapping
WIP	Work In Progress

1 Introduction

This thesis aims to improve operations in a company producing custom architectural LED (Light Emitting Diode) lighting fixtures. LED Lighting, with its offering of higher energy efficiency and cost savings when compared to more traditional lighting technologies (fluorescent, incandescent etc.) (Pattison, Hansen, & Tsao, 2018), has amassed a global market size of about USD 86 billion in the year 2021. Furthermore, the industry has a projected 13% market growth potential in coming years (Statista, 2021). The growing degree of consumer preference for LED lighting has therefore motivated more firms to enter the industry. The LED lighting industry today is two-fold. Standard LED fixtures, which are purchased in high volumes, see a market structure that is oligopolistic in nature with a few key players. On the other hand, custom architectural LED fixtures are purchased in smaller volumes and create a market structure that is similar to that of a monopolistic competition. Companies competing in this domain operate production facilities that are High-Mix Low-Volume (HMLV) where customers order a high mix of products in low-volumes and with a high degree of customization. Here, a wide array of small and medium sized enterprises (SMEs) compete to acquire a higher percentage of the largely fragmented market share. With low barriers to entry, players within the domain compete on factors such as cost, time, on-time delivery, degree of customization, quality, customer service and throughput. Manufacturing in HMLV environments often sees a high degree of in-system waste in the form of WIP (Work In Progress) build-up, defects, overproduction, over-processing and waiting, to name a few. These wastes contribute to long lead times and increased costs.

Lean methodologies have a primary goal to eliminate such waste with the aid of its 5 principles that sequentially specify value, identify the current value stream, create flow, administer flow without interruption and continuously improve (Womack & Jones, 1996). In this chapter, we will first present the background of Lean and our LED architectural lighting company ABC. Then, we will discuss how adoption of lean methodologies will greatly benefit the custom LED architectural lighting industry by allowing it to offer high mix in a time sensitive, cost competitive, and quality compliant manner.

1.1 About Lean

The term "lean" was first popularized by the following two major publications: The Machine That Changed the World (Womack, Jones & Roos, 1991) and Lean Thinking (Womack & Jones, 1996). Lean is rooted in the elimination of waste, which is any activity not recognized as being valuable to the customer. A lean system is the by-product or end result of an application of the philosophy of manufacturing excellence outlined in the Toyota Production System (TPS).

TPS originated in post-WWII Japan, following Toyota's attempt to offer flexibility to its clientele in response to deep competition faced from the lower cost offerings of mass manufacturers such as Ford and General Motors. Toyota realized that shorter lead times and flexible production lines offered notable gains in quality, resource productivity, customer responsiveness, equipment utility and space availability (Liker, 2003). The 4P model of the "Toyota way", structures the Toyota Production System into 4 key principles: philosophy, process, people and problem solving. The 4 principles further branch into 14 distributaries forming the basis of several well-known lean tools including Genchi Genbutsu ("go-see"), Heijunka (load leveling), Poka Yoke (mistake-proofing), Jidoka (quality at the source) etc. (Liker, 2003). However, whilst detailed structural breakdowns provide the roadmap for TPS application, the goal of the system is best summarized by its founder Taiichi Ohno. According to him, TPS is the act of viewing a timeline from the point an order is placed by a customer to the point a payment is received and therefrom, reducing the timeline by eliminating non-value added wastes (Ohno, 2019).

Several paradigms of waste identification have been developed over the years. The most popular among them remain the 3 ‘MU’, the 5 M, the 8 wastes and the cost of poor quality (Chiarini, 2013).

The 3 ‘MU’ approach sees waste as a product of imbalances between production capacity and the amount of workload. In this approach, we are introduced to the terms: Muda, Mura and Muri. Muda refers to real waste that is present in the system when the capacity exceeds the workload. Mura refers to the waste that is introduced in a system that is unsteady (capacity fluctuates about a set target) and finally, Muri refers to waste that arises from situations in which workload clearly exceeds capacity (putting a strain on resources) (Chiarini, 2013). The 4M technique, also popularly referred to as Ishikawa, fishbone or the cause-effect diagram, identifies waste and divides the causes of waste generation into 4 categories, namely: Man, Machine, Method and Material. Waste is however most popularly categorized by using the 8 waste model where all waste is said to originate from 8 broad categories, namely: transportation, inventory, motion, waiting, over-processing, over-production, defects and unused skill (Wibowo, Syah, Darmansyah, & Pusaka, 2018). Finally, the Cost of Poor Quality (COPQ) looks at waste as the monetary losses or the price paid for product non-conformance (Schiffauerova & Thomson, 2006).

With methods of waste identification outlined, lean seeks to eliminate identified wastes through strategic execution of the lean process. The lean process is a 5 step repetitive cycle that aims to extract non-value-added activities (NVAs) in a sequential and iterative manner. The first step is to determine what ‘value’ is to the customer. This is followed by the second step, where a mapping of the value stream is performed in order to outline every activity involved in producing a product. From here, in step three, the value stream is analysed with an intent to eliminate waste and administer uninterrupted flow. In the fourth step, the value stream is redesigned to produce in response to customer pull (the ‘when’ and the ‘what’ of customer demand). Finally, in the fifth step, it is ensured that steps one through four are performed iteratively to ensure continued improvements in the value stream by waste elimination and flow generation (Alston, 2017).

1.2 About ABC

ABC is a privately owned HMLV manufacturer of custom architectural LED lighting fixtures in North America. Having commenced operations two decades ago, the company has scaled exponentially to amass a staff size of over a thousand professionals, all working to uphold the key company philosophy of creating innovative LED lighting products. The company operates in a Make-to-Order (MTO) and Engineer-to-Order (ETO) context. ABC’s flexible design offering and its mastery in client service are what has grown its presence across North America. In the past two years alone, the business has scaled three-fold and the rapid growth of the company, and more importantly the rapid growth of the LED lighting industry, is urging the company to increase its volume and diversity of custom offerings in both indoor (offices, stadiums, universities, residences, retail outlets, warehouses etc.) and outdoor (highways, patios, gardens, parking lots, construction sites etc.) spaces. With threats of losing business to offshore manufacturers of similar products, increasing density of competitors within the North American pipeline and everchanging technology within the lighting industry, ABC needs to look internally to provide quality, low-volume customization, short lead times and on-time delivery, at a competitive cost.

1.3 The role of Lean in ABC

Given its growing demand, ABC is facing pressure from internal and external stakeholders to scale capacity. The market is tending towards a shorter lead time, and a higher degree of complexity. Internally, the present-day ABC production floor is being swamped by WIP. Layout analytics suggest that process cells only occupy 40% of the overall plant area. The labor hours spent reworking damaged or incorrectly processed workpieces is roughly 20%. The daily scrap rate of material is 15% on average and product backlogs are increasing at a rapid pace.

Lean and its associated principles are built to identify and eliminate such sources of waste within systems and create continuous flow. Lean has the potential to mitigate the sea of inventory and lost productivity in the production floor by strategically eliminating NVAs, leveling load, creating pull rather than push production systems and developing a data driven understanding of the capacity required to meet demand.

1.4 Objective

The objective of this thesis is to make ABC more competitive by applying lean and its principles to eliminate waste in the value stream of a given family of ABC's products, in order to increase capacity, reduce cost, improve quality and decrease lead time. With an understanding that there is no well-known recipe for lean application in HMLV environments, careful attention will be paid to the challenges and limitations that apply to ABC's production system. It is aimed that this thesis will provide management with visual and data driven insights into the potential value that can be derived from adopting a lean mindset.

The resultant future value stream developed for the selected product family, if implemented and sustained, can serve as an example of lean effectiveness for other product families within the ABC production floor; which later can pursue their own lean journey. More importantly, this thesis will serve as an example of lean application in high-mix, low-volume and high-customization manufacturing environments. It will aim to introduce a generalized framework that will bolster the applicability of lean in mix model systems.

2 Literature Review

A majority of literature on lean application in the HMLV context is anecdotal with little development of theory. The maturity of research is fairly low, with much of the focus on waste minimization and little attention paid to managing variability. Lean implementation was often found to be tool-based and process specific with little consideration of its applicability at a system or strategic level (Tomašević et al., 2021). Most structured literature reviews agree that research on lean application in HMLV environments is lacking when compared to research on stable low-mix high-volume (LMHV) environments (Danese et al., 2018). The following literature review aims to understand the maturity of lean in HMLV research, realize the gaps causing its limited application and learn about tools and techniques used to implement lean in such environments. In finding literature of relevance, studies in HMLV, Engineer-to-Order (ETO), Assemble-to-Order (ATO), Make-to-Order (MTO) and Mass Customization (MC) contexts were analyzed. The review will also consider developments in the fields of revenue-leveled scheduling optimization and Total Productive Maintenance (TPM) optimization, as they are components relevant to the case at hand.

2.1 Lean compatibility with Mix Model environments

Lean today has evolved beyond its initial application, in the automotive industry following the formation of the Toyota Production System, and is now promoted as a global approach to eliminate waste with a goal to meet customer needs efficiently (Braglia et al., 2006). It is popularized as a set of practices that address market needs, cut costs and help organizations gain competitive edge (Bortolotti et al., 2015). The causes of failed executions are often attributed to organizations that are either using the wrong lean tool, are generalizing the use of a single lean tool to solve all organizational problems or are applying a set of tools repeatedly without sensitivity to their applicability to the case in hand (Pavnaskar et al., 2003). It is important to understand that an incorrect application of lean could result in wasted organizational assets and a reduced employee moral towards the effectiveness of lean (Mostafa et al., 2013). It is critical for organizations to note that 'standard lean tools' popularized in the market today, have been designed to find application in LMHV manufacturing environments (Braglia et al., 2019). LMHV manufacturing is 'product-focused, repetitive and made-to-stock' with little demand variability (Tomašević et al., 2021).

A high-mix, low-volume, high-customization industry largely varies from the aforementioned paradigm. Such environments are vulnerable to: demand and mix variations, extended lead-times and significant order backlogs following limited delivery timeframes (Barbosa & Azevedo, 2019). Often, multiple stages of product assembly is required (Mello et al., 2015). Such environments are subjected to high degrees of customization and require flexibility (Gosling et al., 2013). There is constant competition amongst products that are often thought of as projects competing for shared resources (Alfieri et al., 2012). Furthermore, a challenge lies in the high variation of cycle times and processing steps (routings) for products within the same product family (Rossini et al., 2019). Following case analyses of companies in the ETO context however, it was found that lean implementation was not completely 'misaligned' with the dynamic and complex nature of the system; instead 'mindful customizations' would need to be made in such environments (Birkie et al., 2017).

2.2 Assessment of gaps in traditional lean frameworks

Traditional lean implementation frameworks, as seen delivering success in LMHV environments, are criticized of being incomplete in the HMLV context. Several stances have been taken on the applicability of lean frameworks in HMLV environments. Soliman and Saurin, in their literature review of lean in complex socio-technical systems, found that most studies deal with concepts of complexity in a 'fragmented and loose' manner and that a more systematic approach is needed (Soliman & Saurin, 2017). Bhamu and Sangwan highlight that it is the deficit of standardized execution frameworks that cause the limited utility of lean. To address this, they propose a three-step approach that first promotes 'lean awareness' amongst employees, then identifies SIPOC (Supplier, Input, Process, Output, Customer) systems to create a more wholistic view of the value chain and finally measure gains at a system level rather than a process level (Bhamu & Sangwan, 2014). Bortolotti argues that present day lean focuses on practices such as Just-In-Time (JIT) and often negates organizational culture and soft practices such as 'training, small group problem solving, customer involvement, supplier partnerships and continuous improvement' (Bortolotti et al., 2015). Tying into this thought process, Matt and Rauch also argue that larger scale organizational culture, and its role in propagating a lean mindset, lean training and a need for sustained continuous improvement in such high change environments, will be critical for the success of lean (Matt & Rauch, 2014). Some argue that lean implementation frameworks in HMLV environments are incomplete without considering sufficient capacity buffers to smoothen demand variability (Thürer et al., 2014). The use of capacity buffering is proposed to improve metrics surrounding flow time, lead time, workload control and tardiness (Fredendall et al., 2010). Others explore 'customer enquiry management' and 'controlled order release' as means to dampen demand variability and derive substantial gains from lean in a HMLV context (Thürer et al., 2014). There is also a large emphasis placed on the role of modular design in the success of lean in MC environments (Duray et al., 2000). Furthermore, Stump and Badurdeen explore the role of agile, job shop lean, Theory of Constraints (TOC) established through Drum Buffer Rope (DBR) mechanism, Quick Response Manufacturing (QRM) and Paired cell-Overlapping-Loops of Cards-with Authorization (POLCA) as complimentary models which can enhance lean utility in the HMLV domain (Stump & Badurdeen, 2012). Despite apprehensions toward the wholeness of lean application in HMLV, Chavez (Chavez et al., 2015) outlines a group of case studies that indicate a positive correlation between an adoption of lean practices and improved organizational performance at a market and financial level. Further research into designing theoretical frameworks in such environments is critical.

2.3 Lean Tools and Practices currently used in HMLV environments

Most lean application in the realm of HMLV has been through the fragmented application of lean tools derived from "The Toyota House", developed by Fujio Cho (disciple of Taiichi Ohno), which is depicted in Figure 1 (Liker, 2003). Of these tools, those present in the "Just-In-Time" pillar have found the most value in the HMLV context. Furthermore, it was found that a majority of the benefit was derived from the use of value stream mapping (VSM), followed closely by hybrid Kanban/CONWIP pull techniques and complete cellular manufacturing systems (complete one-piece flow with no shared resources) (Tomašević et al., 2021). Other hybrid and industry 4.0 techniques have proved effectiveness locally for the cases and processes they address but cannot be generalized for global application.

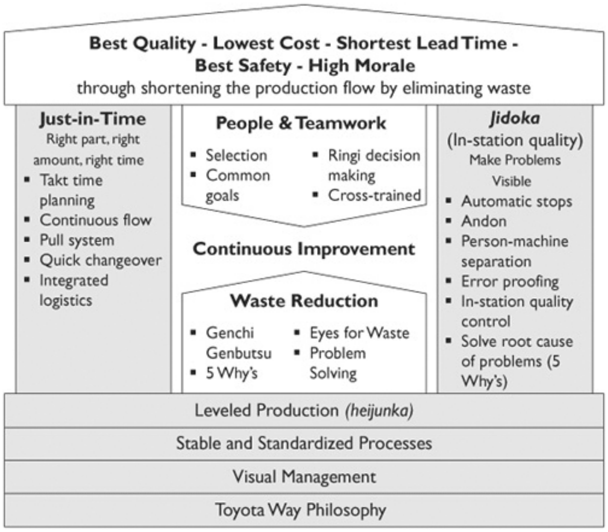


Figure 1: The Toyota House (Liker 2003)

2.3.1 Value Stream Mapping (VSM)

Most cases facing HMLV environments could not use VSM techniques in its pure form owing to unstable demand, high variation in product routings and large variations in cycle time to name a few (Tomašević et al., 2021). Several researchers have either developed adaptions of the VSM approach or have made assumptions to better 'fit' their model to traditional VSM techniques. This unfortunately has led to persistent incomprehension of work content management, pull systems and grouping techniques in HMLV environments .

For example, VSM implementation in the transformer industry facing similar HMLV challenges was said to yield tangible results by adding layers of 'true value' definition (quality, flexibility, customizations), work restructuring, reasonable approximations, simplifications in data collection, tailoring layout to smoothen handling, flow stabilizing scheduling mechanisms, training and the SCARE approach (Simplify, Combine, Add/Automate, Rearrange, Eliminate) for improvement. This saw a 17.3% improvement in cycle time, a 29.78% reduction in waste and an 8.48% reduction in value added activities without any major changes to existing resources. The paper does not however, address product routings, scheduling, machine dedication rates and wholistic pull system application (Seth et al., 2017).

Adapted value stream mapping has also found application in the construction sector. Here, a mix of several trades collaborate to execute a larger project and hence the value stream needs to cater to the flexibility and adaptability needed in such a multi-disciplinary field. Here, the project is first restructured into a group of functional clusters and then, a process pattern is assigned to each cluster (engineer-to-order, configure-to-order, flow production etc.). From this point, a value stream of each cluster and its benefits are obtained using traditional VSM construction techniques. A scoring model is used to derive a weighted project value from individual process patterns. The highest weighted pattern is then used to map the larger construction value stream. The model does not however address how variability in the process patterns will impact the larger system (Matt et al., 2013).

A case study in the Make-to-Order (MTO) handicraft industry (Moroccan woodworking enterprise), focuses on the obstacles of identifying product families and products with uncommon routings. This study utilizes all the industry standard symbols and techniques of VSM but outlines restrictions in defining metrics such as takt time, setup time, material flow, information flow, pitch and shipment date. To tailor the VSM to MTO, it suggests measuring lead time as the longest time taken by all articles launched at the same time or as the cumulation of the longest processing times and wait times at each point along the value stream. This technique however, builds a lot of 'Muda' into the system as several occurrences of capacity exceeding workload will be seen in this worst - case-scenario approach (Chouiraf et al., 2018).

Another case study looks at a machine tool manufacturer in the ETO/MTO sector. Here, the CSM (current state map) is mapped by assigning an average of the cycle times of all products moving through a given process cell. Then, an analysis is performed to determine the % variation to be expected from the average cycle time, in each process. These variations are shown in the process boxes of the VSM in order to offer a view of the degree of potential system variation. The study then dynamically changes work allocation and capacity to ensure that all elements of the system are consistently within the takt time. Systems to control inventory levels however are unaddressed in this case (Ricondo Iriondo et al., 2016).

2.3.2 Kanban/CONWIP based pull techniques

A case study in a hi-tech electromechanics product company explores the implementation of a hybrid ‘Kanban/CONWIP’ system to address demand fluctuations in HMLV systems (Leonardo et al., 2017). Pure Kanban, which is the production by one process cell according to the requirements of the downstream cell (Ōno, 2019), effectively maintains WIP between process cells. Pure Kanban with set supermarket sizes, are however criticized of being slow in readjusting to mix variations and demand fluctuations. The CONWIP (Continuous Work In Process) concept takes Kanban to a system level. Here, WIP in the system is constant and defined by a set of fixed Kanban cards. Only when an order exists the system does a Kanban card become free and an order in the backlog is released into the production system (Spearman et al., 1990). CONWIP without process level Kanban is often criticized of inflating in-system inventory if backlog sequences are mismanaged. This may lead orders (some of which may be high priority) with low processing times to wait in the system (building WIP) for orders with higher processing times to pass through. Therefore, the authors of the case study found the use of the hybrid ‘Kanban/CONWIP’ most effective. CONWIP maintained system level WIP and Kanban controlled process level WIP . The study does however highlight that the framework cannot be generalized for use beyond the local system to which it was applied (Leonardo et al., 2017). Moreover, the required capacity toggling to maintain such a system is under-addressed.

Prakash and Chin provide guidelines for use of the ‘Kanban/CONWIP’ systems in low variety/low volume shop floors (Prakash et al., 2014), however frameworks on how this system can be applied to HMLV environments is under-researched. At this stage, it is interesting to see that Kanban/CONWIP is comparable to the “offset-sequencing” technique outlined by Duggan in his book: Creating Mix Model Value Streams (Duggan, 2013).

2.3.3 Cellular manufacturing

Another concept that is deeply researched is cellular manufacturing, specifically cells that flow in one piece from start to finish through the dedication of all resources in the value stream. Techniques of evolving from traditional functional process cells with collocated equipment known as “process villages” or “job-shops” into cellular manufacturing units with a “stock-to-dock” philosophy comprising cross-trained employees and a mixture of fully dedicated equipment, is another area that is being explored by HMLV researchers. Studies have attempted to break down products into sub-assemblies and then re-grouped sub-assemblies into families based on manufacturing similarities (build and material similarities), in order to amass sufficient demand to substantiate fully dedicated manufacturing cells (Irani, 2011). However, strong criticism of such studies have been received due to lack of focus on the impact of resource specialization on capacity pooling, the implausibility of dedicating resources into definite cells when HMLV demands a flexible layout and the increased levels of buffer capacity required to support such structures (Tomašević et al., 2021).

2.3.4 Hybrid models and Industry 4.0

Several case studies have attempted to design HMLV systems by using a mixture of aforementioned techniques. For example, a case study following a HMLV sub-contractor in the power distribution and control equipment industry applied a combination of CONWIP, takt time control and FIFO (First In First Out) techniques as part of its lean application (Slomp et al., 2009). The system however requires the in-system WIP to always be in excess of capacity, which in turn builds, rather than eliminates, waste in the system.

Other studies look into the 'cyber physical systems (CPS)' and Internet of Things (IoT) and its application in the HMLV environments of SMEs (Small and Medium Sized Enterprises). Here, techniques of developing 'flexible feeder systems' for automated custom machining, modular and flexible assembly lines, robotization of simple tasks, introduction of collaborative robots, pick and place cells for automated handling and remote cloud based standard work procedure communication are explored as means to create a 'Smart Factory' (Grube et al., 2017). These suggestions however are too localized at the process cell level and fail to address larger systematic gains.

2.4 Maintenance Optimization

Literature on frameworks for TPM implementation is vast and typically involves activities including: identification and elimination of the root causes of current reliability deficiencies, institution of autonomous maintenance (creating maintenance routines amongst machine operators), introduction of planned maintenance (performed by skilled professionals at regular intervals to sustain machine health) and training provision to machine operators on machine mechanics with an intention to avoid losses (Pinto et al., 2020).

Machine maintenance, be it planned or unplanned, has important implications in highly volatile environments, as seen in HMLV systems. With the cost of maintaining a machine already being significant, machine stoppage also creates high secondary costs associated with idle operators, orders on hold, increased lead times etc. Maintenance related costs can represent anywhere between 15% and 70% of total production costs (Bevilacqua & Braglia, 2000). For this reason, most maintenance optimization studies focus on cost minimization. For example, research in the oil and gas industry shows how maintenance optimization modelling built with a cost minimization focus has led to tangible savings in the cost of maintenance whilst minimizing production losses and improving machine reliability (Bohlin & Wärja, 2015). Another study in Condition-based Maintenance (CBM), where maintenance is triggered based on machine conditions, also uses cost minimizing objective functions as part of its optimization modelling (Zhu et al., 2015).

2.5 Revenue Leveled Scheduling Optimization

Literature on revenue management and revenue-leveled scheduling is scarce. Most revenue management systems find utility at the order acceptance and quotation stage. For example, a study on make-to-order manufacturing in the iron and steel industry develops a revenue management model which acts as a decision support tool in accepting/rejecting orders and provides bid-pricing schemes by using a multi-dimensional knapsack problem formulation (Spengler et al., 2006). Other revenue management models use deterministic linear programming techniques to provide evidence of controlled revenue as a result of developing ‘flexible products’ that allow for supply-side substitutions (Gönsch et al., 2014). Studies on revenue-leveled scheduling and revenue management at a production level, however, were not to be found.

2.6 Summary of Literature Review

Following a systematic review of present-day literature in HMLV, conclusions can be drawn about the scarcity of available literature and the need for a general framework that applies globally rather than locally. Techniques for product family formation and value stream mapping with integrated inventory management are required. Tools that address variability in mix and demand, will need to be developed. More importantly, techniques of managing cycle time variations will need to be designed in a manner that sustains flexibility. To add to this, robust schedules for maintenance and revenue leveling at a production level will need to be formulated. The intention of this thesis is to address the gaps in HMLV literature today, by using the methodologies outlined in Learning to See (Rother & Shook, 2009), Creating Continuous Flow (Rother & Harris, 2001) and Creating Mixed Model Value Streams (Duggan, 2013) as a base and from there, develop a generalized system that specifically caters to HMLV environments.

3 Methodology

As previously mentioned, the case study follows the guidelines outlined in Learning to See (Rother & Shook, 2009), Creating Continuous Flow (Rother & Harris, 2001) and Creating Mixed Model Value Streams (Duggan, 2013), in order to apply the 5 lean principles of: specifying value, identifying the current value stream, creating flow, administering flow without interruption and continuously improving (Womack & Jones, 1996). Following this, linear programming is used to arrive at optimized maintenance and 'revenue-leveled' schedules which will prove to be essential in the successful execution and sustainability of the systems developed. In this chapter, we will:

- specify value through product family formation and mix variation minimization
- identify the current state map via data gathering
- create the future state map through:
    - process kaizen
    - creation of continuous flow
    - identification of the pacemaker
    - development of weighted averages of total work content at process cells
    - design, scheduling and distribution of work at the pacemaker
- design inventory control measures
- continuously improve through future research suggestions
- optimize schedules for revenue-leveled production and preventive maintenance

3.1 Specifying Value

Defining the value stream for the entire ABC production floor is too large a scope for the purpose of this thesis considering the high product variety and the timeframe within which ABC would like to begin lean implementation. For this reason, it is essential to prioritize the value to ABC from the onset to ensure that the selected product family under analysis is one that the business derives the highest value from. The analysis of customer value begins by looking at all products produced by ABC and forming groups of products that have the same routing. Once the different groups are formed, forecasted demand of each product within the family is cumulated to form the forecasted demand for the family. The demand forecasts are received by performing interviews with ABC's analysts and harnessing data available in the ABC Enterprise Resource Planning (ERP) system. Following this, the group with the highest cumulative forecasted demand is selected for the case study in order to deliver the highest value to ABC. It was noticed that the selected product family had a high number of ordering permutations within each product and this propelled a study to minimize mix variation within the selected group by abandoning product ID classification and reclassifying based on build and material commonalities with an intention to narrow the mix.

In furthering the understanding of customer value, competitive benchmarking reports are looked at and further interviews are performed with key stakeholders. Based on the company's vision, strategic goals and competitive landscape, it is determined that reducing lead time and cost (and increasing capacity), by eliminating waste will lead ABC to derive the highest value. ABC is also cognizant of its own end-user and wants end-user value to also be considered. Value within the context of ABC's end-user is any activity that transforms the product from raw material to a finished lighting fixture by using minimal resources and in the shortest lead time possible, that the end-user of ABC's product is willing to pay for. Thus, causing the thesis to also lay emphasis on either eliminating (waste) or re-assigning (essential non-value-added activities) non transformational activities away from the value stream.

3.2 Identifying the Current Value Stream

The next natural step is to construct the current value stream map. This form of mapping: helps visualize each process cell, identifies waste, fosters a common language of communication about processes, lends to reasoned decision making based on the larger picture of flow, forms the building blocks for implementation and identifies the relationship between material and information in a quantitative manner (Rother & Shook, 2009). In constructing the current state value stream, the bounds of the analysis are first set to be the point from which an order is released to the production floor to the point at which the order exits the production floor and is shipped to the customer.

In order to build the current state, the monthly average customer demand is first determined. Next, the number of functional shifts of production are noted. The frequency of order confirmation sent from the customer, the frequency of order placement to the warehouse for material, the frequency of schedule delivery to the floor and number of schedules developed for each process cell is defined via interviews with the production control department. This interaction provides insights on information flow. Following this, a Gemba walk from downstream to upstream is taken to gain an understanding of the complete value stream. With the process cells identified, the routing defined, the frequency of material entry from the warehouse outlined and the frequency of fixtures leaving the floor determined, the time collection process is initiated.

The Time collection form depicted in Appendix A is used to collect time for each process cell in the current value stream. Using the form, the work elements are outlined, and each of their associated times are determined by picking the mode of 5 data points. The form provides room to categorize activities as value added, waste and necessary non-value added. Finally, the form also provides room to collect information on the number of operators, changeover times (C/O) and comments on the process (high humidity, insufficient operator training, incorrect work tool, conditions for changeover). ERP data is used to generate non-conformance reports and maintenance logs over the past 3 years, in order to help determine yield and uptime statistics.

With process level information collected, the next step is to track the degree of inventory build-up between processes. The inventory count form found in Appendix B is used to perform the inventory count. As is depicted, the inventory at the start of the value stream, at the end of the value stream and in between processes is collected over a 1-month period and then the average of the data at each point is used to determine the inventory buildup. Finally, all the data is visually built into the current state map using industry standard icons. The overall lead time and processing time are then determined.

3.3 Creating Flow

With the current value stream defined, the goal is then to develop a roadmap to a future value stream that mitigates waste and promotes uninterrupted flow within the system. To achieve this, takt time is first realized for the selected group in order to ensure the production is in line with customer demand. Here, demand forecasts for each process cell and the total available time to produce within the cell, previously gathered in the current state, are used to define takt time and therefrom, a planned cycle time that will absorb activities such as changeovers, operator inefficiencies, mix variations, maintenance activities etc. From this, the Takt adherence of each process cell is determined by comparing the total work content of each process cell to the planned cycle time. Findings from the comparison are then the trigger for a process kaizen phase which is initiated with the use of the paper kaizen technique to eliminate or re-assign all non-value-added activities in order to ensure the work content only reflects value added work elements. With waste eliminated from work content, the next goal is to combine processes into a continuous flow cell in order to propagate one-piece-flow. All processes that are dedicated to the value stream, share common takt and flow sequentially, are combined into a single continuous flow cell. Shared processes and processes with differing takt will not be included in this flow and will retain their identity as individual process cells. Given that ABC operates in a high-mix environment, products have significant work content variations. Hence, a weighted average work content analysis is performed next, in order to determine the average work content of the newly revised cells. From here, the resource and overtime requirements are derived to align cycle time with takt time. With all the new process cells in view, a single process cell is chosen as the pacemaker based on criteria that it must be as upstream as possible (given the custom nature of the products) and it must be dedicated to the value stream. From this point, the pacemaker is looked into more closely in order to ensure adequate scheduling, cell design and work distribution.

With the continuous flow cell and pacemaker (in our case these are the same) identified, the process kaizen phase later looks at changeover improvements, mix leveling (Every Product Every interval (EPEi)), Kanban size, dynamic pitch, yield improvements and uptime improvements, in an attempt to further eliminate in-process waste.

3.4 Administering Flow without Interruption

With the process kaizen complete and the continuous flow cell designed, the next stage is to institute flow kaizen practices to ensure that process cells do not function as silos and produce with awareness of the requirements of process cells that succeed them. Therefore, information and material management is administered with a view from a higher vantage point. Processes which cannot be included in the continuous flow cell and are upstream of the pacemaker, need to receive information on which sequence to produce in, given the custom nature of products. Mix model scheduling techniques are explored as a result. Furthermore, inventory between process cells along the value stream will need to be monitored and controlled to ensure efficient material flow. This is achieved by the institution of supermarket-based pull systems and First In First Out (FIFO) flow lanes with finite capacity. As the result of developing the aforementioned building blocks, the Future State Map (FSM) is developed.

3.5 Continuous Improvement

At this stage the FSM is compared to the current value stream map in order to quantify the gains of applying the lean principles. Several implementation projects are outlined and areas for future improvement are mentioned. The future research areas are meant to initiate a series of iterative cycles to continue improving the value stream. An example of this could be the magnification of individual processes to create new process level value streams following the same lean principle application outlined above, in order to keep eliminating waste and improving the flow.

3.6 Schedule Development and Optimization

As a result of the process and flow kaizen execution, it was noticed that ABC requires two schedules to be developed. The first is a preventive maintenance schedule with a purpose of improving uptime and the second is a ‘revenue-leveled’ production schedule to ensure ABC’s condition of setting a constant financial pitch to generate near equal revenue on a daily basis (within a production week) was satisfied. To achieve these schedules, linear programming techniques are utilized. Following interviews and group meetings, the problem statement, assumptions and constraints are first documented. Raw data is extracted from the ERP system to determine the type and size of sets and parameters. From this, the decision variables, the objective function and constraints are mathematically modeled and later programmed using OPL language. This is then inputted into the IBM CPLEX solver to achieve the optimized schedules.

3.7 Summary and Application of Methodology

A summary of the methodology adopted in executing this case study can be found in Table 1 below. A detailed implementation of this methodology will be demonstrated in Chapter 4, 5, 6 and 7, in order to improve ABC’s competitiveness by increasing capacity, reducing cost, improving quality and reducing lead time.

Steps of Methodology	Sub-Steps of Methodology
1. Specify Value	a) Identify project scope b) Group products according on similar process steps c) Select Product Family based on forecasted demand d) Minimize mix variation e) Perform business value analysis for selected group
2. Identify the current value stream	a) Define bounds of analysis b) Collect customer requirements c) Collect shift data d) Collect data on information flow e) Perform Gemba walk to define process and material flow f) Collect time and process cell information (operators, C/O) g) Collect inter-process inventory h) Construct the CSM
3. Create Flow	a) Define takt time and planned cycle time b) Measure takt adherence c) Initiate process kaizen with paper kaizen d) Create Continuous Flow Cell (CFC) e) Identify the pacemaker f) Perform a Weighted average work content analysis g) Determine required resources h) Design, schedule and distribute work at the pacemaker i) Complete process kaizen (Stipulate C/O, Kanban size etc.)
4. Administer Flow	a) Administer inter-process inventory control b) Construct the Future State Map (FSM)
5. Continuously Improve	a) Compare the FSM to the CSM b) Outline implementation projects c) Outline avenues for future improvement
6. Developing Optimized Schedules	a) Define the problem statement b) Document the assumptions c) List the Constraints d) Develop the Sets and Parameters e) Form decision variables, objective function and constraints f) Translate the mathematical formulation to OPL language g) Optimize using the IBM CPLEX Optimizer

Table 1: Methodology adopted in executing the case study for ABC

4 Case Analysis

This case study is conducted in the production facility of ABC. The case observes the production processes of LED architectural lighting fixtures from the point an order enters the production floor to the point the finished order exits the production floor. An order contains a set of order SKUs (Stock Keeping Unit), each SKU reflecting a specific customized permutation of a product. Members of the production department, including the production staff and their managers, contributed to the data collection and analytics of this case study. Furthermore, they served as subject matter experts in clarifying the current state of production and assessing the applicability of the later constructed future state. The adjoining warehouse and corporate office of ABC, their resources and processes, are excluded from the scope of this case study. Members from these areas did however participate in outlining the business and customer needs and provided data for the products included in the case study.

Given the high-mix, low-volume, high-customization manufacturing environment of ABC, determining the case scope and ensuring its alignment with immediate business needs is of primary importance. Therefore, process-wise product segregation in conjunction with future demand forecasts are used to narrow in on a product family that if improved, will provide the highest value to the business. This was followed by a current and future value stream map for the selected product family which provides insights and future objectives for the material and information flow within the production floor. A comparison of the two models is then performed to outline the value proposition of implementing the proposed changes.

Data collection for these components includes primary field data and secondary data (harnessed from the company's enterprise resource planning system (ERP) and meetings with key stakeholders). The primary data collection provides information on the design, build, capacity, work content, inventory build-up, process flow and key wastes in the production floor. The secondary data provides insights on historical demand, future demand projections, key performance indicators (KPIs), customer ordering patterns, business needs and constraints.

In this chapter, our objective is to first outline the current problems faced by the production floor and understand the constraints that must be adhered to. This is followed by a definition of the scope of the case study via careful selection of a product family. We then attempt to minimize the mix variation within the selected product family in order to consolidate our analysis. This is followed by a mapping of the current value stream for the selected group, in order to visualize the material and information flow from the point an order enters the production floor to the point it exits the floor (shipped to the customer). Next, target conditions, the key wastes in the system and their root causes are discussed. Finally the chapter proposes brief solutions which can improve the current state.

4.1 Problem Definition

With an exponential rise in demand following ABC's entry into a rapid growth phase of its business cycle, production is facing several challenges. Managers face a challenge to produce within the given capacity and the business is under pressure to invest in more production space, resources and new equipment in order to sustain the on-time delivery KPI. Furthermore, there is a constant push from industry to add more offerings to the portfolio. The minimum 6-week lead time offered to customers is now facing competitive pressure as other players in the architectural lighting space are now offering lead times between 4 and 5 weeks. Orders placed by customers present the need for a high-mix, low-volume and high customization manufacturing environment which presents a key challenge to flow improvement. Several efforts to implement point kaizens have not proved fruitful as increased pressure to produce often led employees to regress to prior practices. ABC is concerned about the growing cost of poor quality both from an internal production perspective and an aftersales perspective.

Performing a flow analysis in a mix model environment can be challenging for a number of reasons. The sheer structure of the mix model manufacturing environment makes flow improvement a greater challenge when compared to high volume manufacturing environments, which most of lean literature is built on. Possible product ordering permutations exceeding 10^{10} can be daunting from a volumetric perspective. The current production facility is a mix of traditional batch production and prior process area focused attempts at lean tool implementation. This divide is also reflected in the plant culture and attitude of employees towards lean. Currently, any given order can be scheduled to any resource within a process cell. Hence all resources are shared and there are no dedicated resources to any given product family. The layout of the current production facility presents silos of process cells with a sea of Work In Progress (WIP) forming the natural border between the cells. Furthermore the mechanical assembly of the fixture is managed by the “Machine Shop”, which is a separate department from the “Electrical Assembly” department which manages the wiring, testing and packaging of the fixture. There are also several “Sub-Assembly” cells feeding the “Electrical Assembly” department, which again form separate departments. Structural and managerial gaps between departments further slows down the flow time within the production facility.

Furthermore, when analysing the system, it is vital that the study adheres to the following limitations stipulated by ABC:

- Following a non-disclosure agreement, the identity of the company, its employees, its products, its machinery and its financials cannot be released as part of this study
- All safety, health and ergonomic standards must be adhered to

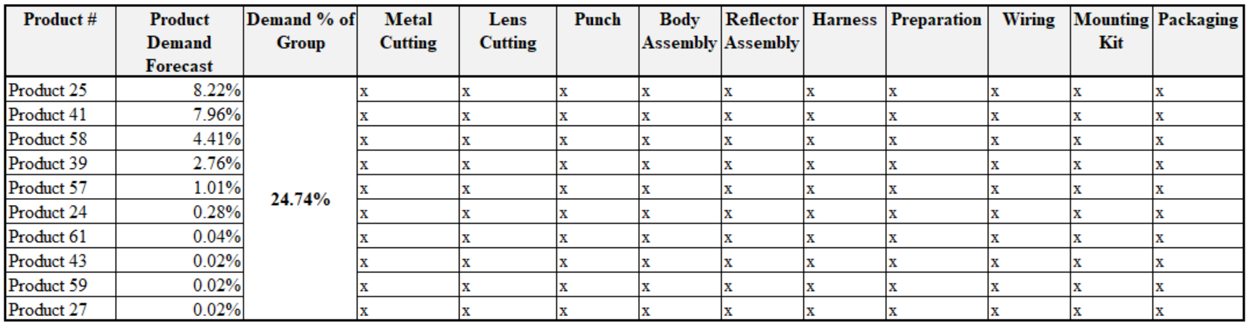
- The company is make-to-order and engineer-to-order; hence no fixtures can be produced if there is no customer order for it
- The corporate office and warehouse require two weeks (10 working days) to process the order from the point of order arrival. This includes quotation approval, design approval, material arrival, material inspection etc.
- The company does not want any finished goods inventory and requires all orders to be shipped the day they are produced
- The company requires near equal revenue to be earned by production on all days within a given production week
- Orders splitting, where a single order is split and produced on multiple days, should be minimized
- No new major machinery should be purchased
- The floor cannot work in excess of two production shifts and overtime cannot cross 12 hours per week per employee
- Every employee must be given a 30 minute un-paid lunch break and two 15-minute paid breaks per shift. Therefore an employee works 8.5 regular hours per shift, 7.5 hours of which is spent producing
- An individual fixture cannot be left partially complete at the end of a production day

4.2 Selection of Product Family

ABC, a key player in the North American LED architectural lighting industry, currently has a product portfolio of over 90 product families. Each of these product families contain between 2-20 products. Each product can be ordered by customers in up to 1.6×10^9 different permutations including variations in length (anywhere between 2’ and 14’), lumens (between 200 and 2000), CRI (Colour Rendering Index) (70, 80, 90,100), color temperature (anywhere between 1000K and 7500K), optics (clear, translucent) electrical circuits (single, double, etc.), finishes (white, black, wooden, metallic, green, blue etc.), voltages (120V, 277V, UNV, 347V), driver configurations (single, double, brand A, brand B), packaging (palletized, boxed), and a plethora of auxiliary inserts including sensors, emergency circuits, fuses, batteries, dimmers etc. Furthermore, a customer may request features and add-ons not present in the current specification sheet. Each permutation impacts the bill of material (BOM), work content and processing steps of the fixture. This degree of flexibility in product offering is industry standard and is essential for the company to sustain market share. Choosing a product family for the case analysis in this mix model environment can easily become overwhelming.

The first step is to document all the production processes. The ABC production floor contains 19 distinct production processes which contribute to the transformation of BOM components to finished fixtures. The second step is to outline the routing or process steps for all permutations of each product. The third step is to group products based on their similarity in routings. This process yielded 63 different product families based on identical routing classification. At this stage, traditional mix model practices suggest to further re-group products such that their work content is within 30% of one another (Duggan, 2013). But given the high number of permutations within each family, any given product already has +30% of work content variations within the product itself. Hence, for high-mix, low-volume, high-customization, the first recommendation is to not perform further product segregations based on work content. Methods of how to address and build flow with high variations in work content will be discussed in Chapter 5.

At this stage, the most logical selection would be to select the group with the highest number of products but, for mixed model applications, this choice may not be ideal. The objective here is to then analyse the demand forecasts for each product and therefrom cumulate individual product demands within a family to find the forecasted demand for each product family. Finally, upon analysing the demand forecast for each product family, the product family in Table 2 is selected owing to identical routing and the highest demand forecast.



Product #	Product Demand Forecast	Demand % of Group	Metal Cutting	Lens Cutting	Punch	Body Assembly	Reflector Assembly	Harness	Preparation	Wiring	Mounting Kit	Packaging
Product 25	8.22%	24.74%	x	x	x	x	x	x	x	x	x	x
Product 41	7.96%		x	x	x	x	x	x	x	x	x	x
Product 58	4.41%		x	x	x	x	x	x	x	x	x	x
Product 39	2.76%		x	x	x	x	x	x	x	x	x	x
Product 57	1.01%		x	x	x	x	x	x	x	x	x	x
Product 24	0.28%		x	x	x	x	x	x	x	x	x	x
Product 61	0.04%		x	x	x	x	x	x	x	x	x	x
Product 43	0.02%		x	x	x	x	x	x	x	x	x	x
Product 59	0.02%		x	x	x	x	x	x	x	x	x	x
Product 27	0.02%		x	x	x	x	x	x	x	x	x	x

Table 2: Final Product family selected with routing and demand forecast %

4.3 Narrowing the mix variation

Despite the product family formation performed in the prior section, the mix variation in terms of order permutations and work content differences is still quite high. This can make data collection extensive and flow improvement complex. In this segment, we will highlight how to structure mix minimization in a high mix product family.

Our product family contains 10 product types. Each product with 1.6 x 10^9 ordering permutations. An interesting finding earlier on in the process was that different products in the product family have significant form differences (circular, square, rectangular, narrow channel, wide channel etc.) but their construction is fairly similar. This caused us to abandon the approach of observing fixtures in the traditional sense of a distinguished product ID and rather made us observe the broader pool to find differences in construction and work content. The next step is to assess each category of customer ordering variation. For example, if the consumer orders several different lengths, this does not lead to any material change nor does it lead to any change in work content as all products in our group have a 90^0-straight cut. Therefore permutations featuring differing lengths can be thought of as a single permutation. The next step is to analyze categories of variation that only feature material change. For example, if a customer orders a specific CRI or colour temperature, this will only change the type of LED used but will not alter the work content. Similarly, ordering a different optic or even a different finish will only change the material whereas the process of cutting the optic or extrusion with the different finish does not face any work content variations. Hence even these permutations are grouped as one.

There are, however, several other categories of ordering such as added sensors, emergency sections, fuses, batteries, dimmers and other auxiliaries which have a definite impact on the work content and the processing time. One good observation is that these components are added on, in a modular fashion, onto the base construction of the fixture. Furthermore, the work content to add these modules is the same regardless of which product ID it is added to. Following these findings, the product family can be redefined as containing regular fixtures (base fixture with same work content and only material variations), a single customization fixture (one of the auxiliary parts have been added to the base construction), a double customization (two auxiliary modules are added to the base construction) and so on. Finally, an analysis of historical ordering patterns of customers over the past five years yields that though the company offers a multitude of permutations, customers are only ordering a hand-full of these permutations.

With all these concepts in mind, the product family mix is narrowed to contain only 31 different permutations, each with distinctly different work content. Table 3 showcases these permutations, which we will, from this point on, refer to as ordering SKUs.

Permutations	
Regular	
SKU 1	Regular
SKU 2	Regular Flangeless
Single Customization	
SKU 3	Emergency Battery
SKU 4	Chicago Plenum
SKU 5	Emergency circuit
SKU 6	End Feed
SKU 7	Flexible Whip Cable (Flex Whip)
SKU 8	Fuse
SKU 9	Generator Transfer Device
SKU 10	Controls (sensors)
SKU 11	Night Light
SKU 12	Length Relief Module
SKU 13	Downlight Insert
Double Customization	
SKU 14	Chicago Plenum, Length Relief Module
SKU 15	Emergency circuit, Emergency Battery
SKU 16	Emergency circuit, Chicago Plenum
SKU 17	Emergency circuit, Controls (sensors)
SKU 18	Emergency circuit, Length Relief Module
SKU 19	Emergency circuit, Flexible Whip Cable (Flex Whip)
SKU 20	Emergency circuit, Fuse
SKU 21	End Feed, Flexible Whip Cable (Flex Whip)
SKU 22	Flexible Whip Cable (Flex Whip), Emergency Battery
SKU 23	Flexible Whip Cable (Flex Whip), Length Relief Module
SKU 24	Fuse, Emergency Battery
SKU 25	Controls (sensors), Emergency Battery
SKU 26	Downlight Insert, Chicago Plenum
SKU 27	Downlight Insert, Flexible Whip Cable (Flex Whip)
SKU 28	Length Relief Module, Emergency Battery
Triple Customization	
SKU 29	Downlight Insert, Flexible Whip Cable (Flex Whip), Emergency Battery
SKU 30	Emergency circuit, End Feed, Flexible Whip Cable (Flex Whip)
SKU 31	Emergency circuit, Chicago Plenum, Length Relief Module

Table 3: Product permutations in the selected product family

Hence, we have successfully remodeled our analysis into a product family composing 31 different SKUs, each with different work contents. We will design our flow system with this categorization in mind but will simultaneously provide room in our flow to accommodate other permutations should they enter the value stream.

4.4 Current State Map

The objective of this segment is to outline the current value stream map of the selected product family. In constructing the value stream map depicted in Figure 2 below, the outline provided in the methodology chapter is adhered to. In this section we will visualize the overall material and information flow. We will also discuss the critical information in each process cell, namely: the work content, cycle time, changeover, uptime and other process area specific challenges.

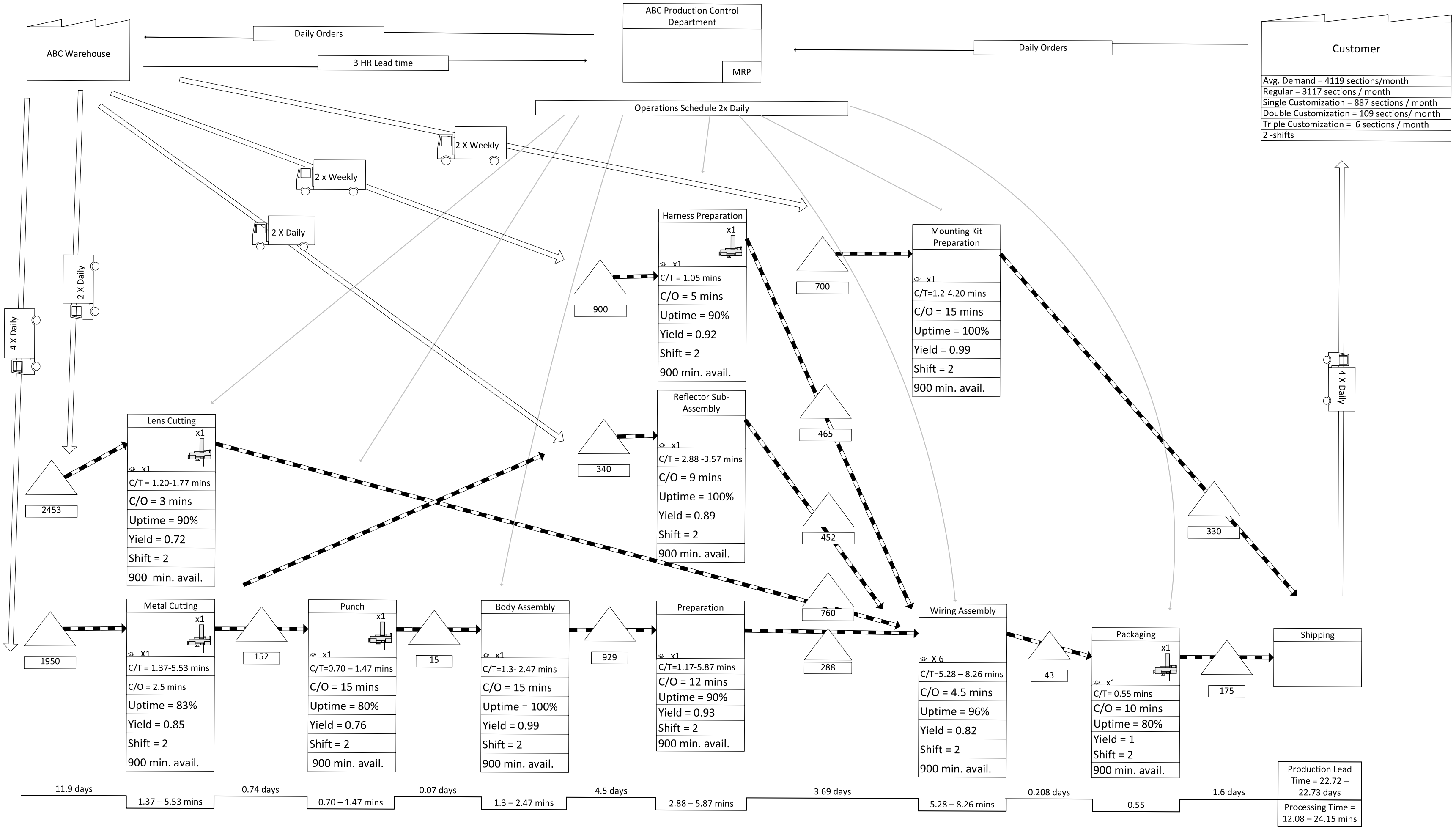


Figure 2: Current State Value Stream Map of ABC for the selected product family

We begin our analysis by observing the customer grid. ABC has a vast clientele spread across North America. The ABC demand forecast results in an average demand of 4119 fixtures per month or 206 fixtures per day (2 shifts) for all SKUs within our selected group. Of this, regular fixtures are demanded at an average of 3117 fixtures per month. Single customization fixtures are demanded at an average of 887 fixtures per month and double customization fixtures are demanded at an average of 109 fixtures per month. Finally, triple customization orders are demanded at an average of 6 sections per month. Customer requests are received on a daily basis. Today, ABC quotes a minimum of 6 weeks for a given order to be fulfilled from the point an order is placed in the system. Upon arrival, it takes two weeks of "order processing" for design finalization, price negotiation, material procurement and material inspection. The order is then released to the ABC Production Control Department, where it is given a production schedule date. Information of the scheduled orders are released on a daily basis to the ABC Warehouse. The Production Control Department also delivers a production schedule for each of the 10 process cells (push-based schedule) twice daily (one schedule per shift). It is vital to note that all process cells in this analysis operate for 900 minutes or two shifts per day.

The ABC warehouse requires 3 hours to pick order material and deliver it to the production floor. This 3-hr lead time is enabled due to the two week "order processing" period which usually enables material availability. The warehouse also buys largely from North American suppliers, which allows for shorter supplier lead times, and maintains sizable buffer stock for parts received from Asian suppliers. The warehouse delivers pre-painted parts to the metal cutting cell 4 times daily, to the lens cutting cell 2 times daily, the reflector sub-assembly cell 2 times daily, the harness preparation cell 2 times weekly and the mounting kit preparation cell 2 times weekly. Smaller components such as screws, brackets, rivets, ground wiring etc. are pulled from the warehouse following a Kanban replenishment system.

4.4.1 Metal Cutting

The metal cutting process performs the cutting operation of all metallic parts including extrusions, flanges, reflectors etc. This process cuts the metallic material to the length specified by the customer based on the push-based schedule provided by the Production Control Department. On average the process is seen to have 1950 units of inventory or 9.46 days of raw material in front of its station which presents a severe space constraint and makes order retrieval an ordeal. The cutting process is conducted using a double blade saw machine. This machine is a shared resource for several product families. This cell is operated by a single operator who performs all the tasks. A detailed list of the work elements and standard time to process parts from the selected product family can be found in Appendix C.

The total work content and in this case synonymously the cycle time varies between 1.37 and 5.53 mins. It is important to note that the machine adjustment made to change the length of the cut is part of the work content and not included in the changeover as the length change occurs with each new part processed. Moreover, since not every part requires a length change (multiple quantity may be requested of the same fixture), the length adjustment time presented in the work elements is the total time to change length divided by 5, which reflects the number of pieces processed before length change is necessitated, on average. Hence each fixture absorbs a fifth of the length change time. The changeover of 2.5 mins is owing to the recalibration process of the machine. The machine is currently maintaining an uptime of 83% which is problematic considering the machine was purchased only 3 years ago. The machine is presently only serviced when it breaks down. This area has a yield of 0.85 with non-conformances owing to incorrect length cuts and handling (scratches, dents). The metal cutting process, is the most upstream process in the critical path. Completed parts are then delivered to the punch cell as part of the critical path and the reflector cell that is not part of the critical path.

4.4.2 Lens Cutting

Simultaneous to the metal cutting process, the lens cutting process is also initiated, though it is not a part of the critical path. The lens cutting process performs the cutting operation of all acrylic parts including lenses, films etc. This process cuts the acrylic material to the length specified by the customer based on the push-based schedule provided by the Production Control Department. On average the process is seen to have 2453 units of inventory or 11.9 days of raw material in front of its station which is, again, a space and retrieval concern. The cutting process is conducted using a single blade saw machine. This machine is a shared resource for several product families.

This cell is operated by a single operator who performs all the tasks. The total work content is therefore identical to the cycle time and varies between 1.2 and 1.77 mins. At this station also, the machine adjustment made to change the length of the cut is part of the work elements and not included in the changeover. Time to change cut length is divided by 5 and a fifth of the cut length adjustment time is assigned to each fixture as a work element, as outlined before. The changeover of 3 mins is owing to the recalibration process of the machine. The machine is currently maintaining an uptime of 90% and is often down due to machine disfunction owing to lens residue accumulation around the motor. The machine is presently only serviced when it breaks down. This area has a yield of 0.72 which is fairly low and is caused by non-conformances such as incorrect length cuts, handling (scratches, bends, cracks) and missing pieces. The lens cutting process directly feeds the wiring process cell.

4.4.3 Punch

The punch process is the second most upstream process in the critical path. The punch process performs the punching operation of extrusions, blanks and end plates. This process punches the mounting holes, power holes, sensor holes etc. on metallic material depending upon the mounting, sensor and power specifications of the customer. Orders are processed in a sequence mandated by the push-based schedule provided by the Production Control Department. On average, the process is seen to have 152 units of inventory or 0.74 days of material in front of its station. The punch process is conducted using a custom punch machine which is only compatible to perform punching operations on products within the selected product family.

This cell is operated by a single operator who performs all the tasks. The total work content and thereby the cycle time varies between 0.7 and 1.47 mins. Changeover in this process occurs when the punch dye is changed for different products within our product family and this takes 15 mins. The machine is currently maintaining an uptime of 80% as parts often get stuck within the dye causing the machine to breakdown and the parts to be scrapped. This also contributes to the significantly low yield of 0.76. The machine is presently only serviced when it breaks down. Completed parts are then delivered to the body assembly cell as part of the critical path.

4.4.4 Body Assembly

The third process cell in the critical path is the body assembly cell. This process performs activities such as end plate build, end plate fixation, flange fixation and power plate fixation. It is the stage where all the machined mechanical subparts are assembled to form the mechanical assembly of the fixture, also referred to as the “housing”. This cell also processes orders according to the push-based schedule provided by the Production Control Department. On average the process is seen to have 15 units of inventory or 0.07 days of material in front of its station. This is a process which is fully manual and, by nature of its assigned work elements and the product design, fairly Poka-Yoke.

This cell is operated by a single operator who performs all the tasks. The total work content and the cycle time varies between 1.3 and 2.47 mins. Changeover in this process takes about 15 mins and is attributed to tooling changes. The process has a virtually perfect uptime and yield from this work cell is 0.99 which is the highest across all production processes. This is attributed to the fairly simple work content and mistake proof design. Completed housings are then delivered to the preparation work cell, which is the first of the electrical assembly processes.

4.4.5 Preparation

The fourth process cell in the critical path is the preparation cell. It is important to note that all prior processes belonged to the “Machine Shop” department. This process is the first cell in the “Electrical Assembly” department. A change in leadership and culture is apparent at this stage. This process performs specific preparation activities including the driver programming, driver cabling, auxiliary (e.g. sensor) programming and insulating activities. This cell also processes orders according to the push-based schedule provided by the Production Control Department. On average the process is seen to have 929 units of inventory or 4.5 days of material in front of its station. This is a process which is manual and carried out with the help of support tools such as programming kits and smaller tools including wire strippers and crimpers.

This cell is operated by a single operator who performs all the tasks. The total work content and the cycle time varies between 1.17 and 5.87 mins. Changeover in this process takes about 12 minutes and is attributed to switching between programming kits. With an uptime of 90%, the process sees delays when the programming kit hangs and is unable to program the sensors and drivers. The yield in this area is 0.93 and non-conformances include incorrect programming, cross-cabling, loose connections and improper insulation. Completed units are then delivered to the wiring assembly work cell.

4.4.6 Reflector Sub-assembly

Alongside the preparation process, the reflector sub-assembly cell simultaneously initiates its process, though not a part of the critical path. This process is performed in a sub-assembly cell that is separate from the "Machine Shop" and "Electrical Assembly" departments. This process performs the activity of constructing the "light engine" which involves affixing LED boards to a reflector. This cell processes orders according to the push-based schedule provided by the Production Control Department. On average the process is seen to have 340 units of inventory or 1.6 days of material in front of its station. This is a process which is manual and carried out with the help of simple support tools such as soldering guns and drills.

This cell is operated by a single operator who performs all the tasks. The total work content and the cycle time varies between 2.88 and 3.57 mins. Changeover in this process takes about 9 mins and is attributed to LED board classification. The uptime of 100% is due to the largely manual process with minimum tool requirements. The yield in this area is 0.89 and non-conformances include board mixing, loose cabling and handling issues (bending). Completed units are then delivered to the wiring work cell.

4.4.7 Harness

Alongside the preparation process, the harness preparation cell simultaneously initiates its process, though not a part of the critical path. This process is performed in a sub-assembly cell that is separate from the "Machine Shop" and "Electrical Assembly" departments. This process performs the activity of constructing the harness, which is a series of cables cut to a desired length, stripped at their edges and joined with the help of a connector. This cell processes orders according to the push-based schedule provided by the Production Control Department. On average the process is seen to have 900 units of inventory or 4.37 days of material in front of its station. This is a process that is carried out with the help of a wire cutting and stripping machine in union with manual operators joining the wires with connectors.

This cell is operated by a single operator who performs all the tasks. The total work content and the cycle time is 1.05 mins. Changeover in this process takes about 5 mins and is attributed to reloading the wiring cutting and stripping machine. An uptime of 90% is due to the largely manual process with minimum tool requirements. The yield in this area is 0.92 and non-conformances include loose connections, incorrect length and cross-wiring. Completed units are then delivered to the wiring work cell.

4.4.8 Wiring

This process is observably a pseudo pacemaker of the overall production flow, as the Production Control department schedules all other process cells, in a backward scheduling format, based on the performance of this process cell. It receives parts from the preparation cell as part of the critical path but also simultaneously is fed sub-parts from several process cells including the lens, reflector and harness process cells. In this process, the complete electrical assembly, residual mechanical assembly (lens fixation) and testing of the fixture occurs. This cell also processes orders according to the push-based schedule provided by the Production Control Department. The maximum material in front of this cell is 760 units of inventory or 3.69 days of material. This is a process which is fairly manual and carried out with the help of several support tools such as drill guns, crimpers, pliers, quality testers etc.

This cell is operated by 6 operators, each operator performs all the work elements on a single fixture from the start to the end of the process. The total work content varies between 31.72 mins and 49.58 mins. The resulting cycle time therefore varies between 5.28 and 8.26 mins. Changeover in this process takes about 4.5 mins and is attributed primarily to wiring drawing interpretation. With an uptime of 96%, the process only sees delays when the smaller tools break down. The yield in this area is fairly low at 0.82. Wrong drawing interpretation, loose connections, cross-wiring and mishandling create non-conformances. Completed units are then delivered to the packaging work cell.

4.4.9 Mounting kit

Alongside the wiring process, the mounting kit preparation cell simultaneously initiates its process, though not a part of the critical path. This process is performed in a sub-assembly cell that is separate from the “Machine Shop” and “Electrical Assembly” departments. This process performs the activity of combining and packaging all the mounting elements which are essential to suspend the fixture from the ceiling. This cell processes orders according to the push-based schedule provided by the Production Control Department. On average the process is seen to have 700 units of inventory or 3.40 days of material in front of its station.

This cell is operated by a single operator who performs all the tasks. The total work content and the cycle time varies between 1.2 and 4.2 mins. Changeover in this process takes about 15 mins and is attributed to mounting bin changes at the assembly table. With an uptime of 100% the process is fully manual. The yield in this area is 0.99 owing to the low mounting kit variations and the relatively mistake proof process. Only incorrect quantity of components or missing components are presented as non-conformances and rarely occur. Completed units are then delivered to the packaging work cell.

4.4.10 Packaging

The final process in the critical path is the packaging process. In this process, the complete fixtures are shrink-wrapped to vacuum seal the fixture. The sealed fixtures are placed on a pallet and are ready to ship with their mounting kits. This cell also processes orders according to the push-based schedule provided by the Production Control Department. The average material in front of this cell is 43 units of inventory or 0.21 days of material. This process is conducted using a heat adjustable shrink wrap machine.

This cell is operated by a single operator and processes orders for several product families. The total work content which is synonymous with the cycle time is 0.55 mins. Changeover in this process takes about 10 mins and is attributed to machine reheating time. With an uptime of 80%, extensive machine shutdowns due to constant issues with the heating element affects machine output negatively. The machine is presently only serviced when it breaks down. The yield in this area is high at 1 as it is a fairly simple and mistake proof process. Completed units are then delivered to the Shipping cell.

4.4.11 Shipping

It is important to note that the shipping cell of ABC does not hold any finished goods inventory. That is, if an order is produced as an output of the packaging process, it must be shipped on the same production day. To meet this objective, the shipping team has 4 trucks that leave the floor on a given production day. A truck leaves the dock every half shift and is therefrom delivered to an external logistics partner that later delivers fixtures to each customer based on the selected method of freight (ship, train, truck, air) and at the specified urgency (regular, express). Presently, the shipping department holds a maximum of 330 units or 1.6 days worth of inventory at the head of its process cell.

4.4.12 Lead Time and Value Added Time

The current value stream map of ABC demonstrates a vast gap between the fixture processing time (value added time) and the time the fixture spends in the production system (total production lead time). With total production lead times varying between 22.72 and 22.73 days; the value added time of the fixtures varies between 12.08 and 24.15 mins. Hence the value-added times are only 0.06 % and 0.12% of the overall production lead time.

4.5 Target Condition

ABC's business is in a growth phase but in order to sustain its growth and accelerate it further, providing a quality product at cost competitive prices in short lead times is critical. There are several goals the business has for its production facility including reduced resource costs, reduced cost of poor quality, increased productivity, increased machine uptime, reduced flow inconsistencies etc. But in recent times the most urgent concern has been focused around competitor lead time offerings of 4 to 5 weeks, which is 1 to 2 weeks earlier than the minimum 6-week lead time offered by ABC. Hence the base target is to reduce lead time by a minimum of 33% in order to sustain and build market share.

4.6 Key Challenges and Root Cause Analysis

There are several critical points of concern with the present ABC value stream such as:

- The production lead time of the fixture, that is the time it spends in the production system, is far greater than the time spent in the physical construction of the fixture
- Several processes contain work elements that do not add value to the fixture construction
- Unbalanced cycle times between process cells disrupt flow
- The yields in several process cells are below expectation hence resulting in significant rework and high scrap rates
- The uptimes, specifically of areas with significant industrial machines are relatively low and servicing is performed only when a machine is down (corrective maintenance)
- A cultural comfort towards batch production in seen on the floor

In the next section, we will analyse these points of concern in the current value stream and identify the root causes for them in order to guide improvement efforts.

4.6.1 Lead Time

A quick review of the current state value stream map reveals that a majority of the total production lead time arises from the excess inventory that is stored at the head and tail of each processing station. The major segments of accumulated inventory are 11.9 days between the warehouse and the start of the machine shop, 4.5 days between the machine shop and the electrical assembly department, 3.69 days at the intersection of several sub assemblies and wiring, and finally 1.6 days between the electrical assembly and shipping department. Though the inventory build-up is significant between departments owing to a change in leadership and department culture, there is also tangible inventory buildup between process cells within each production department.

This is in part due to the scheduling techniques used in ABC today. Each department receives a twice daily schedule which it follows without paying attention to the requirement of the downstream process cell. Another interesting finding is that the schedule provides orders to each process cell to fill the days capacity of the cell. In other words, the schedule is being filled to meet capacity rather than the capacity being adjusted to match a demand driven schedule. Therefore processes with faster processing times produce more inventory than the succeeding process can absorb. In general, push scheduling to each process station is responsible for the inventory accumulation between processes.

4.6.2 Work content

Although processing times are quite short between 12.08 and 24.15 minutes, during the time collection at each work cell, it was noticed that several work elements performed by the operators were non-value-adding. Examples of these work elements include loading, unloading, cleaning, ERP updating, part bundling, staging, secondary precision verification using metrology, labeling for next process step, part retrieval, visual inspection for handling defects and unwrapping. Specifically, at stations that are machining intensive, the machine would stay idle as the operator performed all of these tasks. There is a lot of scope to remove these work elements from the primary workload of the operator.

4.6.3 Cycle Times

The current state shows that there are several inconsistencies in cycle time between different process cells. This is because current day process cells are designed as “Job Shops” and split work based on functional expertise of available operators rather than balanced work distribution with a takt adherence focus. For example, the extrusion cutting cell is designed to contain operators who specialize in cutting and using the double saw cutting machines. The reflector cell is designed to contain individuals who have knowledge of LED boards and build “light engines” using correct cartridge configurations. What this results in, are process cells that vary greatly in their cycle time. There is little evidence of operator numbers being determined as a result of required planned cycle times that are derived from takt time and total work content. This in turn disrupts flow and is visually reflected in further inventory build-up between processes. Figure 3 shows how cycle times (with one operator) vary between different process cells.

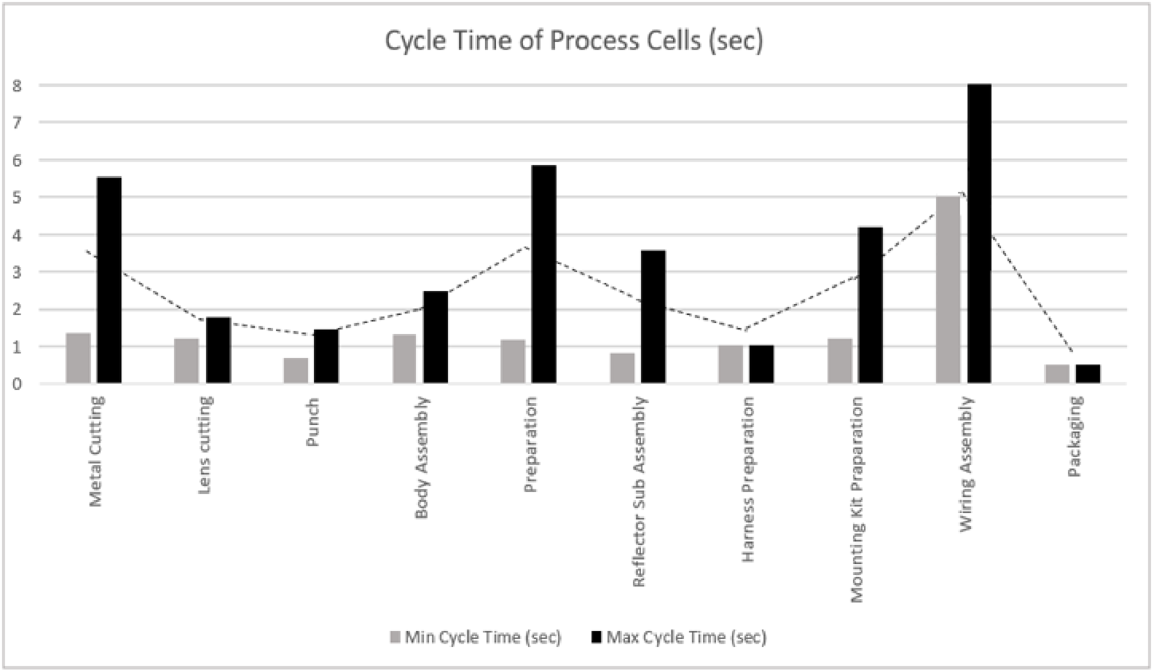


Figure 3: CSM Cycle time variation between process cells in the selected product family

4.6.4 Yield

There are several process cells with low yield values. Non-conformances include missing machining, incorrect machining, cross cabling, loose connections, bends, scratches, dents, incorrect programming etc. The low yield can be thought of as the result of three broad deficiencies: lack of training, improper handling and insufficient quality at the source.

During the time collection process, it was observed that between each consecutive order, specifically in the wiring cell, the operators of the cell would wait for floor leadership (lead hands, managers) to interpret the blueprint and explain the build process to them. The operators then, based on memory of what was recently taught, build the remainder of fixtures within that SKU. This reliance on leadership and errors resulting from memory-based assembly, is in large part due to the lack of operator training to interpret floor blueprints. Furthermore, blueprints are often missing critical information which leadership has memorized based on experience. There is no documentation of detailed methods on how to construct and this is the significant cause of rework and aftersales issues. It is also noteworthy that leadership is currently investing more time explaining build methodology and less time on maintaining flow and KPIs.

Next, we see that the large amount of inventory build-up leads to a pressure on space availability. How the floor solves this problem is to overload buggies with fixtures and parts stacked on top of each other. What this does for painted extrusions, is that it introduces bends, scratches and dents. Lens and optics face a similar handling issue due to excess stacking and therefore the fragile unprotected face of the optic is marginalized.

Finally, though several process cells have implemented quality at the source to some degree, it is often seen that the frequency of inspections, inspection criteria for all critical to quality operations and KPIs relating to the cost of poor quality are incomplete. This often results in parts being sent back for rework (reprocessing the same part or scrapping and using a new part) or wrong parts being assembled and sent out, only to return as aftersales issues.

4.6.5 Uptime

A recurring theme in most process stations is the machine breakdown. Specifically, areas with larger machines such as punches, saws, shrink wrapping machines, wire cutting, and stripping machines were vastly impacted by downtime due to constant breakdowns. An important observation is that in each production cell, it is only the breakdown of the machine that triggered machine servicing. Current maintenance staff work only on a corrective maintenance regime which is both putting a burden on valuable production time and extending servicing times. Moreover, several machines, at the point of service, necessitate replacement parts which if not in stock can lead to machine downtimes of several days. This pressurizes other machines in the cell and reduce the productivity of the floor by sending a chain reaction to all processes downstream of the breakdown.

4.6.6 Culture

The ABC Production floor has been in the industry for 2 decades. It is only in the past five years that the floor started to transition from a pure batch method of production to a production flow that acknowledged lean techniques. Several past attempts at process focused lean implementation with varying degrees of effectiveness have left the floor with mixed feelings about lean philosophies. Several operators lack a wholistic understanding of lean and have been subjected to lean implementation without being involved in the journey of continuous improvement. The lack of training given to the workforce and the lack of participation in the journey to lean, has led to resistance. The habit of batch processing has also formed a zone of comfort among several floor staff and lean implementation would require significant change which operators aren’t always open to. Moreover, the departmentalization of the production groups has led to a large focus on process optimization and less attention has been given to overall flow optimization.

4.7 Areas of Improvement

Now that we have carefully selected a product family, learned of the key concerns within its current production system and investigated the root causes of these concerns, strategic goals for improvement need to be set. A comprehensive future state analysing improved flow must be developed prior to any lean tool implementation in order to develop a global solution, as opposed to solely applying point kaizens which would have reduced effectiveness. Inventory and fixture processing times must be reduced in conjunction with process cell redesign to better balance workload in order to achieve improved lead times and yield. A demand-based schedule must be developed and deployed to a single pacemaker process. A robust maintenance plan featuring preventive maintenance activities must be developed in order to improve uptime. A wholistic quality plan must be developed at each new process cell to promote quality at the source. Finally, operators must be involved in the proposed solution at its development stage and significant time must be spent on building better methods and educating the floor about lean.

5 Proposed system

Now that we have carefully identified the product family, understood ABC's current value stream, the key wastes and the root causes of the wastes; the following section will delve into the process of addressing and thereby improving the current system with a goal to arrive at a future state that will address the organizational objectives of ABC. Here, it is important to note that floor staff, floor management and senior leadership shared their input in the development process. The guiding strategies in developing the future state are to smoothen flow and eliminate waste. Using these strategies we aim to reduce changeover time, eliminate waste and improve quality and thereby, reduce lead time, reduce resource costs, reduce the cost of poor quality, increase productivity and increase machine uptime in a mix model environment.

In this section we will explore the takt time of each process cell and ensure that each cell is producing within takt. First, we will perform a paper kaizen in order to reduce in-process waste and identify candidate processes which can be included in the continuous flow cell. Once the candidates are selected, a pacemaker will be determined. We will then explore how the pacemaker will be scheduled and designed. From this, we will turn our attention to changeover time reduction and therefrom determine mix leveling (i.e. determining the Every Part Every interval (EPEi) for each process cell). The next task will be to determine the Kanban size to institute volume leveling. Dynamic pitch will be introduced as a means to level the volume and manage adherence to schedule. Once this is complete, we will discuss yield and uptime for each process cell before determining the size and placement of various FIFOs and supermarkets between process cells. This will be followed by a presentation of the final future state.

5.1 Takt Time

The ABC production process for the selected product family contains 10 process cells. Some of these process cells can be purely dedicated to the selected product family. Hence in the takt calculation for these cells, the demand for the products within the product family is considered, (206 fixtures per day). However certain process cell such as the metal cutting cell processes orders for product belonging to groups outside our selected product family. For these cases the takt will have to consider the demand for products external to the selected product family as well. Once we understand the beat at which the customer requires the product to be produced in any given process cell, we can develop the planned cycle time, which is usually 95-98% of the original takt time. For a mix-model environment however we will have to give a margin of 80%, leaving the remaining 20% for:

- Operator inefficiency related to high mix variation (which is determined by analysing the average hourly productivity of ABC's current production floor) and planned machine downtimes – 10%
- Allowances related to changeovers – 10%

Ideally this percentage should be lower, but given the mixed model nature of the floor, the organization would like close to 20% buffer in its first continuous flow iteration. Having determined the margin for planned cycle time, we can now turn our attention to Table 4, which is a list of all process cells along with their corresponding demand, takt time and planned cycle times. As Shown in this table, demand for the selected product family is 206, while the demand in certain process cells is higher as they also process orders for other product families.

Process Cell	Demand per Day	Available time (min)	Takt Time (min)	Takt Time (sec)	Planned Cycle Time (min) @ 80%	Planned Cycle Time (sec) @ 80%
Metal Cutting	436	900	2.06	124	1.65	99
Lens Cutting	436	900	2.06	124	1.65	99
Punch	206	900	4.37	262	3.50	210
Body Assembly	206	900	4.37	262	3.50	210
Preparation	206	900	4.37	262	3.50	210
Reflector Sub-Assembly	206	900	4.37	262	3.50	210
Harness Preparation	1174	900	0.77	46	0.61	37
Mounting Kit Preparation	1174	900	0.77	46	0.61	37
Wiring Assembly	206	900	4.37	262	3.50	210
Packaging	1174	900	0.77	46	0.61	37

Table 4: Takt time and planned cycle time (min and sec) of process cells

5.1.1 Takt Adherence

Once the planned cycle times have been determined for each process cell, the next natural step is to compare the current work content of each process cell to the planned cycle time. Figure 4 displays the work content (the minimum and maximum value seen) of each process cell against its required planned cycle time.

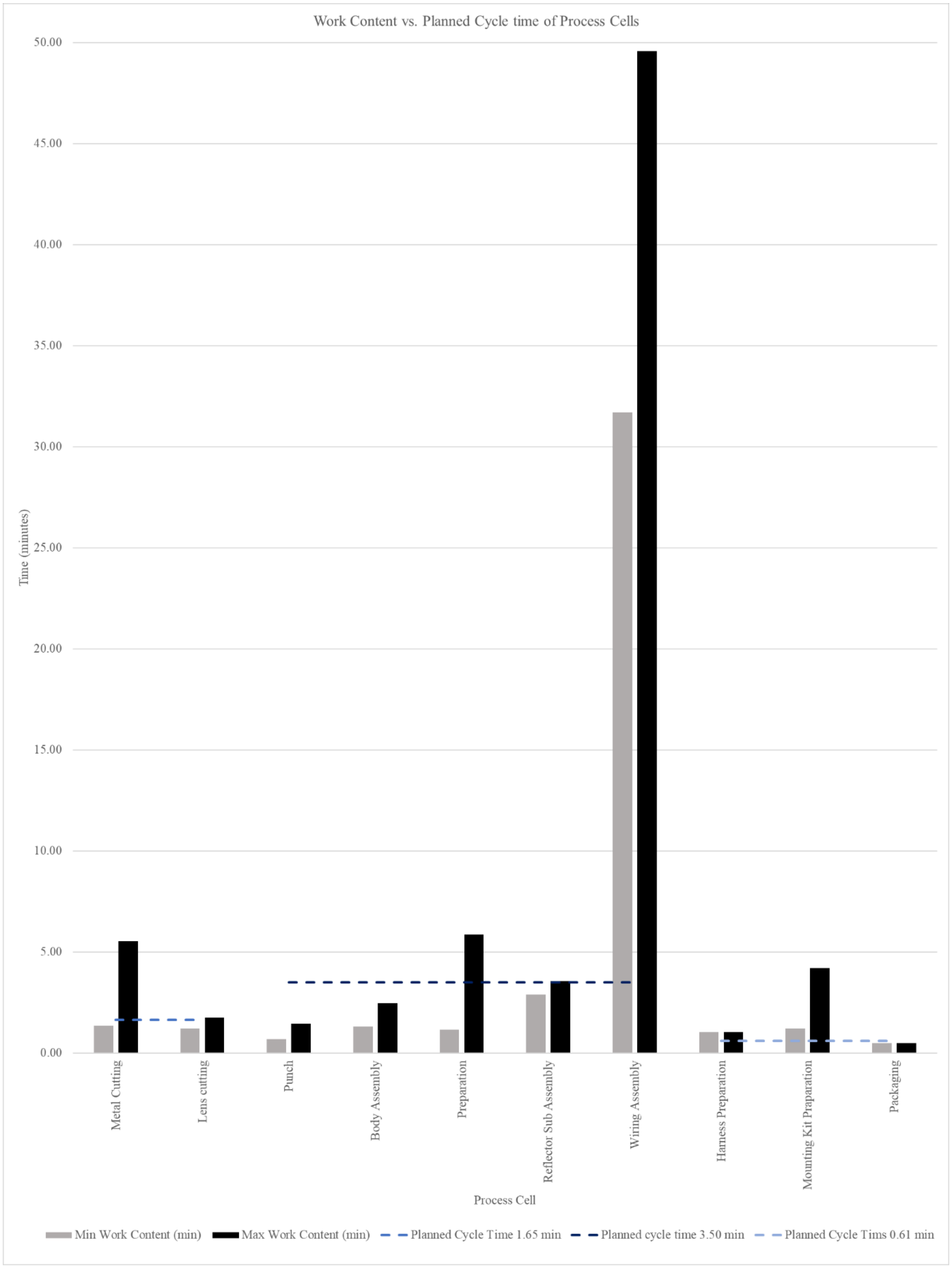


Figure 4: Work Content vs. Planned Cycle time (mins) of Process Cells

By comparing the planned cycle time with the work content, it can be inferred that several processes are not meeting the planned cycle time (takt time with 20% allowance). For example, the metal and lens cutting process has planned cycle time requirement of 1.65 minutes but the maximum work content of these cells (5.53 minutes and 1.65 minutes respectively) exceeds this threshold. The same can be inferred for the preparation, reflector and wiring process cells, whose 3.50-minute threshold has been crossed by their respective maximum work contents. Certain other processes such as the harness preparation and mounting kit preparation cell have work contents beyond their threshold of 0.61 minutes in both their minimum and maximum work contents. Other processes however, such as the punch, body assembly and packaging, are below their threshold, leaving room for "idle time" or a potential for large inventory build-up in succeeding stations. This analysis sparks the need to perform a paper kaizen first, in order to eliminate non-value-added activities from the process cells and then explore combining processes to avoid flow inconsistencies.

5.2 Paper Kaizen

In this section, the work elements of each process cell are analysed with an objective of eliminating in-process waste. Table 5 shows the paper kaizen process performed on the metal cutting process cell. The guiding principle of the paper kaizen process is to observe the process work elements and eliminate/reduce obvious waste (loading, unloading, waiting etc.) on paper prior to instituting the process.

Paper Kaizen: Metal Cutting Process Cell
Data Input: machining interface
~~Retrieve raw extrusion from the buggy~~
~~Verify extrusion for visual defects~~
Place the extrusion in the machine
Set the jigging in place
Cut the extrusion
~~Clean the extrusion~~
~~Verify the precision of the extrusion via metrology~~
~~Affix a label onto the extrusion~~
~~Place the extrusion on an empty buggy~~
~~Mark the operation completion in ERP~~
Data Input: machining interface
~~Retrieve 2 flanges from buggy~~
~~Verify flanges for visual defects~~
~~Wrap the flanges together~~
Place the flanges in the machine
Set the jigging in place
Cut the flanges
~~Clean the flanges~~
~~Verify the precision of the flanges via metrology~~
~~Affix a label onto the flanges~~
~~Place the flanges on an empty buggy~~
~~Mark the operation completion in ERP~~
Data Input: machining interface
~~Retrieve raw extrusion from the buggy~~
~~Verify extrusion for visual defects~~
Place the extrusion in the machine
Set the jigging in place
Cut the extrusion
~~Clean the extrusion~~
~~Verify the precision of the extrusion via metrology~~
~~Affix a label onto the extrusion~~
~~Place the extrusion on an empty buggy~~
~~Mark the operation completion in ERP~~

Table 5: Paper Kaizen output for work elements of the metal cutting process

In performing the paper kaizen for this process, the data input into the machining interface is retained. Traditionally it would be part of the changeover but as discussed previously, this task is a part of the work elements and must be performed by the operator. The ‘retrieve piece’ work element has been eliminated as it includes the operator unloading the piece from a buggy. The verification of visual defects is also removed as it is the responsibility of the previous process to ensure a quality part is passed to the next station. With improved material handling in the delivery to the saw station and better inventory control (avoiding excess stacking on buggies) this defect need not be inspected in the future. Following the cut process, activities such as cleaning the workpiece, verifying precision with metrology and labeling the work piece has been eliminated. Cleaning can be built into the double saw if a vacuum is installed in the system to extract chips. The saw machine has a higher degree of precision than the measuring tape used to verify metrology. Hence, with in-built precision in the machine, the metrology verification is ultimately redundant. Wrapping two work pieces together allows two pieces to be processed by a single cut operation. This wrapping process is wasteful and can be eliminated by designing a jig that holds multiple pieces to enable the same with single cuts. Labels are applied on the workpiece to help identify workpieces with same order numbers as several orders are stacked on the same buggy and placed in a sea of inventory between stations. With more uniform flow and smaller batch sizes, this labeling may not be required. Unloading and ERP entry can be eliminated by an auto eject function and a scanning device.

Though a few floor staff stated that some of these steps could not be eliminated as suggested above, all the staff agreed that these steps wasted talent and led the machine to remain idle when these work elements were being performed. These work elements can thus be looked at as necessary non-value-added activities and can be performed by a helper or handler, should these work elements later be defined as necessary.

Similar paper kaizens are performed for all of the process cells and the corresponding reduction in total work content as a result of this paper kaizen can be found in Table 6.

Process Cells	TWC Before Paper Kaizen (sec)		TWC After Paper Kaizen (sec)		Improvements (%)	
	Min	Max	Min	Max	Min	Max
Metal Cutting	82	332	36	142	56%	57%
Lens Cutting	72	106	28	45	61%	58%
Harness	63	63	37	37	41%	41%
Punch	42	88	26	26	38%	70%
Body Assembly	78	148	46	107	41%	28%
Preparation	70	352	57	314	19%	11%
Reflector	173	214	108	125	38%	42%
Wiring	1903	2975	1036	2108	46%	29%
Mounting Kit	72	252	56	220	22%	13%
Packaging	33	33	20	20	39%	39%

Table 6: Paper Kaizen led Total Work Content improvements

5.3 New Process Cells and Resource Determination

Earlier in our analysis of the current value stream, we identified that inventory (WIP) build up was due to the presence of isolated process cells that followed a push approach. To eliminate this, we must strive to create continuous flow cells by combining as many disjointed process cells as possible. We will then select a pacemaker process.

Shared processes are not included in the continuous flow cell. Hence, processes such as metal cutting, lens cutting, harness, mounting kit and packaging will not be combined as they are shared processes. For all cells which can be dedicated and included in the flow, we will be combining them into a continuous flow cell so long as their changeover differences can be controlled. Techniques on how to schedule in such environments are challenging and will be discussed in section 5.4.1. Our guideline in mix model should be to combine processes into continuous flow cells as long as they can be dedicated and they share the same takt (work the same shifts to allow the same available time). For example, in our case, the punch, body assembly, preparation, reflector and wiring process cells can be combined into one continuous flow cell. Finally, one of the continuous flow cells is selected as the pacemaker and, in the case of custom products, the pacemaker is selected as far upstream as possible (which is where the customization starts).

One may conclude that high variations in work content within the continuous flow cell and other process cells may make resource determination complex. To determine the resources required at each process cell, we first use a weighted average of the total work content.

The total work content to perform the punch, body assembly, preparation, reflector and wiring assembly for each SKU passing through the cell is found. This is then multiplied by the relative demand % of the SKU within the product family. By this approach, the weighted average of the total work content for the continuous flow cell is determined to be 1312 seconds. With a takt time of 262 seconds, 5 operators could address the demand but will require 3.8 hours of overtime. Therefore, it is determined that 6 operators and 39 minutes of overtime will be required to meet the average daily demand requirements, giving a new takt time of 273 seconds. The details of how the weighted average of the total work content of the Continuous Flow Cell (CFC) is calculated and how it is used to determine the required resources is shown in Table 7.

Continuous Flow Cell (Punch + Body Assembly + Preparation + Reflector + Wiring Assembly)			
Product Type	**Product % of Demand within Group**	**Total Work Content**	**Weighted Average Total Work Content**
Regular	67.406%	1264	852.01
Regular Flangeless	8.277%	1243	102.88
Emergency Battery	2.760%	1957	54.02
Chicago Plenum	2.405%	1444	34.73
Emergency circuit	5.246%	1321	69.30
End Feed	0.204%	1282	2.61
Flex Whip	4.131%	1288	53.21
Fuse	1.565%	1329	20.80
Generator Transfer Device	0.028%	1848	0.52
Controls (sensors)	0.635%	1644	10.44
Night Light	0.075%	1291	0.96
Length Relief Module	4.292%	1371	58.84
Downlight Insert	0.202%	1714	3.46
Chicago Plenum, Length Relief Module	0.282%	1551	4.37
Emergency circuit, Emergency Battery	0.067%	2014	1.35
Emergency circuit, Chicago Plenum	0.039%	1501	0.59
Emergency circuit, Controls (sensors)	0.043%	1557	0.67
Emergency circuit, Length Relief Module	0.596%	1428	8.51
Emergency circuit,Flex Whip	0.170%	1345	2.29
Emergency circuit,Fuse	0.073%	1386	1.01
End Feed,Flex Whip	0.002%	1306	0.02
Flex Whip, Emergency Battery	1.270%	1981	25.16
Flex Whip, Length Relief Module	0.047%	1395	0.65
Fuse, Emergency Battery	0.011%	2022	0.23
Controls (sensors), Emergency Battery	0.009%	2193	0.20
Downlight Insert, Chicago Plenum	0.013%	1894	0.25
Downlight Insert,Flex Whip	0.006%	1738	0.10
Length Relief Module , Emergency Battery	0.013%	2064	0.27
Downlight Insert,Flex Whip, Emergency Battery	0.002%	1608	0.03
Emergency circuit,End Feed,Flex Whip	0.073%	1363	0.99
Emergency circuit, Chicago Plenum, Length Relief Module	0.060%	2431	1.45
Weighted Average Total Work Content			**1312**
Customer Daily Demand			206
Overall Required time (sec)			270255
Available time (sec)			54000
Takt time (sec)			262
New Takt (T_{new})			273
Operators			6
Overtime (mins)			39

Table 7: Weighted Average Total Work Content + resource required for CFC

Similar weighted analyses are performed for other process cells not included in the continuous flow in order to determine the weighted average total work content and required resources. Table 8 shows the resources required to sustain demand in each process cell. It is important to note that some process cells, such as the metal cutting, lens cutting, mounting kit and packaging, are under utilized and this opens up the possibility of increasing plant capacity without adding resources or buying new machinery. It is recommended to combine operators and use a single operator in the metal cutting and lens cutting cell as an immediate solution (occasional overtime may be needed). Though combining operators at the mounting kit and packaging cell may also be explored, ABC prefers to keep these processes separate as there is a possibility to load more product families on these cells following design changes.

Process Cell	Takt time (sec)	Planned Cycle time @ 80% (sec)	Weighted Average Total Work Content (sec)	Resources Required	Employees Used	Overtime (mins)
Metal Cutting	124	99	76	0.61	0.7	
Lens Cutting	124	99	29	0.23	0.3	
Harness	46	37	37	1	1	
Cont. Flow Cell	262	210	1312	5.01	6	39
Mounting Kit	46	37	65	1.41	2	
Packaging	46	37	20	0.43	1	

Table 8: Weighted Average Total Work Content and Required resources at process cells

With this we have now determined the required labour to adhere to takt. In the following section, we will select and dive deeper into the internal mechanisms of the pacemaker.

5.4 The Pacemaker

With the continuous flow cell being the most upstream dedicated process cell, it becomes the best candidate to serve as the pacemaker for the value stream. With this understanding, in this section we will explore how to schedule the cell, design the cell and distribute work among operators within the cell.

5.4.1 Scheduling the Pacemaker

Traditional lean requires process cells to have a product work content variation of less than 30% (Duggan, 2013). Our continuous flow cell however has total work content variation of up to 95.6%. We know that the average customer demand per production day is 206 fixtures and should the work content have been within 30%, we would have products leave the continuous flow cell at a constant pace (every takt) until 206 pieces were produced. This is however not feasible in a high-mix, low-volume, high-customization environment. Regardless of how narrow we make our product segregations, variations in work content will always be significant. Therefore in such cases, we will be adopting a strategy which we will call ‘scheduling to capacity’.

From our weighted average work content analysis of total work content, we derived a total cell capacity of 270,255 seconds per day for the continuous flow cell. We now treat this capacity as a scheduling bin. As orders enter the system, they can occupy the available capacity in the scheduling bin until the bin capacity has been reached. Orders that enter the system first, are processed first, that is First-Come First-Served (FCFS). By this technique, regardless of the work content variations, orders can flow through the cell and meet demand requirements. A one-month schedule is prepared for the selected product family using the 'scheduling to capacity' technique. Figure 5 shows the results of this scheduling technique where the resulting average daily fixtures scheduled for this scheduling period (one month or 20 days) is 207 fixtures, with a minimum of 172 fixtures and a maximum of 214 fixtures scheduled. This form of flow modelling allows for greater work content variation accommodations, all whilst adhering to demand. At this point, it is important to note that this model does not address the constraint which requires total revenue earned by production days within a given production week to be a near equal value. Modelling to integrate this policy and discussions of its impact on lead time will be explored in Chapter 7.

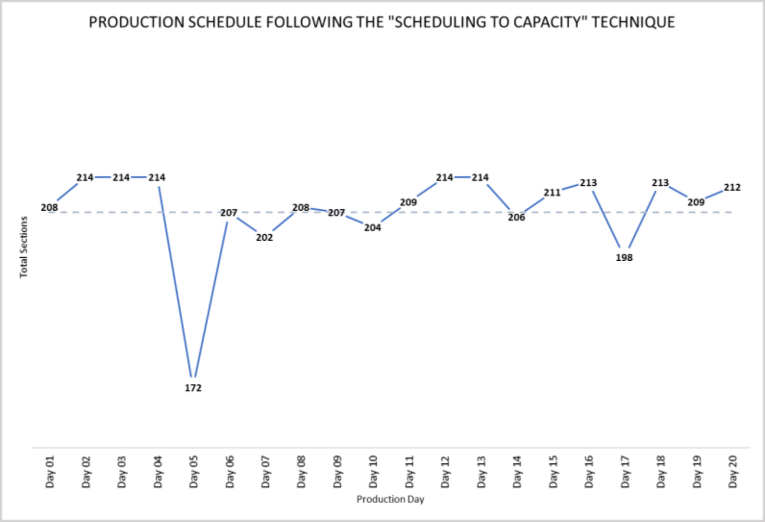


Figure 5: Total sections/fixtures processed per production day over a 20 day period

An important note at this stage is that the new continuous flow cell will serve as the pacemaker and the single point to which the production schedule is delivered. All other process cells that precede this process cell will receive a production sequence identical to the one received by the pacemaker process but offset by one day. Given that the metal cutting, lens cutting and harness process cells are shared, one day offsetting will allow sufficient time for these processes to deliver the required components to the pacemaker process in the following day, which is when they are scheduled to be processed. This is to ensure that the preceding work cells process parts based on the sequence they will be pulled by the continuous flow cell.

5.4.2 Cell Design and Work Distribution

When designing the pacemaker, it must be noted that fixtures passing through this cell may be any one of the 31 SKUs outlined earlier. An analysis of the work elements reveals that the total work content can be divided into three segments: a pre-customization standard segment, a customization segment and a post-customization standard segment. The build of the fixtures does not allow us the privilege of postponing the customization segment to the end of the continuous flow cell, as the customization segment occurs in-between two standard segments. Therefore some SKUs will only pass by the two standard segments, and other SKUs will pass by the pre-customization standard segment, followed by the customization segment and then the post-customization standard segment. Table 9 depicts the three segments of work element distribution for SKU 3, a single customization fixture featuring an emergency battery custom module.

Emergency Battery CFC Work Content	
Pre-Customization Standard Segment	
Work Element	**Time (sec)**
Data Input: machining interface	2
Place the extrusion in the machine	10
Punch holes in the extrusion	5
Clean the extrusion	6
Affix a label onto the extrusion	3
Attach the flanges onto the extrusion	21
Build the End Plates	16
Fix end plates on either side of the extrusion	21
Fix the power plate onto the extrusion	9
Program the driver	17
Attach the cabling to the Driver	35
Attach the driver to the extrusion	59
Ground the driver	42
Label the Driver	5
Pass the harness through the power outlet	82
Affix the led board onto the cartridge	60
Connect adjoining boards with quick connects	18
Connect the harness to the light engine	34
Total Work Content of Segment	**445**
Customization Segment	
Work Element	**Time (sec)**
Program the auxiliary parts	17
Attach the cabling on the auxiliary parts	27
Attach the auxiliary parts to the extrusion	170
Ground the auxiliary parts	42
Label the auxiliary part	7
Connect the driver and auxiliary part to the harness	430
Total Work Content of Segment	**693**
Post-Customization Standard Segment	
Work Element	**Time (sec)**
Use zip ties to ensure proper wire management	52
Insert and attach the light engine into the extrusion	280
Perform a light up, dimming and dielectric testing	320
Attach the lens to the fixture	13
Affix labels on the light engine and the finished fixture	25
Clean the fixture	73
Wrap the fixture with Styrofoam and cardboard	56
Total Work Content of Segment	**819**

Table 9: Segmented Work Content Distribution for SKU 3: Single Customization Fixture featuring an emergency battery custom module

Upon performing the weighted average of the total work content for all SKUs in each segment, it is found that the average work content in the Pre-Customization Standard Segment is 445 seconds, the average work content in the Post-Customization Standard Segment is 819 seconds and the average work content in the Customization Segment is 204 seconds. When compared to the planned cycle time for the CFC, it is found that the Pre-Customization Standard Segment will require 2 operators on average, the Post-Customization Standard Segment will require 3 operators on average and the Customization Segment will require 1 operator on average. This results in a total of 6 operators as previously estimated. It is important to note here that though the cell will not necessitate more than six operators, the number of operators assigned to each of the three segments is not fixed and will vary depending upon the mix of the day. It is essential to constantly balance the cell depending upon the mix of the day.

Figure 6 depicts the flow of material through the pacemaker process. Regular fixtures require no customization and flow from Workbench 01 to Workbench 03. Fixtures requiring customization will flow from Workbench 01 to Workbench 02 (the customization segment), and then to Workbench 03. All workbenches will be standardized with work tools (drills, rivet guns etc.) to conduct the work elements of any of the three segments. That is, on a day where only regular fixtures are in the mix for example, Workbench 02 can cover the excess workload of the Pre-Customization Standard Segment or the Post-Customization Standard Segment, as no customization will be needed. A redistribution of work elements among the 3 tables would be required in this case.

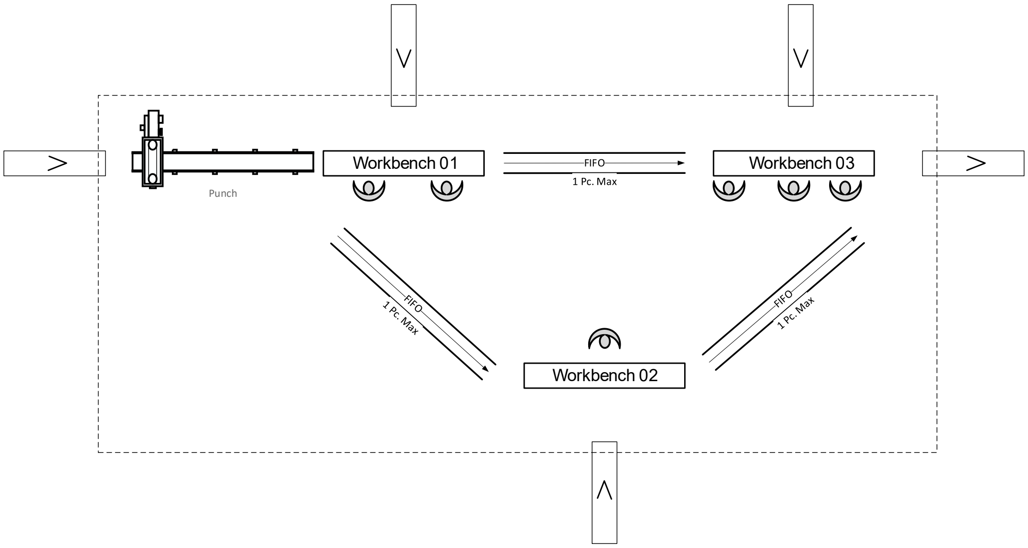


Figure 6: Cell Design for Continuous Flow Cell

The cell is constructed such that material is fed from behind the workbench. Assuming a good balance of work, we do not anticipate a build-up of more than one fixture in the FIFO lanes between stations. This cell will work for 2 shifts and will occupy an area of roughly 1500 sq. ft. on the ABC production floor.

5.5 Changeover Improvements

Thus far we have visibility of the new process cells, the required labour, the cycle time and the elements of the internal working mechanism of the continuous flow cell (our pacemaker). At this point, we will turn our attention to the changeover times at each cell and focus on how they can be improved.

For the metal cutting station, the 2.5 min changeover time will be preserved as this is machine calibration and blade change time which cannot be sped up owing to mechanical machinery constraints. The same applies for the lens cutting machine where the 3 min changeover will be sustained in the future state as well. In the harness preparation section, a test run was performed to see if using SMED (Single-Minute Exchange of Die) approaches to improve the time taken to feed new wires to the machine could be implemented. A jig to auto feed the new set of wires was designed but no tangible differences in changeover time was noticed. For now we will sustain the 5 mins of changeover but some iterations of the prototype jig could lead to potential reductions in changeover. Due to substantial changeover times, these processes should ideally produce in batches and be connected by a supermarket based pull system. However, the custom nature of each part renders it a unique identity from the onset of the first process in the value stream. Setting up a supermarket-based pull system with 'parts sitting in supermarkets *just in case* the next process needs it' (Duggan, 2013) would not be tangible in this high customization setting. The offset sequencing scheduling technique will deliver the sequence of orders to these upstream process cells (metal cutting, lens cutting and harness) 1 day ahead and the parts will be processed and gain identity from the beginning. Given the early definition of part identity, FIFO lanes will be used to connect the processes to each other.

For the pacemaker, we will be able to eliminate the changeover for the punch with the purchase of an adjustable dye which is compatible with all extrusions/ metal pieces within our product family. Similar results can be achieved in the body assembly segment by standardizing the end plate design of all products in the product family to necessitate the same tooling. In the preparation segment, changeover can be eliminated with the purchase of a new multi programmer kit. Reflector board classification used to take 9 mins but new labelling and colour coding techniques implemented at the supplier end can eliminate the need for board classification. The wiring drawing interpretation however will need to be sustained at 4.5 mins as operators have stressed the importance of needing time to comprehend the electrical diagrams, which are specifically designed based on the type of customization. In the future however, a methods program could shorten this time.

At the mounting kit station, significant changeover reductions can be implemented using Single Minute Exchange of Die (SMED) to prepare in advance, the next set of bins required by the operator. Changeover can now be estimated to be roughly 3 mins. Finally, regular maintenance and filament replacements on the shrink-wrapping machine can reduce the packaging changeover from 10 minutes to 5 minutes.

Thus, we have seen how SMED techniques, design for manufacturing (necessitating only one tooling type at the body assembly), new technology purchases (minor) and potential methods implementation can have a tangible impact on changeover times.

Despite reductions in changeover times, changeovers still remain significant at several process cells (metal cutting, lens cutting etc.). As a consequence, these changeovers will lead to batched production in the metal cutting, lens cutting, harness and mounting kit process cells. Furthermore, our targeted planned cycle time is 80% of Takt time with a 10% allotment for such changeovers. The 10% allotment for changeovers allows a sizable number of possible changeovers (discussed in detail in section 5.6.1), hence allowing for smaller batch sizes and EPEis.

5.6 Leveling the Production Mix

Thus far we have an awareness of the labour requirement, the takt time, the new work content (following the paper kaizen) and changeover for the future state process cells. We will now prescribe a production mix variation interval at each of the process cells to determine the Every Product Every interval (EPEi).

5.6.1 EPEi of Metal Cutting Process Cell

At the metal cutting station, the same saw is shared among 4 different product families. Each group is categorized by its own unique cutting angle. For our product family, this angle is 90^0. When a changeover occurs, a recalibration procedure ensues. This recalibration either resets for accuracy OR resets for accuracy + blade angle change. The system necessitates an accuracy reset every 250 parts. The total saw demand is 435 pieces. Hence, purely based on accuracy resets, 2 changeovers are required mandatorily. The saw machine cuts parts for 4 different product family, each with a unique angle as shown in Table 10. This means a minimum of 4 changeovers are now required. It is important to reemphasize that a blade angle change is paired with an accuracy reset by default. Hence a minimum of 4 changeovers a day will satisfy the blade angle and accuracy reset requirements. Observing the required total time with inefficiency + maintenance buffer (10%) of 606 minutes and comparing it to total available time of 630 minutes (0.7 operator), we see 24 minutes left for changeovers and other instabilities. This time is sufficient to cover the required 4 changeovers of 2.5 minutes (a total of 10 mins). In fact, a theoretical maximum of 9 changeovers are possible, enabling an EPEi of 0.44 days. However, since the metal cutting cell is producing at an offset of 1 day from the pacemaker, our pacemaker only processes parts produced by the metal cutting cell a day later. Therefore, one single batch of 206 extrusions can be produced, which is equivalent to an EPEi of 1 day.

Metal Cutting	
Average Daily demand for Group A @ 90 deg	206
Average Daily demand for Group B @ 80 deg	100
Average Daily demand for Group C @ 45 Deg	29
Average Daily demand for Group D @ 60 deg	100
Average Daily Demand for Metal Cutting	**435**
Required # of C/O	4
AWC/T (min)	1.27
Required total time (mins)	551
Required total time with inefficiency + maintenance buffer (mins)	606
Takt time (min)	2.07
Total Available Time (min)	630
Total time left for C/O & other instabilities (min)	24
Time per C/O (min)	2.5
Max # of Changeovers possible	9
Theoretical EPEi	0.44
Selected EPEi	1

Table 10: EPEi for the Metal Cutting Process Cell

5.6.2 EPEi of Lens Cutting Process Cell

Similar to the Metal cutting process cell, at the Lens cutting process cell, the same single saw is shared among 4 different product families. Each group is categorized by its own unique cutting angle. For our product family this angle is 90^0. When a changeover occurs, a recalibration procedure ensues. This recalibration either resets for accuracy OR resets for accuracy + blade angle change. The system necessitates an accuracy reset every 250 parts. The total saw demand is 435 pieces. Therefore, purely based on accuracy resets, 2 changeovers are required mandatorily. The single saw machine cuts parts for 4 different product families, each with a unique angle as shown in Table 11. This means a minimum of 4 changeovers are required. Hence a minimum of 4 changeovers a day will satisfy the blade angle and accuracy reset requirements. Observing the required total time with inefficiency + maintenance buffer (10%) of 231 minutes and comparing it to total available time of 270 minutes (0.3 operator), we see 39 minutes left for changeovers and other instabilities. This time is sufficient to cover the required 4 changeovers of 3 minutes (a total of 12 mins). In fact, a theoretical maximum of 13 changeovers are possible, enabling an EPEi of 0.3 days. However, since the lens cutting cell is producing at an offset of 1 day from the pacemaker (therefore we set a FIFO limit of 1 day), our pacemaker only processes parts produced by the lens cutting cell a day later. Therefore, one single batch of 206 lenses can be produced, which is equivalent to an EPEi of 1 day.

Lens Cutting	
Average Daily demand for Group A @ 90 deg	206
Average Daily demand for Group B @ 80 deg	100
Average Daily demand for Group C @ 45 Deg	29
Average Daily demand for Group D @ 60 deg	100
Average Saw Demand/ day	**435**
Required # of C/O	4
AWC/T (min)	0.48
Required total time (mins)	210
Required total time with inefficiency + maintenance buffer (mins)	231
Takt time (min)	2.07
Total Available Time (min)	270
Total time left for C/O & other instabilities (min)	39
Time per C/O (min)	3
Max # of Changeovers possible	13
Theoretical EPEi	0.3
Selected EPEi	1

Table 11: EPEi for the Lens Cutting Process Cell

5.6.3 EPEi of Harness Process Cell

The Harness station, processes harnesses for 16 different product families. When a changeover occurs, wires specific to the product family are loaded to the cutting and stripping machine. This necessitates a minimum requirement of 16 changeovers as depicted in Table 12. Observing the required total time with inefficiency + maintenance buffer (10%) of 796 minutes and comparing it to total available time of 900 minutes, we see 104 minutes left for changeovers and other instabilities. This time is sufficient to cover the required 16 changeovers of 5 minutes (a total of 80 mins). Since we set the changeover limit to 10% of available time (90 minutes), a theoretical maximum of 18 changeovers is possible, enabling an EPEi of 0.88 days. However, since the harness cell is producing at an offset of 1 day from the pacemaker (therefore a FIFO limit of 1 day), our pacemaker only processes parts produced by the harness cell a day later. Therefore, one single batch of 206 harnesses can be produced, which is equivalent to an EPEi of 1 day.

Harness	
Average Demand/ day	1173
Required # of C/O	16
AWC/T (min)	0.62
Required total time (mins)	723
Required total time with inefficiency + maintenance buffer (mins)	796
Takt (min)	0.77
Total Available Time (min)	900
Total time left for C/O and other instabilities (min)	104
Time available for C/O (min)	90
Time per C/O (min)	5
Max # of Changeovers possible	18
Theoretical EPEi	0.88
Selected EPEi	1

Table 12: EPEi for the Harness Process Cell

5.6.4 EPEi of Pacemaker Process Cell

The Continuous flow cell, as we are aware, is dedicated to our product family. Our group however processes 31 different SKUs. From analysing the demand patterns over the past 5 years, we realize that any given production day sees a mode of 5 SKU variations. This necessitates a minimum requirement of 5 changeovers as depicted in Table 13. Observing the required total time with inefficiency + maintenance buffer (10%) of 793 minutes and comparing it to total available time of 900 minutes, we see 107 minutes are left for changeovers and other instabilities. This time is sufficient to cover the required 5 changeovers of 4.5 minutes (a total of 22.5 mins). Since we set the changeover limit to 10% of available time (90 minutes), a theoretical maximum of 20 changeovers is possible, enabling an EPEi of 0.25 days. We will therefore assign an EPEi of 0.25 or 52 pieces as it also aligns with the 4-time-daily shipping frequency.

Continuous Flow Cell	
Average Demand/ day	206
Required # of C/O	5
AWC/T (min)	3.50
Required total time (mins)	721
Required total time with inefficiency + maintenance buffer (mins)	793
Takt (min)	4.37
Total Available Time (min)	900
Total time left for C/O and other instabilities (min)	107
Time available for C/O (min)	90
Time per C/O (min)	4.5
Max # of Changeovers possible	20
Theoretical EPEi	0.25
Selected EPEi	0.25

Table 13: EPEi for the Continuous Flow Process Cell

5.6.5 EPEi of Mounting Kit Process Cell

The mounting kit station, processes mounting kits for 16 different product families. When a changeover occurs, binning is changed. This necessitates a minimum requirement of 16 changeovers as depicted in Table 14. By observing the required total time with inefficiency + maintenance buffer (10%) of 710 minutes and comparing it to total available time of 900 minutes, we see 190 minutes left for changeovers and other instabilities. This time is sufficient to cover the required 16 changeovers of 3 minutes (a total of 48 mins). Since we set the changeover limit to 10% of available time (90 minutes), a theoretical maximum of 30 changeovers is possible, enabling an EPEi of 0.53 days. This does not coincide with the 4-time-daily ship frequency which requires an of EPEi 0.25 days and hence a larger supermarket with buffer and safety stock will need to be designed (seen in Section 5.11).

Mounting Kit	
Average Demand/ day	1173
Required # of C/O	16
AWC/T (min)	0.55
Required total time (mins)	645
Required total time with inefficiency + maintenance buffer (mins)	710
Takt (min)	0.77
Total Available Time (min)	900
Total time left for C/O and other instabilities (min)	190
Time available for C/O (min)	90
Time per C/O (min)	3
Maximum # of Changeovers possible	63
Theoretical EPEi	0.53
Selected EPEi	0.53

Table 14: EPEi for the Mounting Kit Process Cell

5.6.6 EPEi of Packaging Process Cell

The packaging station processes fixtures for 16 different product families. When a changeover occurs, the machine reheats to the optimal temperature required for shrink wrapping. The system does an auto reheat at 1-hour intervals. This necessitates a minimum requirement of 15 changeovers as depicted in Table 15. Observing the required total time with inefficiency + maintenance buffer (10%) of 430 minutes and comparing it to total available time of 900 minutes, we see 470 minutes left for changeovers and other instabilities. Therefore, the 75 minutes of required time for changeovers (5 minutes per changeover for a total of 15 changeovers) is comfortably satisfied. It is important to note that changing SKUs on the machine does not require changeovers, as changeovers are purely machine based. Therefore we can assign an EPEi of 0.25 or 52 pieces in order to better align the batch sizes with the 4-time-daily shipping frequency.

Packaging	
Average Demand/ day	1173
Required # of C/O	15
AWC/T (min)	0.33
Required total time (mins)	391
Required total time with inefficiency + maintenance buffer (mins)	430
Takt (min)	0.77
Total Available Time (min)	900
Total time left for C/O (min) and other instabilities	470
Time per C/O (mins)	5
Selected EPEi	0.25

Table 15: EPEi for the Packaging Process Cell

5.7 Kanban Size

Determining a natural increment of work in a mix model environment with high variations in ordering quantity can be complex. The best way to navigate this is to analyse ordering quantity over a period of 5 years and find a common ordering multiple. Regardless of the varying size of the orders (between 2 and 2000) it is seen that, in the case of ABC, order quantities are usually multiples of 2 (2, 4, 10, 20 and so on). For this purpose we will set the Kanban size to 2.

5.8 Dynamic Pitch

At this stage, most lean literature strives to set a pitch or a constant number of components to be produced in a set time interval. This pitch facilitates a takt image and allows ease of management through volume leveling. Many studies in HMLV try to limit work content variations to 30% and even continuously vary capacity (toggling resources) in order to sustain this constant pitch. This is however only seen to be successful to some degree in high mix low volume low customization environments. However, in a high mix low volume high customization environment such as ABC’s, assigning a constant pitch and continuously varying capacity is not practical. Here, we will introduce the concept of a ‘dynamic pitch’.

We are aware of the highly variable work content involved in processing fixtures that enter a process cell. Therefore, we first treat each production hour as a bin that can accumulate an hour’s worth of work. We keep scheduling fixtures to the hour until the hour’s capacity is met. This means every hour will have 60 minutes of work scheduled to it. This could however mean that each hour may contain a different number of fixtures to be completed. Production information in each hourly pitch, conveyed to the pacemaker process, will include the quantities of fixture SKUs to be completed and their cycle times. Therefore, for each fixture, operators will have awareness of the timeframe for the completion of each SKU (cycle time) and the hourly targeted number of fixtures to be completed in that particular pitch. Therefore, every 60 minutes will contain 60 minutes of work with varying number of fixtures to be produced, hence the pitch is referred to as ‘dynamic pitch’. This is indeed a more involved scheduling technique. However, this technique also offers more flexibility that is required in HMLV environments, whilst sustaining a constant amount of work completed.

5.9 Yield

The next important parameter of a cell is its yield. The goal is to achieve a yield of minimum 95% across the value stream. In this section we will discuss techniques to achieve this. At the two cutting stations, though incorrect cut lengths owing to human error are to be expected, the remote delivery of predefined cut lists fed directly into the machine as an alternative to operators manually entering cut lengths, could lead to an improved yield. Since the current machine has the capability to remotely load cut sheets, it must be harnessed. Alternatively, first article inspection could also be explored in sections without the necessary in-built technology, such as the harness cutting machine, but the focus will be to first build quality into the machine.

The damages due to handling will significantly be reduced as stacking will not be required in this new lean flow. Negotiations with suppliers to apply protective films on lenses and painted extrusions could also mitigate losses in yield owing to handling damages. Reduced WIP will also reduce the tendency to have work pieces go missing. At the punch, the scrap generated due to the part getting stuck in the punch can be eliminated with the new dye design and a good preventive maintenance schedule. Given the manual nature of the driver programming process in the preparation process cell, some yield losses are to be expected.

However, issues with cross cabling, loose connections and improper insulations seen in preparation and in wiring can be eliminated with a regime for quality at the source including pull tests, visual inspections and cross-cable test regimes for every 5-10 pieces. Board mixing in the reflector segment can be minimized with proper labeling and colour coding as discussed before. Finally, wrong wiring diagram interpretation could be minimized with the help of a more detailed methods and a more Poka Yoke assembly process (different wire gauges for different driver inlets for example).

With these changes in mind, a series of short quality implementation projects to put these proposals in action, could significantly improve yield and help achieve the minimum 95% yield goal for the value stream.

5.10 Uptime

There are several machines and tools spread across the value stream with uptimes ranging from 80% to 96% in cells necessitating machinery. These low numbers have often led to management discouraging any form of automation, for fear of further losses in productivity. It is important to note that uptime losses occur when the machine is down for a longer duration than its allocated downtime. This loss in productivity is attributed largely due to the fact that machines are only being serviced with a corrective maintenance regime. Current maintenance resources are overwhelmed with constant breakdowns and this builds waves of pressure across the value stream and production delays ensue. The solution is to implement a robust preventive maintenance regime. In Chapter 6, we will use linear programming to build a cost optimized preventive maintenance regime, in an attempt to reach an uptime goal of 95-97% in all areas operating with some form of tooling or machinery.

5.11 Pull Systems

Now that all the key parameters and pace for the new process cells and the pacemaker process have been determined, the natural next step is to determine inventory leveling techniques between the continuous flow cell and process cells that are part of the value stream, but not a part of the continuous flow cell. These include the metal cutting, lens cutting, harness, mounting and packaging process cells. We will now prescribe inventory leveling techniques between consecutive process cells moving from downstream to upstream. We will first address inventory leveling techniques along the critical path and then address other parallel processes. Table 16 provides a comprehensive summary of the inventory leveling techniques between process cells.

FIFO Lanes	Supermarkets Based Pull Systems
Packaging & Shipping	Mounting Kit Cell & Packaging Cell
Pacemaker & Packaging	ABC Warehouse & Mounting Kit Cell
Harness Cell & Pacemaker	ABC Warehouse & Metal Cutting Cell
Lens Cutting Cell & Pacemaker	ABC Warehouse & Lens Cutting Cell
Metal Cutting Cell & Pacemaker	ABC Warehouse & Harness Cell
	ABC Warehouse & Pacemaker

Table 16: Inventory Control along the value stream

Our first region in need of inventory leveling is between the packaging and the shipping process cells. Our constraints clearly mention that the company does not want a finished goods supermarket. For this purpose, we will setup a FIFO between the two process cells and given that the fixtures are shipped 4 times daily, we will set a FIFO limit of 52 fixtures, which is roughly equivalent to 1/4th of the number of fixtures demanded by the customer per day. Moving upstream along the critical path, we arrive at the region between the pacemaker and the packaging process cell.

Given that the ship frequency is 0.25 days, we will setup a FIFO lane with a limit of 52 fixtures downstream from the pacemaker process cell. Moving further upstream along the critical path, we now turn our attention to inventory management at the intersection of the metal cutting cell and the pacemaker. Since the custom nature of each part renders it a unique identity from the onset of the first process in the value stream where the offset sequence is sent, the metal cutting cell and the pacemaker are connected via a FIFO. The offset sequencing scheduling technique will deliver the sequence of orders to the metal cutting cell beforehand (1 day in advance) and the parts will be cut to their unique length and gain identity. A limit of 206 pieces is set for this FIFO in accordance with the 1 day offset criteria. Moving further upstream along the critical path we arrive at the final intersection in need of inventory management, which is between the ABC Warehouse and the metal cutting cell. The metal cutting cell will have a supermarket of 0.25 days of raw inventory at the start of the process cell, owing to the 4-time-daily scheduled delivery from the warehouse.

Now that inventory management has been determined for the critical path, let us observe other intersections. Following the logic of inventory management between the metal cutting and the pacemaker, the lens cutting and harness cells also deliver to the pacemaker via FIFO lanes. For the FIFO lane between the lens cutting cell and the pacemaker cell the maximum capacity will be 206 pieces owing to the 1 day offset. For the FIFO lane between the harness cell and the pacemaker, the maximum capacity will be 206 pieces owing to the harness EPEi of 1 day and the one day offset. Supermarkets with 0.25 days of raw material can be found at the beginning of the lens cutting, CFC and harness cells as they too, like the metal cutting cell, receive material from the ABC warehouse with a 4-time-daily frequency.

Next, we will look at the intersection between the mounting kit and the packaging cell. At this junction, we will be introducing a supermarket-based pull system. Mounting kits are standard parts for each product family and regardless of the type of fixture in the product family or the degree of customization, the mounting kit (suspension mechanism of the fixture from the ceiling) is exactly the same. The packaging station will issue withdrawal Kanbans each time a mounting kit is used and this will trigger a series of production Kanbans. We are aware that the EPEi of the mounting cell is 0.53 days. Therefore, we will design a supermarket with a cycle stock of 110 kits (0.53 x 206 kits), a buffer stock of 5 kits considering a 4% demand deviation (4% x 0.53 x 206 kits) and a safety stock of 13 kits owing to 10% in inefficiencies ($(\frac{0.1}{1-0.1})$ x (110 +5) kits). The total supermarket size is therefore 128 kits or 0.62 days between mounting and packaging. Supermarkets with 0.25 days of raw material can be found at the beginning of the mounting kit cell as it receives material from the ABC warehouse with a 4-time-daily shipping frequency.

5.12 The Future State Value Stream

With all the components of the future value stream in place, as shown in Figure 7, we arrive at a future state value stream map for the selected product family of ABC. The production schedule is developed using the ‘scheduling to capacity’ technique and communicated to the continuous flow cell, which serves as our pacemaker. Following the offset sequencing technique, the order sequence information is delivered to the metal cutting, lens cutting and harness cells 1 day in advance. Raw material arrives from the ABC Warehouse every 0.25 days and is delivered to the Harness, Metal Cutting, Lens Cutting, CFC and Mounting kit cells. Extrusions are cut at the metal cutting station and flow to the pacemaker via a FIFO lane. In the Continuous flow Cell (pacemaker) the punch, body assembly, reflector assembly, preparation and wiring processes occur. Following this the fixture flows through packaging and finally shipping via FIFO lanes to complete the critical path of product flow. FIFO lanes also direct cut lenses and processed harnesses to the pacemaker. The packaging cell pulls prepared mounting kits from the mounting kit cell via a supermarket based pull system. The value stream therefore yields a total production lead time of 1.76 days with a value-added processing time of 5.2 mins.

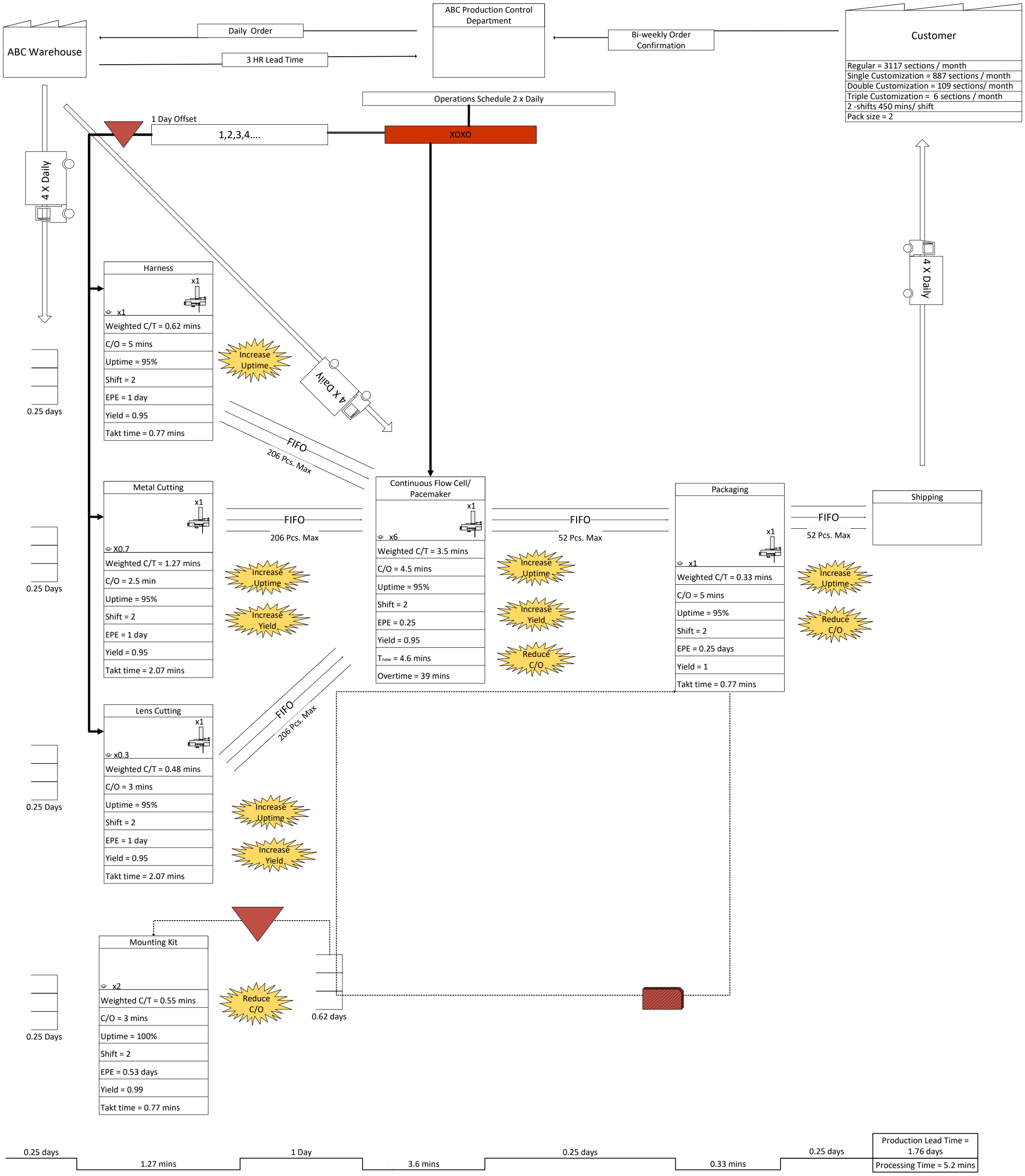


Figure 7: The Future State Value Stream Map of BC for the selected product family

The future state map shows a 92% reduction in production lead time and a processing time improvement between 58% and 79%. The future state also requires several kaizens with a focus on improving uptime and yield whilst minimizing the changeover time. The future value stream requires 11 operators functioning in different process cells. It is important to note here that there may be a requirement of 2 material handlers to fulfill the necessary non-value-added activities at the metal cutting and lens cutting process cell. It is also important to note that a robust conveyance structure must be setup in order to enable just-in-time material availability at the various process cells.

Finally, there are two stand out issues from this chapter that need further attention. First, a preventive maintenance regime will need to be designed in order to address the high machine downtime. Second, our ‘schedule to capacity’ regime needs to be refined to accommodate the company requirement to have ‘revenue-leveled’ production days within a given production week. In the following chapters, we will build optimization models to address these two issues, using linear programming.

6 Design and Optimization of a Cost-Effective Preventive Maintenance Schedule

In its current state, maintenance activities on the ABC production floor are performed using a solely reactive (corrective maintenance) approach. As previously discussed, this approach is overwhelming resources, prematurely ageing machinery, increasing replacement costs and applying significant pressure on on-time delivery. In order to mitigate uptime losses due to unplanned machine breakdown, it was previously proposed that a more proactive (preventive maintenance) approach will need to be adopted. In this section, we will be utilizing linear mathematical modelling and programing as a tool to help develop a preventive maintenance plan that will aim to achieve the organizational goal of 95% uptime in a cost-effective manner.

This section will model a preventive maintenance schedule for ABC which will absorb all the daily and weekly preventive maintenance needs of each machine. We will first define the problem statement and associated constraints. This will be followed by a discussion on important assumptions that will be made. From this point, we will initiate the modelling process. Here, we will outline sets, parameters, decision variables, objective functions and constraints to ultimately form the components of a mathematical optimization model which will deliver, a cost minimized preventive maintenance schedule. The model will then be programmed using OPL language and inputted into the IBM CPLEX solver to find the optimized outcome. Finally, the preventive maintenance schedule and its cost to ABC will be presented.

6.1 Problem Statement and Current State

ABC operates in a 150,000 sq. ft. manufacturing facility and runs two shifts per day, a morning shift and an evening shift. ABC has 206 active industrial machines in its production floor. Some machines are in need of daily and weekly preventive maintenance such as the metal cutting machines, lens cutting machines, CNCs, bending machines, miter saws, pneumatic assembly jigs, hydraulic presses, laser cutting machines etc. whereas other machines have only weekly maintenance requirements and these include: compressors, fume extractors, ionized air guns etc.

Present day in-house maintenance is managed by 2 maintenance technicians who work along the day shift. These resources are currently overwhelmed with corrective maintenance activities and are unable to tend to preventive maintenance needs. For this purpose, ABC has entered a service contract to have preventive maintenance activities for its machines be performed by a third-party contractor named XYZ Inc. ABC hopes that a stable preventive maintenance schedule, once implemented, will decrease the need for corrective maintenance and allow the company to plan the internal resources required to later absorb both preventive and corrective maintenance needs. Currently XYZ can provide 2 full time maintenance technicians for the first shift and 2 full time technicians for the second shift. XYZ can also provide overtime and additional floating technicians if required by ABC, but at a higher cost. ABC would like to learn if the current resources provided by XYZ will suffice. It would like to learn about the number of required overtime hours and if additional floating technicians will be required to cover preventive maintenance needs. ABC would also require a defined preventive maintenance schedule for the technicians being provided by XYZ. All of which, it would like to achieve at a minimized cost.

6.2 Constraints

Now that we understand the problem and current conditions, in this section we will learn about the constraints, posed by both ABC and XYZ, which must be adhered to whilst building the cost optimized preventive maintenance schedule.

6.2.1 ABC's Constraints

ABC has the following constraints which must be strictly adhered to during the modeling process. The first shift works from Monday to Friday between 7:00 am and 3:30 pm. The second shift works from Sunday to Thursday 3:30 pm to 12:00 midnight. The plant is closed on Saturdays and no work (including maintenance) can be performed on that day. Each machine has a stipulated allowable downtime for maintenance, which is in keeping with the 95% uptime requirement. Any maintenance done within this time, will meet the uptime KPI as it will fall within the 10% allowance we allotted for operator inefficiencies due to mix variation and machine maintenance. When the maintenance of the machine is done outside of these hours, we must account for the cost of lost productivity. Some machines are active for both shift whereas others are only operated in the first shift. Daily and weekly maintenance activities for a given machine are independent and cannot be done parallelly. For a given week, it is absolutely necessary for all machines to complete their daily and weekly maintenance activities in order to mitigate the risk of unplanned machine shutdowns. Finally, ABC wishes to develop a schedule that minimizes the cost of maintenance without having to resort to floating technicians or compromising its 95% uptime KPI.

6.2.2 XYZ's Constraints

XYZ, ABC's external maintenance provider, provides 2 full time maintenance technicians at a cost of $35 per hour in the first shift and 2 full time technicians in the second shift at $30 per hour. If the technician works for more than 8 hours per shift, for each additional hour worked, they must be paid 1.5 times the hourly assigned wage. A technician can work a maximum of 3 hours of overtime each day and can work a maximum of 5 days a week. A technician can work a maximum of 12 overtime hours per week. If ABC requires more technicians, it can request additional floating resources from XYZ at a higher price (however ABC does not want to resort to this option). Each technician must receive two consecutive days off in a 7-day work week. Technicians are given one ½ hour lunch break and two 15 min snack/smoke breaks. All of these breaks are paid. A technician cannot work for more than one shift per day. Administrative documentation and procurement of parts take 1 hour per technician per shift, which is paid.

6.3 Assumptions

We will assume that corrective maintenance will be handled by in-house resources and hence will not be modeled. We will assume that preventive maintenance and corrective maintenance will not coincide. We will be assuming that the brand and the age of the machine does not alter the maintenance requirement of the machine. We will assume that all spare parts are readily available. Additionally, we will assume that each maintenance activity (daily or weekly) already accounts for time invested in non-value-added activities like travelling to the machine's location in the plant, finding the right manual, retrieving the tools to perform the maintenance, clean-up etc. We will assume that day shift maintenance technicians will take Saturdays and Sundays off and evening shift technicians will take Fridays and Saturdays off. We will build our optimization model using only preassigned technicians and assume no floating resources are currently present in the system (should current needs not be fulfilled; only then will we consider floating resources and their associated costs). We will assume that resource cost is the only cost incurred in performing the preventive maintenance activity. Finally, we assume that no vacation/sick days will be applied for (as these are contractors) and that even public holidays will be counted as workdays.

6.4 Modeling

Now we will proceed to develop the mathematical model which will aim to yield a cost optimized preventive maintenance schedule. In developing the model, this section will outline key sets, parameters and decision variables prior to determining the objective function. From this, the objective function and associated constraints will be developed to complete the mathematical model.

6.4.1 Sets, Parameters and Decision Variables

In this section we will outline the sets, parameters and decision variables that will help shape our objective function and constraints.

6.4.1.1 Sets

In modelling a preventive maintenance schedule, we will first need to determine the sets for our model. We will first assign a set *M* which will contain an index of all 206 industrial machines which need to undergo preventive maintenance. The next set *T* will be an index of technicians. It will contain the two day shift technicians (Technician 1 and 2) and the two evening shift technicians (Technician 3 and 4). The set *D* will be an index of days and will contain 6 days: Monday (Day 1), Tuesday (Day 2), Wednesday (Day 3), Thursday (Day 4), Friday (Day 5) and Sunday (Day 6). The set *S* will be an index of shifts, namely the morning (1) and the evening shift (2). Finally, set *A* will be an index of maintenance activity types, with the number 1 reflecting a daily maintenance activity and 2 reflecting a weekly maintenance activity. A list of all sets can be found below.

Sets

$M \quad m \in M$ index for machines $M = \{\ 1,2 \ldots .p\}$

$T \quad t \in T$ index of technicians $T = \{1, ..r\}$

$D \quad d \in d$ index of days $D = \{1,2 \ldots e\}$

$S \quad s\ \in S$ index of shifts $S = \{\ 1, \ldots .h\}$

$A \quad a\ \in A$ index of types of maintanence activites $A = \{\ 1, ..u\}\ (1 = daily, 2 = weekly)$

6.4.1.2 Parameters

Now that we have defined the necessary sets, let us outline the parameters needed for modelling. Our parameters will serve as the primary data input into our model. Our first parameter, j_{tsd}, is a binary variable defining the availability of technician *t* in shift *s* of day *d*. For example, technician 1 (who works the day shift) is available in shift 1 of day 1, therefore $j_{111} = 1$, but technician 1 is not available in shift 2 of day 6 hence $j_{126} = 0$. Our second parameter is a real variable c_s, reflecting the cost to employ a technician in shift *s* on an hourly basis. For example, the cost to employ a technician in the day shift is \$35 therefore, $c_1 = 35$. Our third parameter is a real variable v_s, reflecting the overtime cost to employ a technician in shift *s* on an hourly basis. For example, the cost to employ a technician in performing overtime in the day shift is \$35 x 1.5 or \$52.5 per hour, therefore $v_1 = 52.5$. Our fourth parameter l_{ma}, is a real variable reflecting the duration of time it takes to perform maintenance activity *a* on machine *m*. For example, it takes 20 minutes to perform a daily preventive maintenance activity on machine 1 (bending machine), therefore $l_{11} = 20$. Our fifth parameter k_{ms}, reflects the available time for preventive machine maintenance on a machine *m* in shift *s*, in order to stay within the 95% uptime goal. For example, machine 1 (bending machine) has 60 minutes available in shift 1 for preventive maintenance activities, therefore $k_{ms} = 60$. Finally our sixth parameter f_a, reflects the frequency of an activity *a* in a production week. For example, a weekly maintenance activity (2), needs to be performed 1 time a week, therefore $f_2 = 1$. A list of all parameters can be found below.

Parameters:

j_{tsd} : binary on the availability of the technican t in shift s on the day d
c_s : regular cost to employ a technician in shift s per hour
v_s : varibale cost to employ on overtime a technician in shift s per hour
l_{ma} : duration of maintainence activity a on machine m (mins)
k_{ms} : planned availability of machine m in shift s
f_a : number of times activity a must be performed in a given production week

6.4.1.3 Decision Variables

With the sets and parameters defined, we will now determine the decision variables which will be the output variables we aim for our model to return. There are three critical decision variables in this model. The first variable X_{tsd}, is a real number reflecting the number of regular minutes technician t will be working for in a given shift s of day d. The second decision variable Z_{tmasd}, is a binary variable which will decide if a given technician t will be assigned to machine m in order to perform a preventive maintenance activity a for a given shift s on a given day d. Finally, for the third decision variable O_{tsd}, our model will need to output a real number reflecting the number of overtime minutes technician t will need to work for in a given shift s of day d. A list of all decision variables can be found below.

Decision Variables:

X_{tsd} = decision variable representing regular mins technician t is present in shift s of day d

$$Z_{tmasd} = \begin{cases} 1, & \text{is the tech } t \text{ assigned to machine } m \text{ to perform } a \text{ in the shift } s \text{ of the day } d \\ 0, & \text{otherwise} \end{cases}$$

O_{tsd} = decision variable representing overtime mins. for the technician t in shift s of day d

6.4.2 Determining the Objective Function

ABC's goal is to minimize the maintenance cost without compromising the 95% uptime requirement, our objective function will be modeled to reflect the same. First, we divide the X_{tsd} (which is the regular minutes spent by a technician *t* in shift *s* of day *d*) value by 60 because the cost of maintenance is stated on an hourly basis. The cost of maintenance C_s is then multiplied by the hourly X_{tsd} value and then added to the multiplied output of the cost of overtime maintenance activities V_s and the number of overtime hours O_{tsd} used on an hourly scale (dividing by 60). We then find the summation of these costs for all technicians in all shifts of all days. Finally, since two hours of each shift is spent by each operator doing documentation or taking breaks (which is not a maintenance activity, but is paid) we add back for each shift (shift 1 and 2) 20 hours (5 hours of documentation + 5 hours of breaks for each week for each of the 2 technicians which equals 20) which is multiplied by C_s which is the regular shift pay given to a technician. We then find the summation for all shifts. Thus, our objective function will output the minimized overall cost of preventive maintenance. The Objective function can be found below.

Objective function:

$$\min \quad \sum_{t\,\in T} \sum_{s\,\in S} \sum_{d\,\in D} \left(C_s * \frac{X_{tsd}}{60} + V_s * \frac{O_{tsd}}{60} \right) + \sum_{s\,\in S} 20 * C_s$$

6.4.3 Modelling the Constraints

With the objective function defined, we must now turn our attention to mathematically modelling the constraints which our objective function must adhere to. Below, we will present each constraint and provide the mathematical formulation for the same.

The first constraint is set to ensure that that overtime hours O_{tsd} performed by each technician in each shift of each day, does not exceed the daily maximum of 180 mins or 3 hours.

$$O_{tsd} \leq 180 \;\; \forall t \in T, \forall s \in S, \forall d \in D \tag{1}$$

The second constraint is set ensure that the number of regular minutes X_{tsd} performed by each technician, in each shift of each day is defined as less than or equal to 360 mins or 6 hours. Please note that 2 hours used for documentation and breaks have been eliminated here as those hours do not contribute to maintenance activity time, their cost is later accounted for in the objective function.

$$j_{tsd}X_{tsd} \leq 360 \;\; \forall t \in T, \forall s \in S, \forall d \in D \tag{2}$$

The third constraint ensures that the restriction of a given technician's weekly maximum overtime minutes of 720 mins or 12 hours is respected.

$$\sum_{s \in S} \sum_{d \in D} O_{tsd} \leq 720 \;\; \forall t \in T \tag{3}$$

The fourth constraint ensures that for a given day (both shifts) on a given machine, each daily maintenance and each weekly maintenance is performed a maximum of one time and by only one technician.

$$\sum_{t \in T} \sum_{s \in S} Z_{tmasd} \leq 1 \;\; \forall m \in M, \forall a \in A, \forall d \in D \tag{4}$$

The fifth constraint ensures that for each technician in each shift of each day, the sum of all daily and weekly maintenance activities conducted does not exceed the regular and overtime hours of the given technician for that day.

$$\sum_{m \in M} \sum_{a \in A} l_{ma} Z_{tmasd} \leq X_{tsd} + O_{tsd} \;\; \forall t \in T, \forall s \in S, \forall d \in D \tag{5}$$

The sixth constraint ensures that a maintenance activity for a given machine is only allotted to a technician, if the technician is available for the given shift of the given day.

$$Z_{tmasd} \leq j_{tsd} \quad \forall t \in T, \forall s \in S, \forall d \in D, \forall m \in M, \forall a \in A \tag{6}$$

The seventh constraint requires that the daily maintenance of a machine occur for every day that the machine is active and the weekly maintenance of a machine occur once a week.

$$\sum_{t \in T} \sum_{d \in D} \sum_{s \in S} Z_{tmasd} = f_a \quad \forall a \in A, \forall m \in M \tag{7}$$

The eight constraint ensures that for each machine in each shift of each day, the sum of the daily and weekly maintenance activities performed on the day does not exceed the daily scheduled allowable maintenance (this is to sustain the 95% uptime requirement).

$$\sum_{t \in T} \sum_{a \in A} l_{ma} Z_{tmasd} \leq k_{ms} \quad \forall m \in M, \forall s \in S, \forall d \in D \tag{8}$$

Finally we employ a ninth constraint to ensure the number of weekly regular hours for each technician to do maintenance activities does not exceed 1800 mins or 30 hours (remember that the 10 extra hours per technician per week is used for documentation and breaks which is not counted for maintenance but its accounted in the cost calculations of the objective function).

$$\sum_{s \in S} \sum_{d \in D} X_{tsd} \leq 1800 \quad \forall t \in T \tag{9}$$

6.5 Output and Conclusions

The model is programmed using OPL language and inputted into the IBM CPLEX solver in order to find the optimized outcome. The detailed code for the same, can be found in Appendix D. The objective function resulting from the solver yields a minimized weekly total expenditure on preventive maintenance of **\$ 6291.88**. Table 17, which is an output of the regular minutes X_{tsd} worked by technician *t* in shift *s* of day *d*, is shown below. In this Table it can be seen that the cost minimizing objective of the solver has necessitated to use the full capacity (360 mins) of regular minutes spent by technicians in the ABC facility. Thus, first confirming that current XYZ resources are being fully utilized.

x[1][1][1] =	360	x[2][1][1] =	360	x[3][2][1] =	360	x[4][2][1] =	360
x[1][1][2] =	360	x[2][1][2] =	360	x[3][2][2] =	360	x[4][2][2] =	360
x[1][1][3] =	360	x[2][1][3] =	360	x[3][2][3] =	360	x[4][2][3] =	360
x[1][1][4] =	360	x[2][1][4] =	360	x[3][2][4] =	360	x[4][2][4] =	360
x[1][1][5] =	360	x[2][1][5] =	360	x[3][2][6] =	360	x[4][2][6] =	360

Table 17: Output of the regular minutes X_{tsd} worked by technician [t] in shift [s] of day [d]

Furthermore, in Table 18 below, when we look at the output of overtime minutes O_{tsd} worked by technician *t* in shift *s* of day *d*. It is apparent that all the preventive maintenance activities can be performed using only current XYZ resources. This is inferred as the maximum weekly overtime spent is 11 hours (655 minutes) by technician 1 and the least weekly overtime spent is as low as 0.33 hours (20 minutes) by technician 3. There seems to be no need for additional floating resources as there are certain technicians who are working far fewer overtime hours than their stipulated maximum of 12 hours of overtime per week. Therefore, 4 technicians spread across 2 shifts working their entire regular shift and an average weekly overtime of 6 hours per week, should be able to fulfill all the preventive maintenance requirements of ABC.

o[1][1][1] =	75	o[2][1][1] =	175	o[3][2][1] =	0	o[4][2][1] =	0
o[1][1][2] =	165	o[2][1][2] =	60	o[3][2][2] =	5	o[4][2][2] =	0
o[1][1][3] =	155	o[2][1][3] =	155	o[3][2][3] =	0	o[4][2][3] =	0
o[1][1][4] =	105	o[2][1][4] =	10	o[3][2][4] =	0	o[4][2][4] =	0
o[1][1][5] =	155	o[2][1][5] =	180	o[3][2][6] =	15	o[4][2][6] =	170

Table 18: Output of overtime minutes O_{tsd} worked by technician [t] in shift [s] of day [d]

Finally, Appendix E displays the outputted preventive maintenance schedule which covers all the daily and weekly preventive maintenance needs of ABC using current resources provided by XYZ. In the long term, this means that larger breakdowns will be eliminated, and the machine will have a lower depreciation value/ greater lifespan, which again is very profitable to the company. As corrective maintenance activities are minimized, ABC's reliance on contracted technicians can be reduced and more preventive maintenance can be internalized. We have thus successfully designed a cost-effective preventive maintenance regime that will adhere to the 95% uptime requirement of the plant. In the next chapter, we will revisit linear programming, this time to tackle the ABC constraint which requires the total revenue earned by production days in a given production week to be near equal.

7 Design and Optimization of a Revenue-leveled Production Schedule

During the formulation of ABC's future value stream, the concept of 'scheduling to capacity' is introduced. In this concept, weighted averages of work content were used to design each production day as a bin with a finite capacity of producible minutes. As orders streamed into the production system, they filled the production bin with their work content to the point that a given bin (production day) reached its capacity. Then, a new bin would start being filled with further orders as they streamed in (the next production day) and so on. This technique gave priority to the sequence of order arrival in a first come first serve (FCFS) fashion. This technique however, led the production floor to earn different revenues between days within the same production week. ABC's management would like to level the revenue earned by production days in a given production week, which we previously identified as a business need.

This section will be modeling a weekly production schedule which will aim to create a production sequence, which will level the revenue earned by production days within a given production week. In this section, we will begin by defining the problem statement and associated constraints. Following this, we will identify key assumptions made and form the components of a mathematical optimization model. This mathematical model will be constructed to deliver a weekly production schedule featuring production days that earn near equal/ leveled revenues. The model will then be programmed using OPL language and inputted into the IBM CPLEX solver to find the optimized outcome. Finally, the production schedule and its revenue variances will be presented.

7.1 Problem Statement and Current State

In its current state, ABC gives its production floor a weekly total revenue target. Frequently, at the end of the production week, management finds a significant gap between the planned target and the earned revenue. Often, at that point, it is fairly too late to recover. This, in turn, pressurizes future production cycles, increases financial expenditure and puts a strain on short term liquid asset investment.

ABC is concerned that the first-come first-served (FCFS) priority scheduling may blur insights into the daily financial health of the production floor. ABC's management would like to level the financial value earned by the floor on a given day of a production week. According to ABC, it will help the company gauge the deviation of earned financial value from planned financial value within a given week, in a simple, frequent and consistent manner. In ways, one can look at this as a steady financial pitch being set for the company. For reasons of risk management and improved liquidity control, ABC would like to level daily revenue in a given production week. In short, the floor would like to have a production schedule which sequences orders in a manner that yields a highly consistent (with minimized deviation) daily financial output.

7.2 Constraints

In this section we identify constraints, though minimal, which must be adhered to whilst building the leveled revenue based production schedule. ABC has requested that order splitting be minimized. That is, the schedule should aim, to the best of its capability, to produce the entire order in one production day and not fragment the order across several production days. Orders can only be split if they either have a quantity that exceeds the day's production capacity or if SKUs within the order do not belong to our product family (it will have to flow through another value stream in the production facility). Furthermore, ABC requires that all orders scheduled within the production week be complete (this is fair considering we have stipulated capacity to meet demand in Chapter 5). Finally, orders scheduled on a given day cannot exceed the production capacity (bin size) of the day.

7.3 Assumptions

We will assume that SKUs not compatible with our selected product family will already have been segregated from the order (sent to their corresponding value streams) and therefore orders entering our value stream only contain SKUs which are compatible with our product family. We will assume that for a given week, total orders scheduled to the week do not exceed the production capacity of the week (this is a fair assumption given that the capacity is designed to meet demand in Chapter 5). Finally, we will assume that orders, so long as they are not fragmented, can be assigned to any given day within the production week and will therefore loose their first come first serve priority scheduling.

7.4 Modeling

Now that we understand the problem statement, the constraints and the assumptions, we will proceed to develop the mathematical model with a goal to deliver a production schedule that levels daily revenue in a given production week. In this section, we will outline the sets, parameters and decision variables required to build our model. From this, the objective function and associated constraints will be developed to complete the mathematical model.

7.4.1 Sets, Parameters and Decision Variables

In this section we will outline the sets, parameters and decision variables that will help shape our constraints and the objective function.

7.4.1.1 Sets

In modelling a preventive maintenance schedule, we will first need to determine the sets for our model. Our first set *O* contains an index of all orders entering the production floor for a given production week. Our next set *S* reflects the SKUs (one of the 31 permutations we developed in Chapter 5) within the order, which are a part of our product family (non-compatible SKUs have already been removed). Finally, a set *D* features an index of production days. A list of all relevant sets can be found below.

Sets:

O $o \in O$ index for orders $O = \{1,2 \ldots. e\}$
S $s \in S$ index of SKUs within the order $S = \{1,..m\}$
D $d \in D$ index of days $D = \{1,2 \ldots r\}$

7.4.1.2 Parameters

Now that we have defined the necessary sets, let us outline the parameters needed for modelling. Our parameters are the primary data input into our model. Our first parameter is a real number f_{od}, which represents the fixed cost incurred to produce an order *o* on a production day *d*. This is an artificially high penalty cost introduced to ensure that the model reduces order splitting to different production days, unless the capacity is exceeded; in which case the penalty cost will need to be incurred. For example, the fixed cost to produce order 1 in production day 1 is $100,000, therefore $f_{11} = 100000$. If however the order 1 is produced on production day 2 as well, then another fixed cost of f_{12} = 100000 will be incurred. In an attempt to minimize cost incurred, we hope that the model will aim to minimize order splitting to multiple production days. Our second parameter is a real number c_d, which reflects the capacity or total time available to produce orders on a given production day d. For example, on production day 1, there is a total of 270,255 seconds available to produce, therefore c_1 = 270,255. Out third parameter g_{os}, is a real number reflecting the dollar value earned or the revenue earned by producing one unit of SKU s of order o. For example, it costs $442 to produce one unit of SKU 1 which is contained in Order 1, therefore g_{11} = 442. Our fourth parameter t_{os}, is a real number reflecting the time or work content required to produce one unit of SKU s of order o. For example, it takes 1336 seconds to produce one unit of SKU 1 which is contained in Order 1, therefore t_{11} = 1336. Finally, fifth parameter u_{os}, is an integer reflecting the quantity of SKU s of order o to be produced. For example, 6 units of SKU 1 which is contained in Order 1 needs to be produced, therefore u_{11} = 6. A list of all parameters can be found below.

Parameters:

f_{od} : fixed cost incurred by producing order o on day d
c_d : total time available for production on day d
g_{os} : per unit dollar value earned by producing SKU s of order o
t_{os} : per unit time required to produce SKU s of order o
u_{os} : total quantity of SKU s of order o to be produced

7.4.1.3 Decision Variables

With the sets and parameters defined, we will now determine the decision variables. There are 7 decision variables in this model. Our first decision variable K_{od}, is a binary decision variable which determines if order o will be produced on day d. Our second decision variable Z_{osd}, is another binary variable which will decide if SKU s of order o will be produced on day d. Our third decision variable Q_{osd}, is an integer specifying the quantity/ number of units of SKU s of order o that will be prepared on day d. Our fourth decision variable V_d, is the summation of the total revenue earned on a given production day d. Our fifth decision variable $\bar{V}_d$, is the average revenue that should be earned in a given production day d to ensure near equal revenue is earned in each day of the production week. Finally, decision variables X_d and Y_d, represent the positive and negative deviations of a given day's total revenue earned from the average daily revenue to be earned. A list of all decision variables can be found below.

Decision Variables:

$$K_{od} = \begin{cases} 1, & \text{is the decision to produce order } o \text{ on day } d \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{osd} = \begin{cases} 1, & \text{is the decision to produce SKU } s \text{ of order } o \text{ on day } d \\ 0, & \text{otherwise} \end{cases}$$

Q_{osd} = quantity of SKU s of order o that will be produced on day d

V_d = the total dollar value earned by all production on day d

$\bar{V}_d$ = the ideal total dollar value to be earned by all production on day d

X_d = revenue above average on day d

Y_d = revenue below average on day d

7.4.2 Modelling the Constraints

Now that we have identified the relevant sets, parameters and decision variables; we will model the constraints which our objective function must adhere to. Below, we will present each constraint and provide the mathematical formulation for the same.

Our first constraint is a capacity constraint that ensures that the summation of the time taken by all quantities of all SKUs of all orders produced for a given production day, do not exceed the capacity of the day.

$$\sum_{o \in O} \sum_{s \in S} t_{os} Q_{osd} \leq c_d \quad \forall d \in D \tag{1}$$

Our second constraint ensures that for all production days in a given week, for each SKU of each order, the total quantity scheduled for the week is produced.

$$\sum_{d \in D} Q_{osd} = u_{os} \quad \forall o \in O, \forall s \in S \tag{2}$$

Our third constraint outlines how to arrive at V_d which is the total dollar value/revenue earned on a given production day. It is the summation of the multiplication of the quantity and the dollar earned per unit for all SKUs of all orders produced in the given production day.

$$\sum_{o \in O} \sum_{s \in S} g_{os} Q_{osd} = V_d \quad \forall d \in D \tag{3}$$

Our fourth constraint outlines the average daily revenue, $\bar{V}_d$. This variable reflects the dollar value targeted to be met in each day of the week. It is calculated by dividing the total weekly revenue by the number of days.

$$\frac{1}{5} \sum_{d \in D} V_d = \bar{V}_d \quad \forall d \in D \tag{4}$$

Our fifth constraint identifies the resulting deviations of revenue earned on a given day V_d from the average daily revenue $\bar{V}_d$ where X_d and Y_d capture the positive and negative deviations from the average, respectively.

$$V_d - \bar{V}_d = X_d - Y_d \quad \forall d \in D \tag{5}$$

Our sixth constraint ensures that if the decision to produce SKU *s* of order *o* on day *d* is 0 ($Z_{osd} = 0$), then the quantity produced for the same SKU, Q_{osd} is also equal to zero.

$$Q_{osd} \leq M \, Z_{osd} \quad \forall o \in O, \forall s \in S, \forall d \in D \tag{6}$$

Finally, our seventh constraint ensures that if an order o is not scheduled to be produced on a given day d, then no SKUs of that order will be produced on that day either.

$$\sum_{s \in S} Z_{osd} \leq M\, K_{od} \quad \forall o \in O, \forall d \in D \tag{7}$$

7.4.3 Determining the Objective Function

ABC's goal is to ensure that the revenue produced on each day of a given production week is nearly equal. To achieve this, ABC must ensure that the deviations of revenue earned on each day from the average daily revenue, is minimized. It must also aim to achieve this whilst abiding by the constraints that it is subjected to. Our objective function will be modeled to reflect the same.

Our objective function is designed to minimize the sum of all positive and negative deviations in revenue for all production days within a given production week. Our objective function also aims to minimize the penalty cost incurred from producing an order on more than one production day (minimizing order splitting). The function reflecting these objectives can be found below.

Objective function:

$$\min \quad \sum_{d \in D}(X_d + Y_d) + \sum_{o \in O} \sum_{d \in D} (f_{od} * K_{od})$$

7.5 Output and Conclusions

With the mathematical formulation complete, the model is programmed, using OPL language, into the IBM CPLEX solver in order to find the optimized outcome. The detailed code for the same, can be found in Appendix F. The model is run for a given production week and output for the week can be found in Table 19 below.

Production Day	Total Dollar Value	Sum of Qty	Deviation of Dollar from Average
1	$ 121,600.70	202	0.03%
2	$ 121,548.14	201	0.07%
3	$ 121,692.18	201	0.05%
4	$ 121,743.92	190	0.09%
5	$ 121,579.79	194	0.04%
Grand Total	**$ 608,164.73**		
Average	**$ 121,632.95**	198	**0.06%**

Table 19: Optimized output of Revenue-leveled weekly Schedule

As is visible from the table above, the order sequence is reorganized to yield an average 0.06% difference in revenue earned per production day in a given production week. Furthermore, a detailed scheduled with a sequence of which orders are to be produced on which production day in order to achieve this minimized revenue difference can be seen in Appendix G. It is important to view that order splitting only occurred in the case of order 3, where the number of sections in the order clearly exceeded the daily production capacity.

It is critical to note at this point, that the reorganization of orders to ensure revenue control will mean that orders will wait in the production system for longer when compared to the scenario in which they where produced in a FCFS basis. Figure 8 describes how the revenue control schedule increases the lead time of an order. For example, a given order (triangle) enters the system at the beginning of Day 1. It takes a constant two weeks (10 working days) to have quotation approval, design approval, material arrival, material inspection etc. Finally at the beginning of Day 15, the order is released to the floor. Should the first come first serve model of scheduling have been used, the order would have exited the floor on the last truck leaving ABC (1.76 day production lead time) on Day 16 (serrated triangle) at the latest, making its lead time roughly 2.4 weeks. However, due to the ‘revenue-leveled’ scheduling technique, the order must now wait until Day 19 in order to pool the orders for one week and balance the daily dollar value within the week.

From this point on, the optimization is performed to ensure near equal revenue is earned on each production day and then orders are produced per the sequence outputted from the optimized result in the following production week. The reorganization of orders could have led to the order which is received on Day 1 to be shipped on Day 26, thus making its lead time a maximum of 4 weeks.

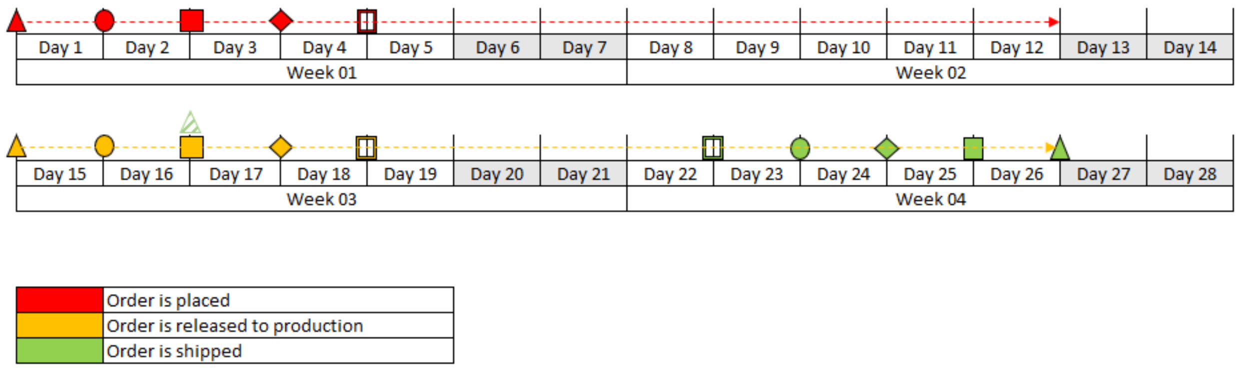


Figure 8: Lead Time delay due to Revenue-leveled Scheduling

The figure above shows how the maximum lead time (worst case) of 4 weeks is arrived at. However, based on the date the order is placed, these lead times can vary. For example a given order (Circle) may exit the system as early as 3.2 weeks. Using our revenue optimized schedule, it is found that an order's lead time will be 3.3 weeks on average if the 'revenue-leveled' scheduling technique is used. Figure 9 shows the lead times of all 47 orders which flowed through a given production week.

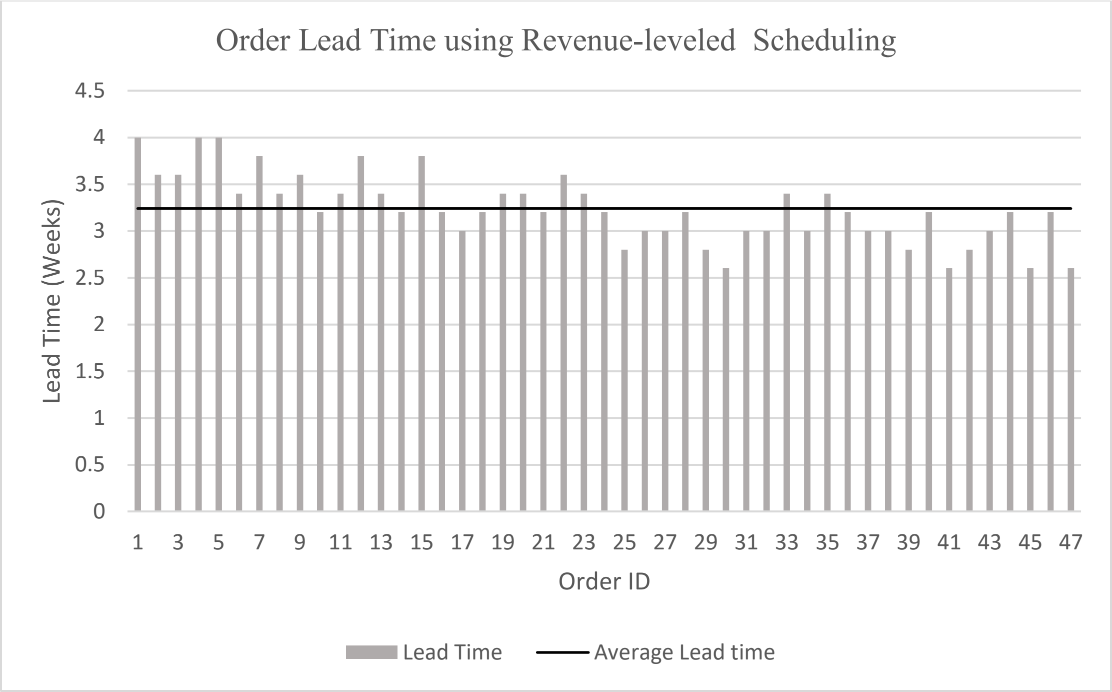


Figure 9: Order Lead Time given a Revenue-leveled Schedule

Therefore, the constant daily financial pitch will cause significant lead time increases for ABC's products. It is important to note that the same weekly revenue target could be met by the business, should it have assigned daily financial targets that were different. The financial pitch would be dynamic in that it would be different each day. But by monitoring the daily adherence of any given day to the dynamic revenue target set for that day, deviations would still be caught early on without compromising lead time.

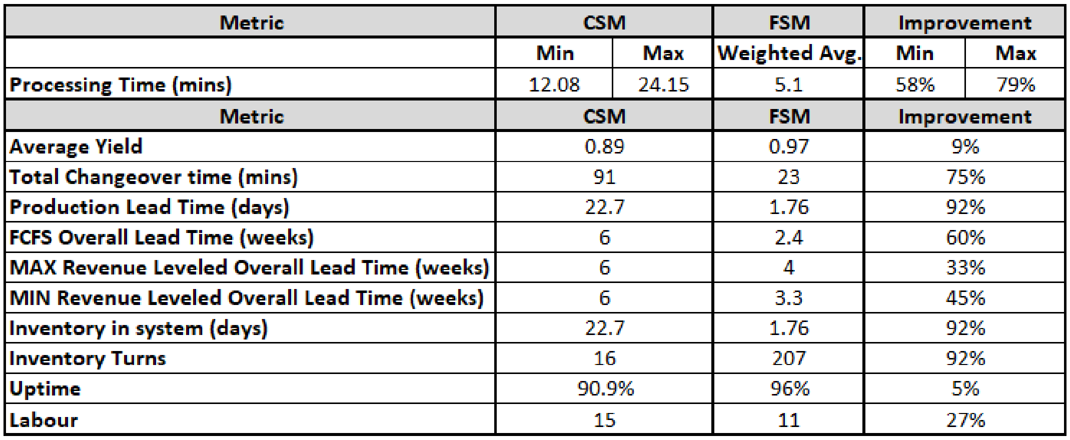
8 Summary, Conclusions and Future Research

In this section we will first summarize the key theoretical contributions of this thesis. We will then outline the benefits of implementing the future value stream and optimized models we have developed in earlier sections. Next, we will assess if the organizational goals were reached and discuss the support systems necessary to implement and sustain changes. Finally, we will also explore areas of future research that will enable the production system to improve continuously and build more baselines for lean implementation in mixed model environments.

8.1 Summary

This thesis aims to increase the competitiveness of SMEs producing a high mix of custom products in low volumes, by developing a lean framework that caters to their HMLV production environment. In achieving this goal, this thesis has developed a number of theoretical concepts which can be globally applied to HMLV production environments. The first concept being a demand-derived product family selection where product families are grouped based on routing similarities and therefrom, demand forecasts are used to select a product family with the highest cumulative projected demand. The second concept is the utilization of a weighted average of total work content to determine resource requirements. 'Scheduling to capacity' is another concept introduced to enable flexibility in fixture processing at process cells. This concept treats each production day as a bin of finite capacity (determined by the weighted average of total work content) and schedules orders to fill the production day. There is a day-to-day variation in the number of fixtures produced, while the long run average remains at the daily average demand (206 fixtures). Finally, the concept of a 'dynamic pitch' is introduced. Here, every 60 minute interval will be scheduled 60 minutes of work. While the number of fixtures produced varies, the daily efficiency (value added time) remains constant. This thesis also offers insight into cost effective preventive maintenance scheduling and 'revenue-leveled' scheduling.

In order to gauge the applicability of the developed concepts, the thesis performs a real-life case study of ABC, a HMLV manufacturer in the Architectural lighting industry. At the onset of the journey, ABC was functioning in a mix model manufacturing environment where high product mix, high product customization and low ordering volume gave rise to significant in-system waste and also diminished competitiveness in the market. We have, as part of our research, used the aforementioned concepts in conjunction with traditional lean principles in order to develop a future state that mitigates waste whilst abiding by the necessary managerial and business constraints set by ABC. In achieving the future state, several metrics have been sizably improved. Table 20 outlines the key improvements achieved in several critical metrics.



Metric	CSM		FSM	Improvement	
	Min	Max	Weighted Avg.	Min	Max
Processing Time (mins)	12.08	24.15	5.1	58%	79%
Metric	**CSM**		**FSM**	**Improvement**	
Average Yield	0.89		0.97	9%	
Total Changeover time (mins)	91		23	75%	
Production Lead Time (days)	22.7		1.76	92%	
FCFS Overall Lead Time (weeks)	6		2.4	60%	
MAX Revenue Leveled Overall Lead Time (weeks)	6		4	33%	
MIN Revenue Leveled Overall Lead Time (weeks)	6		3.3	45%	
Inventory in system (days)	22.7		1.76	92%	
Inventory Turns	16		207	92%	
Uptime	90.9%		96%	5%	
Labour	15		11	27%	

Table 20: Metrics for Product family and their resulting improvements

If the proposed future state is implemented as previously outlined, it will result in a reduction in processing time between 58% and 79%. This is achieved through a careful elimination and/or reassignment of non-value added and necessary-non-value added activities from the system. In the case of processing time, careful attention was also paid to resource allocation in order to achieve cycle times which adhered to takt time and therefore propagated aforementioned results. Frequent, defined and process specific quality inspection criteria and KPIs reflecting their adherence will help institute build-in quality systems which will improve yield by 9%. SMED techniques, design for manufacturing, new technology purchases and a robust methods program will aim to improve time spent on changeovers by 75%. Better flow administration as suggested in the future state will reduce inventory build-up and increase the number of inventory turns by 92%. This is a significant improvement which will also increase production space and reduce the cost of poor quality. The implementation of a preventive maintenance program will aim to improve uptime by 5% on average. Finally, significant improvements in labour and lead time will be seen.

In the case of labour, there will be a 27% reduction of in-process labour. However, at this point it is important to note that the remaining labour will need to be re-invested in building an effective conveyance (just-in-time material availability) and handling (for necessary non-value added work) system. Furthermore, the training of labour resources will be vital in maintaining adaptability to build variations in this high mix environment.

The implementation of the future value stream can result in production lead time reductions of up to 92%. ABC currently offers lead times of 6 weeks to its customers (2 weeks for office/administrative and 4 weeks for production). With its future value stream, ABC can offer lead time of roughly 2.4 weeks using a first-come first-served (FCFS) scheduling technique. Should it require a revenue-leveled schedule, this lead time would climb to a maximum of 4 weeks and an average of 3.3 weeks. Therefore, first-come first-served (FCFS) scheduling can yield a total lead time reduction of 60% and the ‘revenue-leveled’ scheduling will yield a lead time reduction between 33% (maximum delay) and 45% (average). In both cases, we will be able to achieve the organizational target of a 33% lead time reduction.

Finally, it is important to note that one of the motivations for ‘revenue-leveled’ scheduling is to have a simple daily financial pitch so that weekly targets were not missed. However, the same can be achieved by using the first-come first-served (FCFS) strategy with daily dynamic dollar value targets, and the proposed lean implementation will ensure that these daily and hence weekly targets are met, without having to extend lead times.

8.2 Conclusion

With the roadmap to a future value stream outlined, ABC will need to develop a series of short and long term projects to achieve the same. These projects will need to also be defined, planned, executed, monitored and closed with a lean mindset. For this purpose, agile techniques such as story point development, iterative sprints, daily stand-ups and frequent retrospectives will need to be adopted for project success and for building a culture of continuous improvement within the production system. More importantly, the consistent cooperation of all production personnel and the participation of senior management will be pivotal as it is not only lean implementation but also sustained commitment to lean practices that offer true results. The future state, when achieved, will not only increase the productivity of the current value stream and improve the customer experience (reduced lead times, improved quality) but will also set the precedent for other product families to follow suit and provide opportunities to scale the business without the need for increased labour, machinery or space.

The value derived from this thesis, however, can extend beyond the ABC production facility to all production facilities operating in a high-mix low-volume high-customization setting. Beyond the lighting industry, small to medium sized manufacturing businesses in several industries thrive on being able to offer high customization products and rely on growing their market share by making these product offerings cost competitive. In such environments, the role of lean in growing profitability is critical, however, flow administration is often abandoned in light of high work content variations. Point kaizens at the process cell level become the sole source of lean implementation; all to yield non-tangible and non-sustainable success in the larger value stream. Production systems thus continue to sustain problems of high waste, high inventory build-up, diminished quality and low managerial control.

As displayed in this thesis, the treatment of such environments requires new systems of lean thinking that use traditional approaches as a baseline and build new techniques such as demand-derived product family selection, weighted average work contents, ‘scheduling to capacity’ and ‘dynamic pitch’ as compliments to create a more tailored solution. Therefore, this thesis also aims to serve as a reference for lean implementation in all mix model environments with high-customization.

Finally, the ever growing presence of globalization puts North-American manufacturing at risk. Several companies are resorting to off-shore manufacturing practices in a bid to cut costs. This has a crippling impact on domestic labour and environmental sustainability. Off-shore manufacturing will have longer lead time if manufacturers try to customize. However, if local manufacturers learn to implement lean (eliminate waste → shorten lead time, reduce cost), they can customize and also reduce lead time and cost, and gain competitive advantage. The solutions proposed as part of this thesis will be vital in motivating current domestic manufacturing systems to focus on waste reduction and continuous improvement in order to offer customized fixtures with shorter lead-times, higher throughput, and comparable costs in addition to its present high-quality offering.

8.3 Future Research

There is significant scope to further the work present in this thesis. In this section we will discuss areas of future research for the ABC facility and more broadly, for mix-model production systems in general.

- In this thesis, we have improved the value stream of a single group of ABC's products. Future research can develop the value stream for the remaining product families and then techniques of level pull can be used to implement a system kaizen in this mix setting. Process level value stream can also be explored to continuously improve.
- In designing the continuous flow cell, we have assigned the average number of resources required at each sub-station based on our weighted average analysis. Further research can yield an optimization model which can provide daily balancing of resources to meet the mix requirements of a given production day
- Developing methods in a mix-model environment can be challenging. Further research can be performed to develop modular techniques of methods implementation in such high change environments
- Our analysis assumed that the number of product types in the system remained fairly the same. However, every quarter, several new products are introduced, existing products face design change, new technologies are discovered and products are obsoleted. Research into the development of dynamic, flexible and modular value streams would be vital in such cases
- ABC's production facility has fairly level demand throughout the year for the selected product family. However, several mix model environments have seasonality factors to be

considered in demand forecasting. Further research could yield solutions for production planning in seasonal demand environments

- Our revenue-leveled scheduling model assumed that the orders for a given production week did not cross the weekly production capacity. However, further models can be built to optimize for revenue control in cases of exceeded capacity
- Simulation modelling tools, such as Arena, can be utilized to simulate results presented in this thesis in order to provide results on metrics such as lead time in a more stochastic and dynamic manner
- Finally, growing variety in industrial automation offerings and its impact on throughput and quality in mix model environments can be explored

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Appendix A: Time Collection Form

ABC Time Collection Form		**Activity Type:**		**Document Revision:**	1
		VAA	*Value-Added Activity*	**Time Collected By:**	
Process Cell:		***NVA***	*Non-Value-Added Activity*	**Unit of Measure:**	*Seconds*
Date:		***NNVA***	*Necessary Non-Value-Added Activity*	**Product Code Observed:**	
Operator Count:		***C/O***	*Changeover Activity*	**Order #:**	

Work Element	**Activity Type**	**Observation 1**	**Observation 2**	**Observation 3**	**Observation 4**	**Observation 5**	**Mode Value**	**Comments**

Appendix B: Inventory Count Form

ABC Inventory Count										
Document Revision: 1					**Date:**					
Counted by:					**Time:**					
Inventory Between	**Day 01**	**Day 02**	**Day 03**	**Day 05**	**Day 06**	**Day 07**	**Day 08**	**Day 09**	**Day 10**	**Average**
Warehouse & Metal Cutting										
Warehouse & Lens Cutting										
Warehouse & Reflector Sub-Assembly										
Warehouse & Harness Preparation										
Warehouse & Mounting Kit Preparation										
Metal Cutting & Punch										
Punch & Body Assembly										
Body Assembly and Preparation										
Preparation & Wiring Assembly										
Lens & Wiring Assembly										
Reflector Sub Assembly & Wiring Assembly										
Harness Preparation & Wiring Assembly										
Wiring Assembly & Packaging										
Packaging & Shipping										
Mounting Kit Preparation & Shipping										

Appendix C: Metal Cutting Cell work elements and standard time (sec) for selected group

VORK ELEMENTS	Regular	Regular flangeless	Emergency Battery	Chicago Plenum	Emergency Circuit	End Feed	Flex Whip	Fuse	Generator Transfer Device	Controls (sensors)	Night Light	Length Relief Module	Downlight Insert	Chicago Plenum, Length Relief Module	Emergency circuit, Emergency Battery	Emergency circuit, Chicago Plenum	Emergency circuit, Controls (sensors)	Emergency circuit, Length Relief Module	Emergency circuit,FLex Whip	Emergency circuit,Fuse	End Feed,FLex Whip	FLex Whip, Emergency Battery	FLex Whip, Length Relief Module	Fuse, Emergency Battery	Controls (sensors), Emergency Battery	Downlight Insert, Chicago Plenum	Downlight Insert,FLex Whip	Length Relief Module , Emergency Battery	Emergency circuit, Chicago Plenum, Length Relief Module	Emergency circuit, End Feed,FLex Whip	Downlight Insert, FLex Whip, Emergency Battery	Min	Max
Metal Cutting	**202**	**82**	**202**	**202**	**202**	**202**	**202**	**202**	**202**	**202**	**202**	**250**	**332**	**250**	**202**	**202**	**202**	**250**	**202**	**202**	**202**	**202**	**250**	**202**	**202**	**332**	**332**	**250**	**250**	**202**	**332**	**82**	**332**
Data Input: machining interface	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10		
Retrieve raw extrusion from the buggy	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9		
Verify extrusion for visual defects	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15		
Place the extrusion in the machine	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3		
Set the jigging in place	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
Cut the extrusion	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17		
Clean the extrusion	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3		
Verify the precision of the extrusion via metrology	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5		
Affix a label onto the extrusion	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		
Place the extrusion on an empty buggy	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3		
Mark the operation completion in ERP	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7		
Data Input: machining interface	10		10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10		
Retrieve 2 flanges from buggy	13		13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13		
Verify flanges for visual defects	30		30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30		
Wrap the flanges together	8		8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8		
Place the flanges in the machine	6		6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
Set the jigging in place	8		8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8		
Cut the flanges	17		17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17		
Clean the flanges	4		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		
Verify the precision of the flanges via metrology	5		5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5		
Affix a label onto the flanges	8		8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8		
Place the flanges on an empty buggy	4		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		
Mark the operation completion in ERP	7		7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7		
Data Input: machining interface													16													16	16				16		
Retrieve raw extrusion from the buggy													12													12	12				12		
Verify extrusion for visual defects													20													20	20				20		
Place the extrusion in the machine												3	6	3				3					3			6	6	3	3		6		
Set the jigging in place												10	10	10				10					10			10	10	10	10		10		
Cut the extrusion												20	33	20				20					20			33	33	20	20		33		
Clean the extrusion												3	4	3				3					3			4	4	3	3		4		
Verify the precision of the extrusion via metrology													7													7	7				7		
Affix a label onto the extrusion												2	7	2				2					2			7	7	2	2		7		
Place the extrusion on an empty buggy												3	6	3				3					3			6	6	3	3		6		
Mark the operation completion in ERP												7	9	7				7					7			9	9	7	7		9		

Appendix D: OPL coded CPLEX Input mod file for Preventive Maintenance Optimization

```
int p = ...;
int r = ...;
int e = ...;
int h = ...;
int u = ...;
range M = 1..p;
range T = 1..r;
range D = 1..e;
range S = 1..h;
range A = 1..u;
int Two_Dim_j[1..r*h][D]=...;
int Three_Dim_j[t in T][s in S][d in D]= Two_Dim_j[(t-1)*h + s,d];
float c[S]=...;
float v[S]=...;
int l[M][A]=...;
int k[M][S]=...;
int f[A]=...;
dvar float+ x[T][S][D];
dvar float+ o[T][S][D];
dvar boolean z[T][M][A][S][D];
minimize sum(t in T,s in S,d in D)(c[s]*(x[t][s][d]/60) + v[s]*(o[t][s][d]/60)) + sum(s in
S)c[s]*20;
subject to {
forall(t in T,s in S,d in D)
constraint1: o[t][s][d] <= 180;
}
subject to {
forall(t in T,s in S, d in D)
constraint2: x[t][s][d] <= 360;
}
subject to {
forall(t in T)
constraint3: sum (s in S, d in D)o[t][s][d] <= 720;
}
subject to {
forall(m in M,a in A, d in D)
constraint4: sum (t in T, s in S)z[t][m][a][s][d] <= 1;
}
subject to {
forall(t in T,s in S, d in D)
constraint5: sum (m in M, a in A)l[m][a]*z[t][m][a][s][d] <= (x[t][s][d] + o[t][s][d]);
}
subject to {
forall(t in T,s in S, d in D, m in M, a in A)
```

```
constraint6: z[t][m][a][s][d] <= Three_Dim_j[t][s][d];
}
subject to {
forall(a in A,m in M)
constraint7: sum (t in T, d in D, s in S)z[t][m][a][s][d] == f[a];
}
subject to {
forall(m in M, s in S, d in D)
constraint8: sum (t in T, a in A)z[t][m][a][s][d]*l[m][a] <= k[m][s];
}
subject to {
forall(t in T)
constraint9: sum (s in S, d in D)x[t][s][d] <= 1800;
}
execute
{
        var file =new IloOplOutputFile("Maintenance_Module_Soln1.csv");
        file.writeln("Objective value = ", cplex.getObjValue());
        for( var t in T ) {
        for(var m in M)          {
        for(var a in A){
        for(var s in S)  {
        for(var d in D){
                file.writeln("z[",t,"][",m,"][",a,"][",s,"][",d,"] =
",",",z[t][m][a][s][d].solutionValue,",");
}
}
}
}
}
}
execute
{
        var file =new IloOplOutputFile("Maintenance_Module_Soln2.csv");
        file.writeln("Objective value = ", cplex.getObjValue());
        for( var t in T ) {
        for(var s in S)  {
        for(var d in D){
                file.writeln("x[",t,"][",s,"][",d,"] = ",",",x[t][s][d].solutionValue,",");
}
}
}
}
execute
{
        var file =new IloOplOutputFile("Maintenance_Module_Soln3.csv");
```

```
        file.writeln("Objective value = ", cplex.getObjValue());
        for( var t in T ) {
        for(var s in S)  {
        for(var d in D){
                file.writeln("o[",t,"][",s,"][",d,"] = ",",",o[t][s][d].solutionValue,",");
}
}
}
}
```

Appendix E: Optimized Schedule for ABC's Preventive Maintenance Activities

For Technician 1 and Technician 2 in the Day Shift:

Technician 1 Machine_Activity					Technician 2 Machine_Activity				
Day 01	Day 02	Day 03	Day 04	Day 05	Day 01	Day 02	Day 03	Day 04	Day 05
3-1	21-1	13-1	16-1	2-1	2-1	1-1	3-1	2-2	1-1
9-1	21-2	24-1	27-1	4-1	4-1	2-1	8-2	3-1	3-1
16-1	26-1	33-2	28-1	11-1	5-2	3-1	10-1	3-2	9-1
16-2	32-2	35-2	34-2	22-1	10-1	4-1	17-2	9-1	10-1
45-2	39-2	36-1	51-2	25-1	11-1	9-1	22-1	11-1	12-1
53-1	47-2	37-2	52-2	26-1	13-1	10-1	25-1	24-1	13-1
79-1	63-2	38-1	61-2	34-1	22-1	11-1	26-1	34-1	16-1
92-1	65-2	46-2	64-2	35-1	23-1	12-1	28-1	36-2	21-1
114-1	66-2	48-2	75-1	53-1	24-1	13-1	29-2	53-1	23-1
116-1	70-2	54-1	78-1	75-1	25-1	16-1	31-2	72-1	24-1
122-1	74-1	72-1	79-1	76-1	35-1	27-1	33-1	73-1	27-1
127-1	79-1	77-1	81-2	77-1	37-1	34-1	38-2	111-2	28-1
128-1	82-2	78-1	112-2	79-1	38-1	35-1	42-2	112-1	33-1
129-1	83-2	91-1	115-1	89-2	49-2	52-1	53-1	114-1	36-1
130-1	84-2	117-2	116-1	99-2	54-1	53-1	53-2	124-2	37-1
131-1	87-2	120-2	121-2	115-1	55-2	72-1	57-2	125-2	38-1
132-1	88-2	122-1	122-1	116-1	58-2	73-2	68-2	132-1	52-1
133-1	91-2	122-2	123-1	122-1	67-2	113-1	72-2	160-2	54-1
155-1	93-1	123-1	128-1	127-1	71-2	154-1	73-1	164-1	72-1
156-1	114-1	130-1	154-1	128-1	72-1	155-1	75-1	166-2	73-1
157-1	138-1	131-1	155-1	129-1	73-1	156-1	76-1	177-2	74-1
158-1	152-2	132-1	157-1	130-1	75-1	157-1	123-2	180-2	78-1
164-1	153-2	133-1	165-2	131-1	77-1	158-1	126-2	191-1	91-1
173-2	154-2	134-2	168-2	133-1	90-2	164-1	144-2	193-1	92-1
183-2	167-2	138-1	170-2	151-2	93-1	192-1	164-2	195-1	93-1
191-1	178-2	140-2	179-2	154-1	100-2	195-1		196-1	95-2
192-1	182-2	175-2	181-2	155-1	101-2	196-1			112-1
193-1	189-2	185-2	188-2	155-2	115-1	199-1			113-1
194-1	197-1	191-1	190-2	158-1	118-2				114-1
195-1	202-2	192-1		159-2	123-1				123-1
197-1		193-1		161-2	147-2				132-1
198-1		197-1		162-2	169-2				138-1
199-1		200-1		163-2					156-1
200-1				164-1					157-1
203-2				186-2					193-1
				191-1					194-1
				192-1					195-1
				197-1					196-1
				198-1					200-1
				199-1					

For Technician 3 and Technician 4 in the evening shift:

Technician 3 Machine_Activity					Technician 4 Machine_Activity				
Day 01	**Day 02**	**Day 03**	**Day 04**	**Day 06**	**Day 01**	**Day 02**	**Day 03**	**Day 04**	**Day 06**
15-2	25-1	6-2	2-1	9-1	1-1	1-2	1-1	1-1	1-1
26-1	33-1	16-1	10-1	10-1	12-1	14-2	2-1	4-1	2-1
33-1	36-1	18-2	12-1	12-1	21-1	22-1	4-1	4-2	3-1
36-1	37-1	19-2	22-1	13-1	27-1	23-1	7-2	13-1	4-1
52-1	38-1	20-2	26-1	22-1	28-1	24-1	9-1	21-1	11-1
69-2	40-2	23-1	37-1	23-1	30-2	28-1	11-1	23-1	16-1
76-1	44-2	27-1	38-1	24-1	34-1	54-1	12-1	25-1	21-1
86-2	59-2	74-1	52-1	25-1	43-2	76-1	21-1	33-1	26-1
92-2	60-2	74-2	54-2	28-1	74-1	78-1	34-1	35-1	27-1
94-2	62-2	92-1	74-1	36-1	78-1	91-1	35-1	36-1	33-1
96-2	73-1	112-1	77-1	38-1	91-1	92-1	37-1	41-2	34-1
97-2	75-1	113-1	91-1	73-1	98-2	110-2	52-1	50-2	35-1
103-2	77-1	115-1	93-2	77-1	102-2	112-1	56-2	54-1	37-1
105-2	80-2	116-1	127-1	79-1	106-2	115-1	79-1	76-1	52-1
108-2	85-2	127-1	129-1	115-1	107-2	116-1	93-1	92-1	53-1
109-2	135-2	128-1	130-1	123-1	113-1	122-1	104-2	93-1	54-1
112-1	171-2	136-2	131-1	128-1	138-2	123-1	114-1	113-1	72-1
119-2	172-2	137-2	141-2	130-1	154-1	127-1	129-1	133-1	74-1
138-1	174-2	139-2	143-2	132-1		128-1	154-1	138-1	75-1
196-1	193-1	142-2	156-1	133-1		129-1	164-1	158-1	76-1
	200-1	145-2	176-2	138-1		130-1	194-1	184-2	78-1
	204-2	146-2	187-2	156-1		131-1	196-1	192-1	91-1
	205-2	148-2	194-1	194-1		132-1	198-1	197-1	92-1
		149-2	199-1	196-1		133-1		198-1	93-1
		155-1	200-1	198-1		150-2		206-2	112-1
		156-1	201-2	199-1		191-1			113-1
		157-1		200-1		194-1			114-1
		158-1				198-1			116-1
		195-1							122-1
		199-1							127-1
									129-1
									131-1
									154-1
									155-1
									157-1
									158-1
									164-1
									191-1
									192-1
									193-1
									195-1
									197-1

Appendix F: OPL coded CPLEX Input mod file for Revenue-leveled Production Optimization

```
int e = ...;
int m = ...;
int r = ...;
range O = 1..e;
range S = 1..m;
range D = 1..r;
float f[O][D]=...;
float c[D]=...;
float g[O][S]=...;
float t[O][S]=...;
float u[O][S]=...;
dvar float+ v[D];
dvar float+ vbar[D];
dvar float+ x[D];
dvar float+ y[D];
dvar int+ q[O][S][D];
dvar boolean k[O][D];
dvar boolean z[O][S][D];
minimize (sum(d in D)(x[d]+(y[d])) + sum(o in O,d in D)(f[o][d]*k[o][d]));
subject to {
forall(d in D)
constraint1: sum(o in O,s in S)q[o][s][d]*t[o][s] <= c[d];
}
subject to {
forall(o in O,s in S)
constraint2: sum(d in D)q[o][s][d] == u[o][s];
}
subject to {
forall(d in D)
constraint3: sum(o in O,s in S)q[o][s][d]*g[o][s] == v[d];
}
subject to {
forall(d in D)
constraint4: (1/5)*sum(d in D)v[d] == vbar[d];
}
subject to {
forall(d in D)
constraint5: v[d] - vbar[d] == x[d] - y[d];
}
subject to {
forall(o in O,s in S,d in D)
constraint6: q[o][s][d] <= 1000000000000*z[o][s][d];
```

```
}
subject to {
forall(o in O,d in D)
constraint7:sum(s in S)z[o][s][d] <= 1000000000000*k[o][d] ;
}
execute
{
        var file =new IloOplOutputFile("Dollarvalue_Optimization_Module_Soln1.csv");
        file.writeln("Objective value = ", cplex.getObjValue());
        for( var o in O ){
        for(var s in S) {
        for(var d in D){
                file.writeln("q[",o,"][",s,"][",d,"]= ",",",q[o][s][d].solutionValue,",");
}
}
}
}
```

Appendix G: Optimized Schedule for Revenue-leveled Production at ABC

Order	Sections Produced per production day					Grand Total of sections
	1	2	3	4	5	
1	0	0	0	0	10	10
2	0	0	40	0	0	40
3	187	0	54	0	0	241
4	0	0	0	0	4	4
5	0	0	0	0	11	11
6	0	56	0	0	0	56
7	0	0	0	120	0	120
8	0	41	0	0	0	41
9	0	0	0	16	0	16
10	0	15	0	0	0	15
11	0	0	6	0	0	6
12	0	0	0	0	6	6
13	0	0	17	0	0	17
14	0	15	0	0	0	15
15	0	0	0	0	6	6
16	0	15	0	0	0	15
17	7	0	0	0	0	7
18	0	8	0	0	0	8
19	0	0	5	0	0	5
20	0	0	1	0	0	1
21	0	22	0	0	0	22
22	0	0	0	16	0	16
23	0	0	6	0	0	6
24	0	0	7	0	0	7
25	2	0	0	0	0	2
26	0	8	0	0	0	8
27	0	9	0	0	0	9
28	0	0	18	0	0	18
29	3	0	0	0	0	3
30	3	0	0	0	0	3
31	0	0	2	0	0	2
32	0	0	12	0	0	12
33	0	0	0	0	12	12
34	0	0	13	0	0	13
35	0	0	0	0	104	104
36	0	0	0	0	5	5
37	0	0	0	21	0	21
38	0	0	0	16	0	16
39	0	0	6	0	0	6
40	0	0	0	0	10	10
41	0	9	0	0	0	9
42	0	0	14	0	0	14
43	0	0	0	1	0	1
44	0	0	0	0	23	23
45	0	2	0	0	0	2
46	0	0	0	0	3	3
47	0	1	0	0	0	1