DISSERTATION

SYSTEMS ENGINEERING ASSESSMENT AND EXPERIMENTAL EVALUATION OF QUALITY PARADIGMS IN HIGH-MIX LOW-VOLUME MANUFACTURING ENVIRONMENTS

Submitted by

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ABSTRACT

SYSTEMS ENGINEERING ASSESSMENT AND EXPERIMENTAL EVALUATION OF QUALITY PARADIGMS IN HIGH-MIX LOW-VOLUME MANUFACTURING ENVIRONMENTS

This research aimed to evaluate the effectiveness of applying industrial paradigm application in high-mix low-volume manufacturing (HMLV) environments using a Systems Engineering approach. An analysis of existing industrial paradigms was conducted and then compared to a needs analysis for a specific HMLV manufacturer. Several experiments were selected for experimental evaluation, inspired by the paradigms, in a real-world HMLV manufacturing setting. The results of this research showed that a holistic approach to paradigm application is essential for achieving optimal performance, based on cost advantage, throughput, and flexibility, in the HMLV manufacturing environment.

The findings of this research study provide insights into the importance of considering the entire manufacturing system, including both technical and human factors, when evaluating the effectiveness of industrial paradigms. Additionally, this research highlights the importance of considering the unique characteristics of HMLV manufacturing environments, such as the high degree of variability and frequent changes in product mix in designing manufacturing systems.

Overall, this research demonstrates the value of a systems engineering approach in evaluating and implementing industrial paradigms in HMLV manufacturing environments. The results of this research provide a foundation for future research in this field and can be used to guide

organizations in making informed decisions about production management practices in HMLV manufacturing environments.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I: Introduction

In the United States, manufacturers have been steadily shifting from low-mix high-volume (LMHV) manufacturing toward high-mix low-volume (HMLV) manufacturing since the 1970's [67]. There have been many notable manufacturing strategies and principles that have represented changes in industrial paradigms both before and since then (see Figure 1). However, a vast majority of the applicable models for implementing manufacturing "best practices" have largely neglected the needs and considerations of high-mix low-volume manufacturers and focused primarily on low-mix high-volume manufacturing [67].

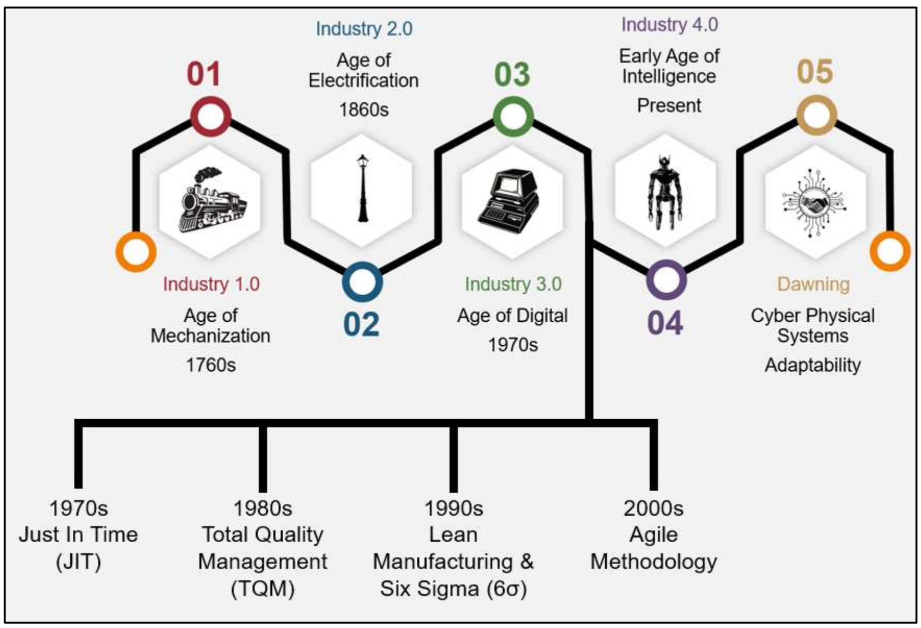


Figure 1: Brief Timeline of Industrial Paradigms in the United States

This research seeks to understand the state of the art for HMLV manufacturing practices, and to develop a strategy to relieve some of the major detractors from cost-competitiveness and lead time reduction that this environment experiences.

1.1.High-Mix Low-Volume Manufacturing

A survey of existing literature reveals that the term "high-mix low-volume" is generally used in manufacturing environments where there are a large number of part numbers and all of them are made in relatively small quantities [29]. In some cases, the definition also includes that there is high variability in processes, demand rates, and product complexity [47]. Regardless of how it is defined in terms of number of distinct components or production volumes, there is a strong distinction in high-mix low-volume manufacturing processes when compared to high-volume manufacturing. For instance, most of the product line will not be produced in continuous operations and machines and work areas will experience component or product changeovers in significantly shorter timeframes than will high-volume producers [64]. The inevitable result of this will be the need for highly skilled staff and a focus on efficiency in changeovers, aspects that are often minimized in the context of high-volume manufacturing [3].

One of the significant contributors to United States manufacturers making the change to HMLV has been the need to offshore high-volume component production due to decreased costs and customer demands for consumer product customizations and options. High-volume producers are able to specialize their production facilities to improve efficiency and decrease the cost to components. Those components are then used to produce the more customized solutions that consumers are looking for. The demand patterns also shift rapidly and therefore require quick custom product turnaround. The result has been an increase in HMLV manufacturers in the U.S. while high-volume production is more preferred in foreign manufacturing facilities where continuous production with unskilled labor is more cost effective [22].

This research will not focus on reducing the consumer product variation and customization that makes HMLV manufacturing necessary. That variation is the result of a specific sales philosophy that has allowed manufacturers in the U.S. to continue to grow despite the stiff foreign competition on low-cost production. Additionally, instead of focusing on low-cost, many U.S. manufacturers have focused on the customer driven product customization that high volume manufacturing cannot easily adapt to [15]. Table 1 summarizes the key differences between LMHV and HMLV manufacturing.

Table 1: Summary of Key Differences Between LMHV and HMLV Manufacturing

LMHV Manufacturing (Traditional)	HMLV Manufacturing
Low mix of product in high volumes	High mix of product in low volumes
Economies of scale exist at a part level	Low volume for all parts creates potential for economies of scale only at a process level
Low customization of product	High customization of product
More likely offshore manufacturing (U.S.)	More likely onshore manufacturing (U.S.)
Volume-based cost strategy	Customization-based cost strategy
More typical for unskilled labor	More typical for skilled labor

For this research, a United States HMLV manufacturer will be the subject of study with the intent to implement changes to manufacturing strategies that then serve as a roadmap for other HMLV manufacturers. The specific manufacturer that will be the point of focus for this research has approximately 8,500 active part numbers (and several "inactive"), component machining batch quantities averaging 40 pieces, with many much lower, and assembly batch quantities that are typically between 1 and 24 assemblies. The manufacturing facility consists of approximately 39,000 square feet of machine shop space and 25,000 square feet of assembly plant space (including inventory storage and product testing). This manufacturer employees approximately 100 shop floor employees and 30 office support staff.

In the machine shop area, there is a mix of manual equipment, semi-manual equipment, and fully automated CNC equipment. The main production line consists of primarily CNC mills, lathes, grinders, and hobs. The assembly plant space consists of a component stock room, assembly stations, product test stations, product paint area, and a crating area for shipping. The end product is fire pumps that typically weigh between 500 and 1,000 pounds.

1.1. Industrial Paradigms and Industry State of the Art

To understand the difficulties that HMLV manufacturers experience, we must explore the industrial paradigms (Figure 1) that have benefited more conventional high-volume producers. Each of the following are well-researched manufacturing paradigms commonly used to inspire interventions in the LMHV manufacturing industry.

1.1.1. <u>Just in Time (JIT)</u>

Just in Time (JIT) is a concept that was made popular by Toyota in the early 1970s. The concept focuses on removing "waste" from a process and gets its name from the reduction of work in process (WIP) or, parts arriving at a process "just in time" to be used. The popularity of this concept is not just because of decreased WIP, though. JIT manufacturers have reported positive gains in quality, productivity, and efficiency [42]. By having less WIP, a process can react to component design changes and quality issues very quickly and with relatively little component waste.

For JIT to work properly, with its heavy focus on process efficiency, each step in the process must be highly specialized. Each process must also be carefully orchestrated so that production flows smoothly with little to no disruption. Inventory between operations (WIP) is typically indicative of an uneven flow of product through processes. To achieve this level of process control, highly specialized equipment and a steady demand pattern for the components is needed.

The major hurdle to implementing JIT in HMLV manufacturing is the need for process flexibility. The low production volumes require frequent process changeovers, and the high mix reduces the likelihood that a changeover is from one similar component to another.

1.1.2. Total Quality Management (TQM)

In the 1980s, the concept of Total Quality Management (TQM) was popularized in the United States. Although its origins date to the 1920s when Bell Telephone Laboratories started using statistical controls, it wasn't a widely used concept until Japanese companies, who were driven by low-cost production initiatives, made U.S. companies focus on domestic cost competitiveness. TQM focuses on quality management as a form of cost reduction through standards. These standards are used to control processes, including how to conduct a root cause, corrective action (RCCA) for products or processes when they are deemed "out of control" based on whatever process control has been defined by the company. In the late 1980s, this industrial management strategy gained further popularity with the introduction of complementary ISO (International Organization for Standardization) standards [16].

RCCA methods are more difficult to use in HMLV manufacturing. This is because processes have to be both flexible and "in control" for all of the different components and product lines that those components go into. Additionally, a single component may be used in several different product lines. A small change to that component or process will therefore require a significant amount of investigation to ensure that the change is acceptable for every application that will be affected.

In comparison, LMHV manufacturing allows for standardized equipment that is optimized to produce the small variety of components that it is intended to. The equipment and processes can be fine-tuned to the specific component or product line that they are intended to manufacture. The product can also be optimized to fit the manufacturing process. This allows for significant cost reduction through efficiency gains during the manufacturing process. The standardization efforts in LMHV manufacturing are therefore possible at both the product and the process level [5].

In HMLV manufacturing, low volume production and a high mix of components and products require that the processes used have to be flexible for changeovers and the wide variety of component geometry. Therefore, standardization in a HMLV environment typically only happens at a process level, and to a limited extent, rather than a product level [5].

1.1.3. Theory of Constraints (TOC)

In the 1990s, Eliyahu M. Goldratt introduced a concept known as the "Theory of Constraints" (TOC) [26]. TOC is a management paradigm where the focus is on what the limiting factor of a system is. If we consider this in the manufacturing environment, we will likely identify the constraint as the work area where the most WIP is in front. This may also be considered the "pacesetter" or "bottleneck" for the operation. TOC first identifies that pacesetter and then exploits it by ensuring any non-constraint that is supplying the constraint is not oversupplying it. In other words, we allow the constraint only the production that it can effectively manage and reduce upstream operations to supply at only this level to reduce WIP while reducing downstream operations to only process what the constraint can supply.

After identifying and exploiting the constraint, we can address the constraint and reduce its impact on the overall system. This is typically done through a focused effort that involves specializing the process for the components or products that it is used for. This will then change the pace and increase production. Of course, once we address one constraint, a new one will appear, and we repeat the process. This creates a cycle of continuously improving constraints and allowing the system to be optimized towards higher performance.

In LMHV manufacturing, this typically results in more and more product specialized equipment where the equipment is optimal for the specific product. In HMLV manufacturing, this means continuously improving the flexibility of the equipment. The focus in HMLV is on reducing changeover times and standardizing processes as much as possible for the non-standardized product [30].

1.1.4. Overall Equipment Effectiveness (OEE) and Total Productive Maintenance (TPM)

Originally introduced in Japan in the 1970s, OEE is a performance measure that focuses on ensuring that equipment is producing parts as often as possible. This is done through continuous improvement activities, such as kaizen events, and planned maintenance to ensure that equipment breakdowns are unlikely. Total Productive Maintenance (TPM) measures equipment effectiveness by measuring potential losses (and reduction of them) including availability (breakdowns, changeovers, and adjustments), performance (stoppages, reduced speed), and quality (defects, scrap). In general, OEE works best for measuring single pieces of equipment rather than entire production systems [48].

In HMLV manufacturing, measuring processes by equipment uptime (as suggested by OEE and TPM) is possible. However, the uptime will not be comparable to LMHV manufacturing, where a “world-class” OEE is 85 – 99% [77]. In continuous operations, such as LMHV manufacturing. This percentage of uptime is achievable with specialized equipment and processes. In HMLV manufacturing, uptime of 85% or higher may signify the overproduction of components or products because the easiest way to achieve this score is to reduce the number of changeovers.

1.1.5. Lean Manufacturing and Six Sigma

Lean Manufacturing was made famous by Toyota in Japan in the 1930s after inspiration from production flow at Ford Motor Company. Henry Ford specifically focused on removing waste from the production line of Ford automobiles in the 1910s with the Model T. Although Ford Motor Company achieved marked success using waste reduction methods, market demand for product customizations pushed Sakichi Toyoda (Toyota) to adapt Ford's methods and create a production line that allowed for these light customizations [56].

In the 1950s, United States manufacturers took notice of Toyota's success in adapting the Ford methodologies in manufacturing. From these adaptations came concepts such as JIT, single-minute exchange of dies (SMED), and "pull" systems. With production levels increasing, quality controls became more crucial so that a single source of defect would not affect large volumes of products. This created rise to Six Sigma concepts in the 1980s when they were adopted by General Motors, and Motorola [21].

Six Sigma is a means of statistically controlling processes. The premise is that quality values, like feature tolerances, tend to fall on a normal distribution curve when the process was "in control". When the process requires correction, the distribution is skewed. This allows manufacturers to focus on process corrections only when necessary, rather than constantly adjusting processes which can be expensive and unnecessary. This is also a departure from traditional measurements, such as defects per million, which don't provide in-process quality controls and allow for corrections to keep the process in control [45].

Lean and Six Sigma are typically used together for these reasons. They are also an obvious combination of previous industrial paradigms. Many of the concepts are transferable in any environment. However, in LMHV manufacturing, the focus is on product standardization that then allows for better process control. In HMLV manufacturing, standardization can be achieved at a process level but the need for product customizations requires that process flexibility be a focus. Lean manufacturing is a typical starting point for HMLV manufacturers. However, traditional measures, such as equipment uptime must be measured differently to avoid "waste" as defined by Lean concepts. "Waste" includes transportation, inventory, motion, waiting, overproduction, over-processing, defects, and skills.

Examining the types of waste in Lean with the HMLV manufacturing lens, we can start to see that the concepts, although beneficial, must be redefined to enable the flexibility required of HMLV, and adjustments to the measurements used to define success. Below is an examination of the 8 wastes in Lean and how the traditional applications in LMHV manufacturing must be adapted for HMLV manufacturing environments.

Transportation

Transportation waste includes the transporting of people, tools, inventory, equipment, components, or products. Reducing transportation involves finding the shortest possible route for any of these to travel. This is typically achieved with specialized equipment where components or products are processed complete and do not have secondary operations. In LMHV manufacturing, a typical approach is to create a component or product "line", such as an assembly line where specific operations are performed at each station or stopping point in the line [35].

In HMLV manufacturing, the high mix of components and products, and the wide variety of processes that they go through makes it difficult to design a layout that reduces transportation. One approach used in HMLV manufacturing is to create work “cells”. Work cells may be comprised of various types of equipment that are capable of performing multiple types of processes. Components and products will then be grouped by what processes need to be performed to manufacture them. For instance, several components may require turning operations and then milling operations. These components may have very few similarities in form but can be grouped into the work cells based on the processes needed to manufacture them. This then reduces transportation waste [38].

Inventory

Inventory includes raw materials, WIP, components, and products. A typical method for addressing inventory is to receive raw materials just before they are needed and load-leveling production operations to reduce WIP and decrease throughput time. This is more easily achieved when component and product demand patterns are stable and predictable. It is also more easily achieved when the entire production flow can be scaled to meet demand (up or down) at the same time [66]. Fluctuation in demand is typically managed through fluctuation in labor resources. For instance, a company may add labor (people or overtime) when demand is up and reduce labor (no overtime, layoffs) when demand is down.

In HMLV manufacturing, demand is rarely stable [30]. This is because of the wide variety of components and products being manufactured. If we consider that HMLV manufacturing is characterized by a large variety of components and products at relatively small volumes, we can then understand the complexity of managing production in this environment. There will be no piece of equipment that makes only one component (or a small number of components). Balancing the work across the entire production system is complicated because of the number of potential components and products that must be produced [5].

In addition to the complexity of managing the production operations, the low volume for any given component in HMLV manufacturing also reduces any potential benefits that may come from economies of scale on the supply side for raw materials [9]. Additionally, the more customized a component or product is, the more likely it is that a lower number of potential suppliers for raw materials exists. This means that the inventory of raw materials increases due to potential lead time or lack of availability. Component inventory also increases because of the complexity and inefficiencies inherent in the production environment and the need to meet the product lead time that the customer expects [1].

Motion

Motion waste is the unnecessary movement of people, equipment, or machinery. The focus is on the efficiency of movement where anything necessary to the manufacture of the component or product is positioned in an easily accessible place. In LMHV operations, this will be apparent with items such as tooling positioned directly above where the point of use is. It also means that inventory is available to the laborer or equipment with little to no motion [10].

In HMLV manufacturing, the number and variety of potential components reduces the ability to use concepts such as point-of-use storage. It is also difficult to specialize work areas for a specific component or product. As mentioned previously, one potential solution to this issue is the creation of work cells. However, these work cells, given the need to maintain flexibility, are not likely to achieve the same level of efficiency gains that can be seen in LMHV manufacturing [18].

Waiting

Waiting as a waste includes labor resources waiting for equipment and equipment waiting for labor or materials (idle). This can also include labor resources waiting for proper instructions to begin the manufacturing operation. In LMHV manufacturing, waiting waste is typically handled through workload leveling, simplified, visual instructions, and error-proofing methods such as poka-yoke. Each operation is designed to reduce the training required to perform the process and allow for labor resources to be moved to where they are needed with very little production loss due to training [10].

In HMLV manufacturing, some of these same methods can be used to reduce waiting waste. Cross-training is a typical method used to reduce the impact of labor shortages and move resources to areas where work is needed [79]. However, cross-training is a difficult task when considering the amount of flexibility that each process has due to component and process variations. It is also more likely that equipment is not duplicated because of the number of different operations that need to be performed in the facility. This requires a more technically skilled workforce for operations labor or a more robust front-end technical staff that provides specialized instructions, error-proofed jig and fixturing methods, and readily available support for troubleshooting issues during manufacturing operations.

Overproduction

Overproduction waste occurs any time that some or all of a manufacturing operation occurs before it is needed for the next step in its process. This could mean machining the first operation for a component before the next operation is available to process it. It is typically evident with large volumes of WIP or finished components or product inventory. In LMHV manufacturing, this is controlled through workload leveling across operations and significant planning to ensure that methods such as JIT are practiced. It is also more easily controlled in environments where demand does not fluctuate significantly.

In HMLV manufacturing, overproduction occurs for multiple reasons. Fluctuations in demand, including large swings in the product mix required, as well as difficulty in load leveling operations due to a large number of different components and products, contribute to overproduction [20]. Some of this can be managed through modular product design where components and subassemblies are more standardized across product lines. Another method is to hold inventory in the form of raw materials rather than finished components or goods. Raw materials represent a lower cost in inventory than components or products that have had labor applied to their value.

Over-Processing

Overprocessing waste occurs when a component or product has been processed more than required or uses more inputs than required. For instance, a component machined to a finer surface finish than the application requires would be overprocessed [4]. For a product, overly complex assembly processes or product features that are not required by the customer are overprocessed.

In LMHV manufacturing, this is more easily controlled because products have little customization and can be manufactured with continuous operations. The end user's needs have been pre-determined and a product line that represents a "one size fits all" is more likely.

In HMLV manufacturing, customizations that drive the low volumes and high mix of components and products make standardization difficult without over-processing [45]. For instance, when creating a component that can be used in multiple applications, the likelihood of features that are not used for all applications is higher. An example of this is a housing that requires a drain. The housing can be rotated based on the application. The drain must be at the bottom of the assembly. To make a single component work in multiple applications, multiple drains would need to be machined, and based on the application, the orientation of the housing would determine which drain is used. The others would be plugged. Machining multiple drains and plugging the unneeded ones is overprocessing.

Defects

Defects are when a component or product cannot be used because of imperfections and/or nonconformity to the intended design. These are typically controlled by process changes or adjustments or by component or product design that reduces the possibility of defects [63]. One way this may be done is through the use of specific raw materials. For instance, a forged metal material could be used in place of a cast metal material to remove the possibility of air or other contaminant inclusions. Defects can also be reduced through error-proofing methods for manufacturing such as specialized jigs and fixtures.

In LMHV manufacturing, alternative raw material processes are frequently used [53]. However, dies for forged materials and components are cost-prohibitive below production volumes that cannot overcome the break-even point of the initial investment. It is also possible to design processes that are specialized for the operation that they are intended to perform. For instance, in assembly-line style production, a single operation may be optimized with specially designed tooling fixturing. Processes can be refined based on component or product volume through the line which allows for continuous improvements.

In HMLV manufacturing, production volumes frequently prohibit the use of raw material processes such as forgings or die casting. Frequent changeovers, with the intent of operational flexibility, also require more detailed analysis to be optimized for the wide variety of components or products that will undergo the operation.

Skills

Skills as waste are labor-centric. It occurs when labor resources are working below their potential. It is one area where HMLV manufacturing has intrinsic advantages over LMHV manufacturing. If we consider the constant refinement to optimize processes and error-proof operations in LMHV operations, we can understand that the result is that less and less skill is needed by the human labor resource. Although this is beneficial when hiring labor resources because specific skills are not required, it also reduces the input that the human labor resource has in how the operation is performed. Many LMHV manufacturers implement continuous improvement events such as kaizen events to engage the workforce. An engaged workforce results in a happier workforce that then increases production numbers, decreases defects, and improves overall company culture [60].

In HMLV manufacturing, labor resources are typically highly engaged because of the ever-changing processes that they must perform. This means that skilled labor is more critical in

HMLV manufacturing, which then drives up labor costs [62]. One approach that a HMLV manufacturer may take to combat this is to strategically implement front-end processes, such as engineering, to drive down the need for direct high skill labor input.

1.1.6. Quick Response Manufacturing (QRM)

Quick Response Manufacturing (QRM) focuses on reducing lead times throughout an enterprise (internal and external). The goal is to rapidly respond to customer requests for customized products through design and manufacturing. QRM is based on four concepts: (1) the power of time, (2) organization structure, (3) system dynamics, and (4) enterprise-wide application [71]. Because of their abstract and broadly applicable nature, the concepts of QRM have been applied extensively outside of manufacturing.

QRM focuses on identifying and improving the critical path for an enterprise while creating or maintaining flexibility. This begins with the customer order and the external supply chain rather than focusing only on internal production. “Flexibility” is also a somewhat vague term and not all types of flexibility are appropriate or beneficial [78].

QRM, considering the similarities to predecessor paradigms, is a logical next step that HMLV manufacturers can take where LMHV manufacturers may see their maximum benefit with the implementation of Lean and Six Sigma practices.

1.1.7. Industry 4.0

Industry 4.0 is a term being used to describe what is referred to as “the fourth industrial revolution.” To focus of Industry 4.0 is process integration and product connectivity to facilitate higher industrial performance [12]. This represents a premise that a “connected” system through technology will provide significant advancements for manufacturing and other industries. The expectation is that the connectedness will provide real-time flexibility to improve strategic and operational decision-making [6].

As an example, a connected shop floor would provide large amounts of data such as process tolerances in real-time, production levels, preventative maintenance, etc. That data could then be analyzed and used to adjust processes before they are out of control. The skills needed to effectively manage this type of manufacturing environment differ significantly from the traditional production worker skill set. An argument could be made that this also provides an opportunity for workforce skill advancement that provides more job satisfaction by reducing manual labor and improving critical reasoning skills.

A connected shop floor would also provide advantages in scheduling where the data collected would allow for a computerized version of load-leveling across equipment and work cells when coupled with enterprise resource planning (ERP) software [45]. The cost to implement such a system may be prohibitive for some manufacturers. In many cases, aged equipment is in use and creating the ability to connect that equipment to gather data will require a substantial upgrade or replacement.

1.2. Exploring Paradigms for Experimental Applications in HMLV manufacturing

Having now reviewed the key concepts and paradigms in manufacturing, the following chapter aims to provide an analysis of existing literature on industrial paradigms and their potential application in HMLV manufacturing. By understanding the benefits and challenges of these paradigms, experimentation can be used in a HMLV environment to determine the applicability and whether similar benefits to LMHV manufacturing can be achieved.

Given the high degree of variability that is characteristic of HMLV environments, strict implementation of industrial paradigms designed for high-volume manufacturing may not always be appropriate or effective. Therefore, the experiments that will be conducted will be inspired by these paradigms and are not meant to represent strict implementations of the paradigms. The inspiration from these paradigms will serve as a guide for HMLV manufacturers to experiment and adapt these principles to their unique manufacturing environment.

2.1. State of the Art for HMLV Manufacturing

In HMLV manufacturing, the production flow can seem chaotic. There are rarely dedicated "production lines" and the information needed to produce the large variety of components and products is overwhelming. Figure 2 shows a sample process flow in the HMLV environment.

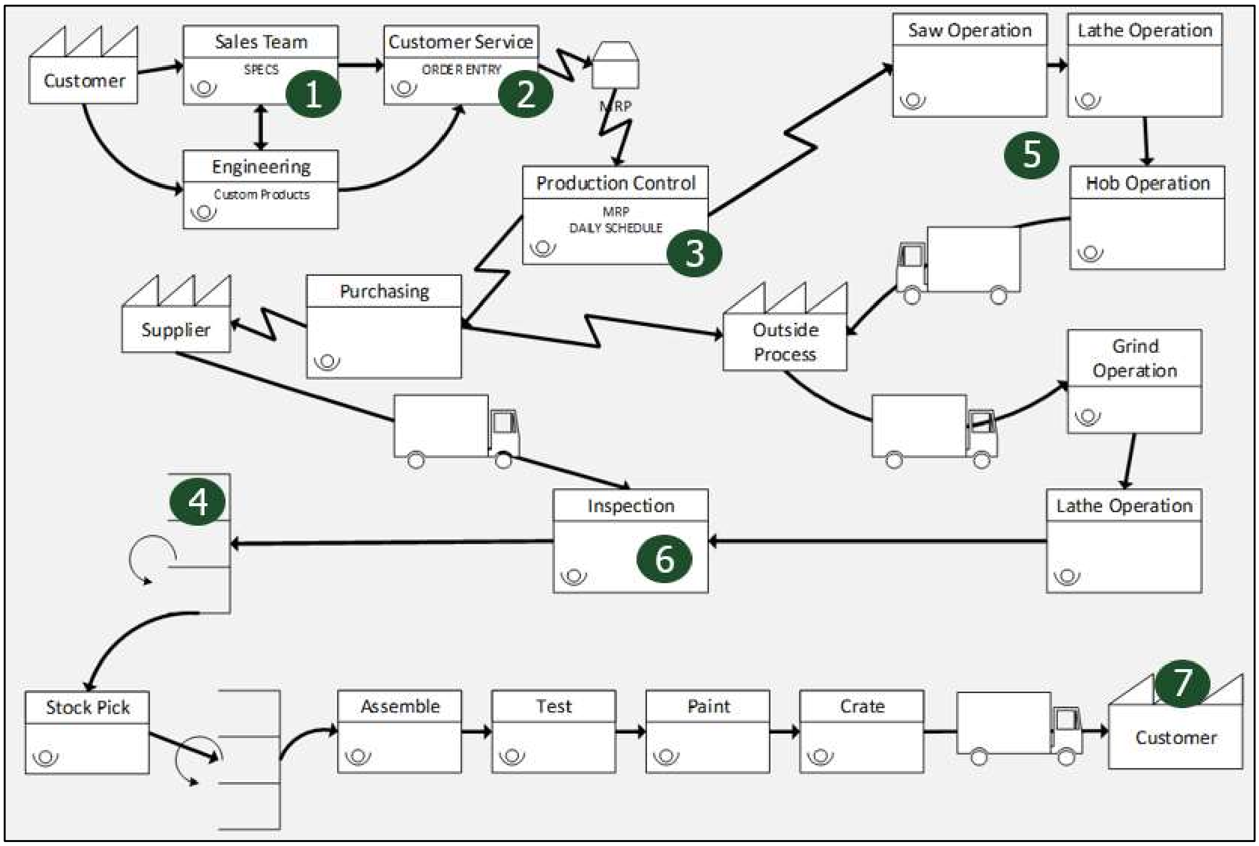


Figure 2: Sample Process Flow in HMLV Manufacturing

Going through a sample value stream (Figure 2), for HMLV, we can identify the points where challenges arise in HMLV manufacturing.

2.1.1. Sales Philosophy (1)

The sales philosophy for HMLV manufacturing, as noted above, is the result of a need to satisfy customer demand for customized products. This is an essential component of ensuring that U.S. manufacturers have a competitive advantage compared to foreign high-volume producers. The sales focus is to provide such things as custom configurations and private labeled products [13].

The main disadvantages to the HMLV sales philosophy are cost and lead time. Customizing solutions is costly because it means establishing a highly trained production staff (skilled labor), engineering solutions frequently, and potentially carrying high levels of inventory to accommodate many different product variations [45].

2.1.2. Customer Order (2)

With the large number of product offerings, customer order processes can be complex and require a large and highly technically trained sales team and customer service team facilitates the order entry process. The creation of new offerings must constantly be weighed against the cost to produce and the return on investment for the development/ engineering costs [72].

The HMLV manufacturer that this research will be conducted at also focuses heavily on product quality which includes supporting legacy product for as long as it is in service. In some cases, this can be decades. This adds another layer of complexity to the need to carry high amounts of inventory to support legacy products.

2.1.3. Production Scheduling (3)

With relatively small batch sizes for all components and consumer products, HMLV production scheduling is a balancing act to try to keep products flowing through production. Components may be scheduled at work centers to be machined based on the product that was produced before them to reduce machine change over times by reducing the number of tools or fixtures that need to be changed over. The time to change over a work center is critical because it represents equipment downtime and the small batch sizes mean that the cost of that downtime is amortized over a small number of components, adding directly to the per piece cost [75].

There are also issues with overproduction when we attempt to reduce the impact of the work center change over time. The traditional method for doing this is to increase batch sizes. The production scheduler may therefore pull in production demand over a longer period of supply. This means that many of the components being produced will sit in inventory for a longer time. This also means that the machine is overproducing components that are not immediately needed while pushing production for needed components further back in the production schedule.

2.1.4. Inventory Control (4)

Inventory management in a HMLV environment requires that a large number of different components are carried in the correct quantities [18]. Adding to the complexity are demand variability and support for legacy products. Additionally, when the consumer product is made to be modular, the safety stock levels at the component and subassembly level must cover the many different products that they could potentially be used for. Each of those products will have its own demand variations.

It is also difficult to manage work in process (WIP) because of the uneven loading that varied and volatile demand creates for equipment and work cells. There are often multiple value streams feeding single work cells which makes prioritization more difficult [18]. To reduce the number of product changeovers, schedulers will often increase batch sizes to pull in demand from longer periods of supply. This compounds the issue of WIP because the equipment is then making more of something than what is needed to cover the demand in the current production window.

2.1.5. Internal Processing (5)

Similar to the inventory control issues in HMLV manufacturing, overall internal processing requires that predictions about future demand are made. This can sometimes be done based on historical demand patterns but is often made more difficult by unpredictable demand [25]. Internal processing is also subject to external factors such as raw material supplies. When these are interrupted, then internal processing is rushed when materials arrive, and scheduling is severely disrupted.

Internal processing is also subject to many accounting controls that may counteract other cost reduction efforts [38]. For instance, a piece cost, determined by standard accounting practices, is the cost of the run time (actually creating the piece) combined with the time to set up the work cell to make that piece divided by the batch quantity. In practice, this encourages larger batch quantities as a per piece cost reduction strategy and increases the potential to overproduce.

Overhead costs in HMLV manufacturing are also regularly misrepresented at a per piece level. Overhead includes all of the costs associated with "keeping the lights on" at the facility. This includes everything from the equipment operation costs to the taxes that are being paid to continue to do business. This also includes indirect labor costs such as office resources. Capturing these costs gives a way to measure overall operating expenses and is therefore necessary. It also leads to cost reductions in areas where it may not make sense. For instance, increasing indirect costs, such as wages for additional engineering staff, may reduce direct labor costs substantially [37].

2.1.6. Quality Control (6)

Quality control in HMLV manufacturing is a complex process. In many cases, components will be used across multiple products and the quality levels required may vary based on the application [40]. This means that components must be produced based on the highest level of quality required for any application. This leads to overprocessing in many areas and increases component costs for applications where the quality level used is not the level required.

With the many applications for single components, it is difficult to engineer components and many changes may be needed throughout the component lifecycle. These changes are also difficult and time-consuming considering the wide range of applications that must be considered.

Quality control is also difficult due to a large number of different components [55]. Equipment must be used that is often overly capable for the component that is being produced because it must be used for other, more complex, and higher tolerance components. It is difficult to standardize processes with the large mix of components and this leads to a significant emphasis on highly skilled production staff. Compounding this are the large training cycles needed with the variation and high skill level when standardization is difficult to achieve.

2.1.7. Shipping (7)

Although the process of shipping the product is somewhat standardized, the product variations make the packaging process more difficult. Each product requires packing that is specific to the configuration and is therefore difficult to mass-produce. Depending on the scale of the product, this may mean specialized shipping containers that are built only when the product is through the production processes.

The other difficulty in order fulfillment comes from the customized nature of the product. Finished goods cannot easily be made in advance of a customer order and this eliminates a potential option to ship the product using a first-in-first-out (FIFO) methodology [38].

2.2. Baseline Understanding

The largest contributor to the difficulties that HMLV manufacturers experience when attempting to gain operation efficiencies is the complexity and customization of the product. When we consider the existing industrial paradigms that have benefited high volume manufacturing, the majority suggest that standardization is the best means to increase process efficiency. This can only be done to a limited extent in HMLV manufacturing before the main point of growth is then stunted. Offering customized products is where HMLV manufacturers are able to thrive. Reducing the ability to customize will reduce this growth.

In HMLV manufacturing, there are opportunities to standardize to an extent [2]. The real measure of efficiency in this environment is, however, the ability to pivot between products and incorporate customized options. This measure must be considered throughout the entire product lifecycle and must include internal and external factors such as the supply chain. There is an opportunity to further expand on the existing research and determine the best methods for HMLV manufacturers to achieve high levels of efficiency, in the form of lead time reduction, cost reduction, and quality controls.

2.3. Review of Current Literature

The purpose of this literature review is to provide an understanding of conventional manufacturing paradigms and propose application methods for HMLV manufacturing environments. To define the application methods, an exploration of the barriers that exist to implementing traditional management methods in HMLV manufacturing must be conducted.

The Need for HMLV Manufacturing

In the United States, manufacturing continues to be an integral part of the economic sector [8]. Overall, being a producing nation adds to society's wealth, increases innovation, and raises the standard of living [54]. Manufacturing in the United States has generated more economic activity than any other sector with current estimates showing manufacturing contributing over 12% of the total GDP and putting the U.S. in second place (behind China) in manufacturing value per capita [74].

There are many advantages to onshore production, and these have been further highlighted with the recent pandemic Supply chain issues have stymied many industries in the manufacturing sector and the need for flexible operations has become more apparent [52]. Low-mix high-volume manufacturing offshore has been significantly impacted by supply issues where highly specialized equipment that allows for mass production with a pedestrian workforce cannot maintain output [7]. Additionally, the inability to shift production output quickly, such as the product line offering, has prevented these operations from growing in the changing economic landscape.

United States Manufacturing has been most competitive in the global economy in the areas of research and development (R&D) and design-based activities, and least competitive in scale-based and standardized activities [50]. Capitalizing on the current competitive advantage, an opportunity exists for U.S. Manufacturers to further their lead in R&D and design-based activities. This has contributed to the steady rise of high-mix low-volume manufacturing in the

U.S. [71]. This has also highlighted the need to better understand how HMLV manufacturing fits into competitive strategies that focus on productivity increases, quality controls, and flexible operations [37].

To understand where the specific opportunities exist, we must first understand the significance and application of the industry paradigms that have so far assisted in revolutionizing manufacturing both in the U.S. and abroad [24]. Next, we must identify the key performance metrics that have been used to determine manufacturing competitiveness and understand how they apply in a HMLV manufacturing environment. Lastly, identification of current barriers that exist when applying industry paradigms that have been largely developed for low-mix high-volume manufacturing to HMLV manufacturing will provide a baseline for further development [61].

Current paradigms

The manufacturing and industrial landscape in the United States has undergone many transformations. We are currently in what is considered the "fourth industrial revolution" which is a transition to digitized production [80]. The focus is on implementing "smart" technologies to make gains in production, cost, and quality. HMLV manufacturing is making continuous efforts to integrate shop floor production by allowing machines to communicate with and learn from each other [11]. This revolution is a fascinating glimpse into what many consider the future of manufacturing operations. However, the technology to bring all factory operations online is expensive and cost-prohibitive for many manufacturers. This is especially true in high mix manufacturing where there are many more variables for consideration, only increasing costs further [69].

Indeed, many of the industrial paradigms that have benefited high volume manufacturing have had limited applications in HMLV manufacturing. The focus has been on standardizing products and processes to allow for a narrowed focus and then streamlining manufacturing operations. With the shift towards more and more customized production operations, this strategy becomes less optimal [40]. Research that promotes operation improvements when there is a need for significant flexibility is sparse and slow to emerge. The next sections examine the literature that has been published, illustrating that there is still a strong need for further investigation and applicable studies to be conducted for HMLV manufacturing [69].

Barriers to Application in HMLV Manufacturing

Reviewing industry paradigms and the introduction of the many "tools" that have been used to increase manufacturing flow, there is a place in all manufacturing for such concepts as Total Quality Management (TQM), Theory of Constraints (TOC), Overall Equipment Effectiveness (OEE), and Lean Manufacturing. The basic principles of each of these are applicable in every environment. The problem in HMLV manufacturing is realizing the full benefits of these approaches. There is a point where they can no longer be optimized because of the product and process complexity that makes further improvement through standardization cost-prohibitive [40].

One approach that may provide the best benefit to HMLV manufacturers is to implement a hybrid solution where any potential "higher volume" products and processes follow one optimization plan and the "lower volume" follows another [23]. Although all production in HMLV falls into the "low volume" category compared to traditional manufacturing, there are distinctions that manufacturers typically make for "repeat business" versus "one-off". This distinction could be used to categorize the type of production and therefore the approach to improving it. To do this, the Lean Manufacturing method of value stream mapping (VSM) could be applied at a system level rather than a product level [51]. Specialized software would be required to create the VSM for HMLV applications [22].

Once a VSM is completed for the entire system, hybrid solutions can be applied. For instance, the portions of the system that have higher volume flow could be streamlined using more traditional methods such as line production. The portions of the system that have lower volume flow and/ or higher variability, could be made more modular, allowing specialized processes on a smaller scale. Another challenge is that these modular components are subsystems that then interface with the overall production system [22].

Taking this conceptual production flow further, Goldratt, in his Theory of Constraints (1990) contends that the best option for streamlining a system is to focus on the constraint(s) that they contain, exploit them, and then improve them [31]. This same thinking applied at a whole system level, and within the bounds of HMLV manufacturing, can be used to begin to level first the subsystem (work cell) and then the component level flow. This method is reminiscent of Lean Manufacturing methodologies that focus on the elimination of "waste" to eliminate the constraint.

Lean Manufacturing (Lean) provides another basis for further research in the environment of a HMLV manufacturer [76]. The traditional implementation of Lean methods has involved high levels of standardization for both the product and the processes that are used to make it. Adapting Lean methodologies to HMLV manufacturing requires a stronger emphasis on process improvement than product standardization. The basic Lean principle of "flow", where sequential manufacturing operations are optimized for throughput, can be adapted to HMLV applications at a process level and, subsequently, at a system level.

Dr. Irani, President of Lean and Flexible LLC, a consulting company in Houston, TX has examined the challenge of Lean in HMLV manufacturing. Dr. Irani calls his approach "Job Shop Lean" where specific Lean principles, such as 5S, standard work, and product and process standardization are used to create flow on the manufacturing floor. He developed a software (PFAST) that is capable of examining thousands of part routings based on where the product physically travels during manufacturing operations [39]. This then gives insight into how the manufacturing floor should be organized, such as machine placement, to improve flow and reduce the wasted motion of travel for the product [37]. This methodology could provide the base for the proposed hybrid system if used for the "higher volume" or "repeat" production in HMLV manufacturing. It is an elegant solution to the typical concerns for implementing Lean in HMLV environments where value streams are extremely complex, creating difficulty in achieving efficient product flow. It does not, however, easily address the "one-off" production that also occurs in this environment [27]. This demand is unpredictable and difficult to manage, typically consuming a large number of resources [70]. It is also necessary because the lower volume production represents the highly customized portion of customer demand that is steadily growing.

Modular production operations (rather than traditional line production) have also offered many advantages for HMLV manufacturers. Using this methodology, manufacturers break their production processes into work "cells" that group operations to provide flow for lower volume production [53]. This can be done by either grouping products based on product families or based on similarity in processing. Cellular manufacturing essentially creates subsystems that are then managed individually. The creation of these subsystems also allows for simplified system-level scheduling. The positive impact of cellular manufacturing has been demonstrated by many manufacturers. It allows the complexity of HMLV manufacturing to be scaled down and be more easily managed [49]. Given the complexity and volatility in production demand, the flow between the cells (subsystems) must also be considered. Dr. Irani suggests Lean tools such as first-in, first-out (FIFO), pacemaker scheduling and product-specific Kanban have been demonstrated to be poor choices for HMLV operations [36]. However, other literature suggests Kanban is a typical tool used when continuous flow is not possible. Kanban between cells is used for ease of scheduling operations rather than WIP reduction [56]. Kanban is also intolerant of demand volatility and, using the standard Lean toolset, scheduling can be positively impacted but the cost is higher WIP which means higher costs with higher inventory carrying costs [43].

The natural conclusion that many HMLV manufacturers come to through a Lean "transformation" is that flexibility is difficult to achieve with the focus on product standardization [19]. To further productivity increases, quality controls, and flexible operations, HMLV manufacturers must look beyond the implementation of Lean tools for solutions to operations variability. The variability in the production system can be classified as either dysfunctional variability or strategic variability. Dysfunctional variability is the result of errors, poor organization, and ineffective systems. This is the type of variability that a HMLV manufacturer should focus on eliminating. Strategic variability is purposeful, and the intent is to maintain or gain a competitive advantage. Managing strategic variability will also reduce the dysfunctional variability [71].

Quick Response Manufacturing (QRM) is the suggested next step after a HMLV manufacturer has implemented the Lean tools that apply to their operations. QRM shifts the focus from manufacturing “touch time” (process time per operation) to the Manufacturing Critical Path Time (MCT). MCT focuses on reducing the total lead time, measured in calendar days rather than traditional Lean or cost accounting “value-added” time [68]. The biggest advantage to this measurement as a performance indicator is that any state of a product, including time in inventory when complete is considered part of the MCT. This then broadens the effort to also reduce inventory, which is a major concern when applying traditional Lean techniques in HMLV manufacturing. Improving efficiencies in operations, such as is done with traditional Lean, neglects the majority of the actual MCT. In most cases, the “value-added” time is less than 10% of the total time in the VSM [32], leaving a huge opportunity for improved throughput [71].

Throughput gains, using QRM and Lean, come from the elimination of waste and reduction of MCT [67]. Additional metrics of cost and quality are also necessary, but it is important to remember that there is a potential for “trade-off” that must always be considered. Improving one metric must be a carefully considered process where it does not lead to then negatively impacting another. In HMLV manufacturing, the added metric of flexibility can make improvements in the other metrics more complex [43].

With the amount of complexity that is apparent in HMLV operations, the introduction of technology to manage that complexity can be both beneficial and difficult to maintain [28]. Since a large amount of the product is customized, standardization that allows for easier improvement of processes is not as likely.

In manufacturing, Industry 4.0 has been focused on the use of technology and the interconnectedness of machines and systems to improve operations. Many emerging techniques examine and make use of the availability of information. As industries shift towards more customized products, the focus remains on value creation, but the definition of value also shifts. Applying technologies allows manufacturers to transition between products and production systems more readily. This presents a potentially significant advantage to HMLV manufacturers if the cost to implement can be justified [14].

Manufacturers must also focus on adjusted performance metrics to fully realize the benefits of technology adoption. In HMLV manufacturing, competitive advantage is not measured by the volume of output alone. Instead, the ability to absorb new technology, create manufacturing flexibility, efficiently adopt iterative design cycles in both product and process, and share knowledge between production and engineering become a stronger measurement of competitive advantage. All of this is done through integrated technologies where the lines become blurred between the physical system and its digital profile [73].

Potential Optimizations

From this survey of existing literature, there are a few potential opportunities that become apparent for HMLV manufacturing. First, the identification of the correct performance metrics for this environment is necessary. There are multiple potential opportunities for metrics as identified by the existing literature. Focusing on improved throughput, quality, and cost, these can be distilled into categories as represented in table 2.

Table 2: Preliminary Proposed Research Metrics and Their Means of Optimization Interventions

Metric	Potential Interventions
Throughput/ Lead time	• Shift to QRM principle of MCT • Design cycle optimization • Flexibility – measured by the ability to shift between products and processes • Strategic variability

Quality	• Visual controls/ management • Percentage of scrapped parts due to internal processing errors • Percentage of scrapped parts due to external processing errors • First pass yield of the product tested
Cost	• Employee engagement in product and process development and refinement • Decreased lead time • Decreased carry costs (WIP, Stock, etc.)

Not all of these interventions are amenable to the HMLV manufacturing environment. Metrics that are counterproductive to HMLV manufacturing include any measurements that address only one measurement of effectiveness. For instance, lead time to a customer can be shortened with finished-goods inventory on the shelf (for the "repeat orders". However, this also leads to higher carrying costs for inventory. The proposed metrics to remove are listed in Table 3.

Table 3: Proposed Metrics Interventions to Remove as Measures of Effectiveness

Metric	Interventions Not Applicable to HMLV Manufacturing
Throughput/ Lead time	• Value Stream Mapping that focuses only on "value-added" time or direct costs • Pacemaker scheduling • Inventory supermarkets – such as finished goods on the shelf to reduce lead times to the customer from order
Quality	• Rework – this should not be included in the % of parts that are not considered "scrap"
Cost	• Customer lead time that includes the shipment of product in inventory • Percentage of product "saved" through rework

Third, the identification of optimization methods for HMLV manufacturers to use is needed. This presents a research opportunity where methods are applied at a HMLV manufacturer, and the resulting metrics are compared. To define this, significant consideration should be given to the holistic nature of HMLV manufacturing. If we consider each of the cells as representing a subsystem, and the MCT representative of the process lifecycle, we can understand that there are additional opportunities to use Systems Engineering (SE) practices and principles, coupled with enablers defined by other industrial paradigms, to improve the HMLV metrics of throughput, cost, and quality.

An approach to manufacturing operation optimization using SE guidelines has been suggested by Oppenheim through the use of enablers from Lean principles [58]. Given that, as suggested by the existing literature, Lean is a prelude to optimization techniques in more flexible environments, such as HMLV requires, Oppenheim's defined methodology can serve as a guideline for implementation approaches. One of the major advantages of SE practices is the focus on requirements to define the system. In the case of HMLV manufacturing, those requirements are defined by throughput, cost, and quality with an emphasis on flexibility and, therefore, competitive advantage.

Oppenheim asserts that the basic Lean principles, used within the context of SE, still provide merit. These include value, mapping the Value Stream, flow, pull, perfection, and respect for people. Beginning with these, adjusting for the manufacturing environment, and considering the extra requirement in HMLV manufacturing of flexibility, we can begin to develop an applicable model through experimentation.

The specific opportunity for this research is to provide experimental evidence that SE, enabled by Lean, and adjusted for HMLV environments, inspired by alternative industrial paradigms, has the potential to assist HMLV manufacturers in gaining competitive advantage [65].

Using real-world applications at a subject HMLV manufacturer, this research seeks to understand the barriers that HMLV manufacturers face when applying traditional industrial paradigms to production operations. Doing this presents an opportunity to build an applicable framework for these manufactures where industrial paradigms that have benefited LMHV manufacturers can be used for similar benefits in HMLV manufacturing environments. Figure 3 illustrates the process flow for the experimental design for this research.

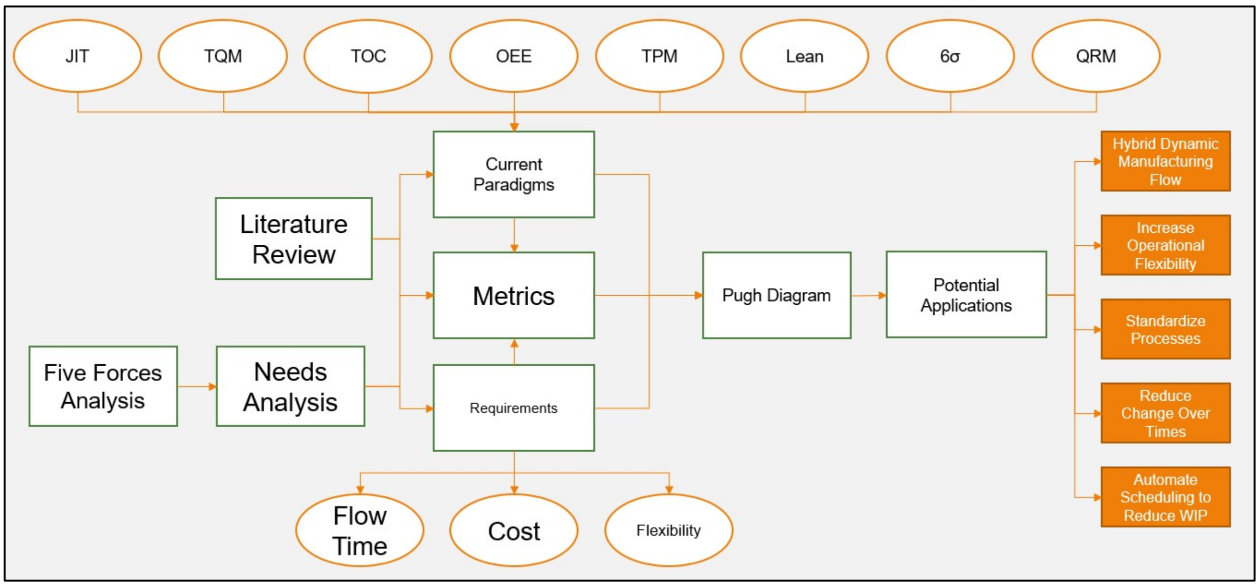


Figure 3: Experimental Design Process Flow

Based on the survey of existing literature for current industrial paradigms and the Needs Analysis (see Appendix A) at the subject manufacturer, the following hypotheses for experimentation have been defined:

- Existing industrial paradigms can selectively be used to inspire applicable Systems Engineering practices, and refined to improve flexibility, flow time, and cost in HMLV manufacturing.

a) It is hypothesized that this can be tested by first determining the requirements for HMLV manufacturing, deriving metrics, and then comparing those to existing industrial paradigms.

b) It is hypothesized that the comparison process will yield success factors, that can then be distilled into applicable project-based testing.

c) The project-based testing will then provide a roadmap for transferrable applications.

- Defining an approach for the use of adjusted SE principles for the sample applications defined will allow potential transferable processes for other applications at the subject manufacturer.
- The subject manufacturer and the successful application of practices will provide a framework that can be reused in additional manufacturing sectors where HMLV manufacturing occurs.

Using real-world applications at a subject HMLV manufacturer, this research seeks to understand the barriers that HMLV manufacturers face when applying traditional industrial paradigm philosophies to production operations.

4.1. Research Question 1

Research question 1 seeks to use a scholarly literature review method to provide an understanding of conventional manufacturing and lean manufacturing as applied in a HMLV environment. This question pushes the research to identify barriers that the dominant approaches have while proposing and testing proper metrics for measuring the performance of the manufacturing system by determining metrics that are beneficial and removing those that are counterproductive. Research question 1 is posed as follows:

Using a literature review method, what are the comprehensive set of manufacturing philosophies that have been considered in managing, optimizing, and enabling HMLV, and what is the consensus in the field on their application and success?

Inputs to this research question include a survey of the current state of the art as represented in published literature. Observational and experience-based input will be included to determine how existing industrial paradigms can be used in HMLV manufacturing and where they cannot.

This research is intended to understand the implementation of various paradigms that act as enablers within a Systems Engineering context.

Research Tasks

Task 1: Identification of existing literature for review that is representative of the work to date for improving operations in HMLV manufacturing.

Task 2: Group existing literature based on the industrial paradigm suggested in the literature for use in HMLV manufacturing.

Task 3: Articulate findings and identify potential applications for HMLV manufacturing, including possible test scenarios.

Task 4: Determine measurement techniques for successful implementation of paradigm(s). These include throughput, cost, quality, and flexibility.

Based on the requirements of HMLV manufacturing and the existing industrial paradigms, Figure 4 illustrates the comparison process and defines the additional projects that are worth exploring. A complete table of comparisons can be found in Appendix A.

The following paradigm definitions were used in the decision-making process [59]:

Just in Time: A manufacturing system in which materials or components are delivered immediately before they are required to minimize inventory costs.

Total Quality Management: A system of management based on the principle that every staff member must be committed to maintaining high standards of work in every aspect of the company's operations.

Theory of Constraints: A methodology for determining the most important limiting factor in a production system (the constraint), exploiting the constraint to become the pacesetter for the system, and then improving the constraint.

Overall Equipment Effectiveness: A scoring method used for mechanical equipment that considers availability, performance, and quality to determine effectiveness.

Total Productive Maintenance: A holistic approach to maintaining equipment in manufacturing to achieve the maximum possible production levels.

Lean Manufacturing: An ideology used in manufacturing to maximize productivity while minimizing waste within the system.

Six Sigma: A set of management techniques intended to improve business processes by greatly reducing the probability that an error or defect will occur.

Quick Response Manufacturing: A strategy to reduce lead times in every area of operations (office and shop) while optimizing responsiveness to change for the system.

		Requirements							Paradigms								
Candidate Process	**Description**	**F1: Minimize purchased goods lead time**	**F2: Minimize manufacturing flow time**	**F3: Maintain legacy product support**	**F4: Maintain customized product**	**F5: Maximize operational flexibility**	**F6: Reduce cost**		**Just in Time (JIT)**	**Total Quality Management (TQM)**	**Theory of Constraints (TOC)**	**Overall Equipment Effectiveness (OEE)**	**Total Productive Maintenance (TPM)**	**Lean Manufacturing (Lean)**	**Six Sigma**	**Quick Response Manufacturing (QRM)**	**Description of Decision Making**
Hybrid dynamic manufacturing flow	Separate ultra-low volume from main production flow	N/A	+	+	+	+	+		N/A	-	+	-	-	-	-	-	Hybrid dynamic flow is ideal for HMLVmanufacturing. It allows for efficiency gains in the main product flow
Increase operational flexibility	Improve flexibility in process changeovers, workforce, and product	N/A	+	+	+	+	+		-	+	-	-	+	+	-	+	Define measures of flexibility and optimize
Standardize processes	Focus on process rather than product standards	N/A	+	+	+	+	+		+	-	-	+	+	+	+	+	Process standardization instead of product maintains production customization options
Reduce change over times	Time to switch between products	N/A	+	+	+	+	+		+	-	+	+	+	+	+	+	Reducing changovers is always beneficial because changeovers are indirect time
Automate scheduling to reduce WIP	Load leveling operations to reduce material between operations	N/A	+	+	+	+	+		+	-	+	+	+	+	-	+	This makes sense overall. There is little downside and implementation costs would be offset by reduced indirect labor input.

Figure 4: Down selected candidate projects compared to requirements and paradigms

4.2. Research Question 2

Research Question 2 seeks to determine the scope of application for a sample set case study. The research proposes to implement the industrial paradigms that have been suggested based on existing literature within the manufacturing system under test. The results of this process will be the experimental findings to begin to build an applicable model for HMLV manufacturing. This leads to the following research question:

Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms *provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?*

Research Inputs

Inputs to this research question will include the previously conducted literature review, a Needs Analysis derived from the relevant stakeholders, a set of proposed metrics of manufacturing system performance (derived from RQ1, Task 3), and experimental access to the HMLV manufacturing environments.

Research Tasks

Task 1: Using the metrics derived from Research Question 1, determine the specific measurement method to be used.

Task 2: Within the unaltered experimental HMLV manufacturing system, document the baseline measurement for each metric, including the metrics that were identified to be removed in Research Question 1.

Task 3: Determine the application scope for the HMLV environment, including a specific area of focus (product, process, or combination).

Task 4: Implement suggested paradigm changes using the hypothesis defined in Research Question 1 as the baseline.

Task 5: Measure output metrics from activities.

Task 6: Determine correlations between implementation methods and metrics measured. Derive beneficial and detrimental practices for HMLV manufacturing based on the output metrics.

Task 7: Begin to articulate an applicable model to be used in HMLV manufacturing

4.3. Research Question 3

Research Question 3 seeks to define the paradigm application methods that provided the highest potential to contribute towards the needs defined by the subject manufacturer. The goal is to create a model for implementation of the determined industrial paradigms for HMLV manufacturing based on the research findings. This leads to the following Research Question:

> *Using a needs analysis to determine specific requirements and applying existing industrial paradigms in a real-world setting based on the potential to satisfy those needs determined, what paradigms provide promising results for further research?*

The inputs to this research question will include the literature review conducted, the Needs Analysis, and the results of the application of the various industrial paradigms.

Research Tasks

Task 1: Document correlations determined between metric outputs and the implemented paradigm(s)

Task 2: Determine the "best case" application of traditional industrial paradigms for high-mix low-volume manufacturing.

Task 3: Determine the scalability of the application outside of the subject manufacturer. This includes potential barriers to application based on potential differences between manufacturers within the classification of HMLV manufacturing.

Task 4: Define a suggested application model for further implementation in HMLV manufacturing environments.

Organization of Paper

Table 4: Paper organization by Research Question and Task

Research Question	Task	Description	Chapter
RQ1	Task 1	Determine state of the art	1: Introduction
	Task 2	Determine applicable paradigms	1: Introduction
	Task 3	Identify potential applications	2: Review of Literature
	Task 4	Determine metrics	2: Review of Literature
RQ2	Task 1	Determine measurement methods	3: Research Design and Methods
	Task 2	Document the baseline	4, 5, 6, 7, 8: Experiments
	Task 3	Determine experiment scope	4, 5, 6, 7, 8: Experiments
	Task 4	Implement paradigm(s)	4, 5, 6, 7, 8: Experiments
	Task 5	Measure experimental outputs	4, 5, 6, 7, 8: Experiments
	Task 6	Determine correlations	4, 5, 6, 7, 8: Experiments
	Task 7	Preliminary applicable model	4, 5, 6, 7, 8: Experiments
RQ 3	Task 1	Document correlations for all experiments	9: Presentation of Research (Results)
	Task 2	Determine "best case" application	10: Summary, Implications, Conclusions
	Task 3	Determine scalability	10: Summary, Implications, Conclusions
	Task 4	Define suggested applicable model	10: Summary, Implications, Conclusions

Chapter IV: Experiment 1: Hybrid Dynamic Manufacturing as a Theory of Constraints Application Method

HMLV manufacturing operations present unique challenges for manufacturers as they balance the need for flexibility and customization with the need for efficiency and competitiveness in the form of lower costs and lower lead times. Although various industrial paradigms have been suggested in existing literature, it is not clear which of these paradigms provides the strongest potential for improving these metrics.

The following experiment has been designed to use a controlled and systematic approach to evaluate the impact of the application of a defined set of paradigms to the key performance indicators of throughput, cost, and flexibility. This includes the definition and measurement of the components of each of these indicators.

This experiment is the first of (5) that will seek to answer the following research question (Research Question 2):

> *Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?*

For an illustration of the experimental design for Experiment 1, see Appendix E, Figure 34.

4.1. Description:

As a means to evaluate the effectiveness of TOC (Theory of Constraints) methodology in enabling improvements within a HMLV environment, an experiment was conducted to determine if a constraint in the main production line could be resolved by removing work from that area and processing it in an offline cell. This offline cell represented a much lower up front capital expense in comparison to the production line work centers. This cell will be referred to as the "ultra-low volume" cell or "LV". TOC asserts that reducing the number of setups in the main production line and therefore increasing the number of parts that could be produced, along with the added production from the LV cell would provide an overall cost and productivity benefit. This benefit would be offset by the cost of this LV cell. Manufacturing of the LV components on equipment that wasn't optimized for the process would reduce efficiency and raise the cost based on standard costing methodology.

The LV work cell outside of the main production line was created to manufacture components considered ultra-low volume. This work cell consisted of manual and semi-manual equipment such as a conversationally programmed mill and manual lathe. This equipment represented a relatively low capital investment in comparison to the computer numerically controlled (CNC) equipment used in the main production line.

Over the course of a 3-month period, this area was evaluated to be used to manufacture ultra-low volume components to offload the main production line.

4.2. Paradigm(s):

Application of TOC in HMLV a manufacturing environment is more complex than in LMHV manufacturing where the specific constraint(s) are more easily identified through the examination of standard work and single value streams. In HMLV manufacturing, numerous and converging value streams means that, although constraints can be identified by WIP, the effect of reducing the constraint can be difficult to measure. There is process complexity that forces a systems level view, rather than a single value stream, to understand the cost and resultant value created.

This experiment is motivated by the use of TOC, which aims to remove constraints from the main production flow. In this experiment, the constraint was identified as a mill machining center where components are manufactured that are considered ultra-low volume or are better classified as job shop style production and cause disruption such as additional setups and shorter runs. The production volumes are extremely low even in comparison to the low volume in normal production work. These batch sizes may be 1 – 5 components that are manufactured less than twice in a 3-year period.

4.3. Bounds:

This experiment focused on components for a specific product line. This particular product was in the process of being replaced by the next generation of the product. During development, the R&D (LV) version of the components were manufactured in ultra-low volumes. Because of this opportunity, approximately 10 years of production data was reviewed to create a baseline that could be used to measure the experimental data against. This was the best possible opportunity for direct comparison because of the substantial similarity of the existing components to the new components of this product.

4.4. Metrics:

To effectively assess the impact of the application of the defined paradigms, the metrics and the specific measurement method have been defined for this experiment (RQ2, Task 1).

The metrics for this experiment were determined based on the classic metrics used by the TOC literature [26]. The measurement methods, however, were adjusted to suit the specific HMLV environment in which the experiment was conducted. These metrics included:

Throughput (PPH) or (PPH(T)): Throughput is defined as the quantity of components that were manufactured over a set period of time. For this specific experiment, throughput will be measured by the number of components manufactured per hour over the experiment period.

Inventory ($(T)): Inventory is a measurement of the cost to carry raw materials, partially completed components or products, and complete components or products. During the manufacturing process, value is added to components by each operation. Components and products waiting between operations will have different values based on their percentage of completion. Inventory is the sum of all values of all components in production.

Cost ($): Cost can be calculated for all measures of time and materials, including overhead. For instance, the cost of equipment used in production is different than the cost of the equipment used in the ultra-low volume cell.

All metrics were distilled to 2022 USD for the purpose of comparison between the baseline and the experiment. Throughput was converted to USD by determined the part value (PV = profitability) created over the time period of the experiment (PPH).

4.5. Experimental Design:

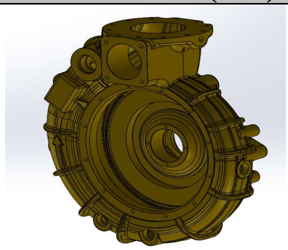
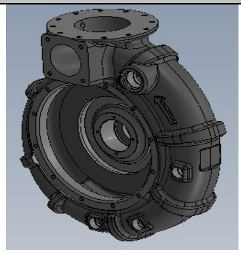
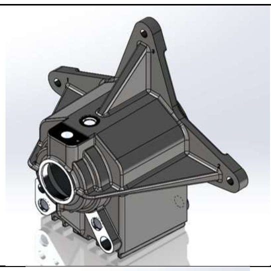
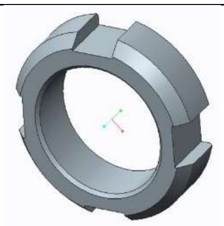
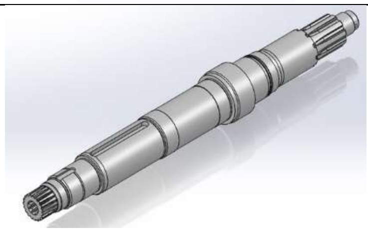
This experiment measures the costs and benefits of the ultra-low volume components that were manufactured. To do this, an ultra-low volume work cell was created that included smaller, semi-automated or fully manual equipment. This equipment was selected based on the capability to perform the operations required to manufacture the LV components. Figure 5 shows this work cell and its location on the production floor.

Figure 5: Ultra-Low Volume Work Cell (Ex 1)

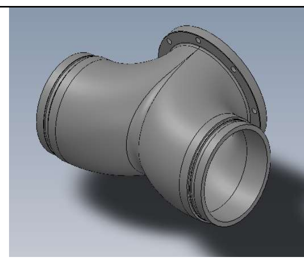
A set of specific components was chosen to be manufactured in the LV cell. These components needed to be manufactured in quantities of 3 for the purpose of research and development testing before being added into the main production line. Once in main production, these components would be manufactured in much larger quantities as the replacement components for a baseline product. For each experimental component, a baseline component was selected. Table 5 shows the physical comparison between the ultra-low volume R&D

components and the predecessor components for the product that they will replace (and had been in the main production area for over 10 years).

Table 5: Comparison of Ultra-Low Volume R&D Components to Substantially Similar Production Components (EX 1)

Component	Main Production (MP)	R&D/ Ultra-Low Volume (LV)
Pump Casing		
[1]Inboard Head/ Transmission Case		
Locknut		
Impeller Shaft		

[1] The inboard head from the main production line and the transmission case from the ultra-low volume R&D components, although not visually similar, have substantially similar operations performed to them during the manufacturing of the components.

Discharge Extension		
Companion Flange		
Suction Tee		

The metrics used to be measured in both production and the LV cell (production + LV) are defined in Table 6. For the purpose of this experiment, the “ultra-low volume” area is denoted by the “LV” subscript. The main production line is denoted by the “MP” subscript.

Table 6: Experiment variables descriptions and definitions for (EX 1)

Variable	Definition	Measurement Method
H_{MP} [hr]	Hours in the main production line	Hours in main production were determined based on the number of work hours available in a 3-month period (the comparison period for the experiment). 80 hours per week * 4.3 weeks per month * 3 months = 1032 hours available per machine over a 3-month period.
H_{LV} [hr]	Hours in the LV cell	Hours in the ultra-low volume cell were determine based on the number of work hours available in a 3-month period. In

		this area, only 1 operator is used (516 total hours in 3 months).
IW_{LV} [$(hr)]	Inventory value in WIP in the LV cell	Hours in the LV cell were determined based on the number of work hours available in a 3-month period. 40 hours per week * 4.3 weeks per month * 3 months = 516 hours available per machine over a 3-month period.
IW_{MP} [$(hr)]	Inventory value in WIP in the main production line	Inventory value in WIP between operations in main production with applied overhead multiplier for the average number of days parts are in WIP (between operations in main product = 4.44 days average). Inventory value was measured at 5 increments over the 3-month experiment period and then averaged to determine the dollar value typically in WIP.
M_{LV} [-]	Number of machines in the LV cell	This is the number of machines in the ultra-low volume area (2).
M_{MP} [-]	Number of machines in the main production line studied	This number of machines in main production was determined based on the machines that were used to manufacture the production parts that provided the best comparison to the R&D components that were manufactured in the low volume cell for the study. This was 16 machines.
OH_{EX} [-]	Overhead multiplier for the experimental period (3 months)	Multiplier for overhead to represent the overhead multiplier accounting for the 3-month experimental time period (1 year = 25%, therefore 3 months = 6.25%)
OH_{LV} [$]	Overhead for the parts produced in the LV cell (3 months)	Overhead for the parts produced in the ultra-low volume area over the 3-month period and multiplied by the overhead constant.
OH_{MP} [$]	Overhead for the parts produced in the main production line (3 months)	Overhead for parts produced in main production determined by number of hours in production multiplied by the overhead constant.
O_{LV} [-]	Number of operators in the LV Cell	The number of operators in the ultra-low volume area used to operate the machines.
O_{MP} [-]	Number of operators in the main production line	The number of operators in the main production area used to operate the

		machines that were within the scope of the experiment.
OW_{MP} [$/hr]	Operator wage in main production line	Operator wage in main production is considered a constant value that is $1.00 per hour less than the operator wage in the low volume cell.
OW_{LV} [$/hr]	Operator wage in the LV cell	Operator wage in the LV area is considered a constant value that is $1.00 per hour more than the operator wage in the main production line.
PPH_{LV} [1/hr]	Parts per hour produced in the LV cell	Determined based on the 2 machines studied over the 3-month period. Production information was gathered to determine the number of parts each machine produced per hour and then averaging this data. The result was 0.8 PPH for the 2 machines in the LV cell that were studied.
PPH_{MP} [1/hr]	Parts per hour produced in the main production line	Determined based on the 16 machines studied over a 10 year period. Production information was gathered to determine the number of parts each machine produced per hour and then averaging this data. The result was 7.51 PPH for the 16 machines in the main production area that were studied.
PV_{LV} [$]	Part value for parts produced in the LV cell	Part value in the LV cell determined by taking the average selling price multiplied by the parts per hour produced and the number of hours per machine in the LV cell over the 3-month period and the number of machines within the experiment scope (2 machines in the LV cell).
PV_{MP} [$]	Part value for parts produced in the main production line	Part value in main production determined by taking the average selling price multiplied by the parts per hour produced and the number of hours per machine in main production over the 3-month period and the number of machines within the experiment scope (16 machines in main production).

Using these variables, the following formulas were used to measure the defined metrics for the baseline and the experiment:

Throughput (F) = Measured value based on part completions over the course of the experiment

Inventory (C_I)= IW * OH_{WC} * OH_{EX}

Cost (C_P) =

Baseline:

[1] $(OW_{MP} * H_{MP} * OH_{MP})+(H_{MP} * OH_{MP} * OH_{MP})+(IW_{MP} * OH_{MP} * OH_{WIP})$

Experiment:

[2] $(OW_{MP} * H_{MP} * OH_{MP})+(H_{MP} * OH_{MP} * OH_{MP})+(IW_{MP} * OH_{MP} * OH_{WIP})+(OW_{LV} * H_{LV} * OH_{LV})+(H_{LV} * OH_{LV} * OH_{LV})+(IW_{LV} * OH_{LV} * OH_{WIP})$

Value (V) =

Baseline:

[3] $V_B = (PPH_{MP} * PV_{MP} * M_{MP})H_{MP} – (OW_{MP} + OH_{MP})H_{MP} – IW_{MP}$

Experiment:

[4] $V_{EX} = ((PPH_{MP} * PV_{MP} * M_{MP}) + (PPH_{LV} * PV_{LV} * M_{LV}) H_{LV} – (OW_{MP} + OH_{MP} OW_{LV} + OH_{LV})H_{LV} – IW_{MP} – IW_{LV}$

For comparison of the baseline to the experimental treatment, Table 6 describes the components of the cost and benefits of each treatment. Table 6 shows how costs were added or subtracted for both the baseline metrics and the metrics after the LV Cell was added. The components in Table 7 are representative of Equations [1], [2], [3], and [4]:

Table 7: Metrics summed to determine overall value for baseline versus experiment data (EX 1)

Baseline – Equations [1] and [3]			
+ (Benefit)		**(Cost)**	
Value added in PPH in main production over 3-month period	$PV_{MP}*PPH_{MP}*H_{MP}*M_{MP}$	Direct labor paid in main production over the 3-month period	$OW_{MP} * H_{MP} * OH_{MP}$
		Overhead in main production per hour over the 3-month period	$H_{MP} * OH_{MP} * OH_{MP}$
		Value of inventory between operations	$IW_{MP} * OH_{MP} * OH_{WIP}$

		in main production multiplied by carrying cost (OH constant over time period)	
Experiment – Production operations with Ultra-Low Volume Cell – Equations [2] and [4]			
+ (Benefit)		**(Cost)**	
Value added in PPH in main production over 3-month period	PV_{MP}*PPH_{MP}*H_{MP}*M_{MP}	Direct labor paid in main production over the 3-month period	OW_{MP} * H_{MP} * OH_{MP}
Value added in PPH in low volume over 3-month period	PV_{LV}*PPH_{LV}*H_{LV}*M_{LV}	Direct labor paid in low volume over the 3-month period	OW_{LV} * H_{LV} * O_{LV}
Value of PPH_{MP} gained by offloading to ultra-low volume cell	186 parts * PV_{MP}	Overhead in main production per hour over the 3-month period	H_{MP} * OH_{MP} * OH_{WIP}
		Overhead in low volume per hour over the 3-month period	H_{LV} * OH_{LV} * OH_{WIP}
		Value of inventory between operations in main production multiplied by carrying cost (OH constant over time period)	IW_{MP} * OH_{MP} * OH_{WIP}
		Value of inventory between operations in ultra-low volume cell multiplied by carrying cost (OH constant over time period)	IW_{LV} * OH_{LV} * OH_{WIP}

4.5. Baseline Measurements:

To effectively evaluate the impact of the defined paradigms, it was necessary to establish a baseline measurement for each metric. The baseline was used to provide a starting point from which to assess the effectiveness of each paradigm and draw meaningful conclusions about their potential for improving the defined metrics (RQ2, Task 2).

As part of the baseline definition, the scope for the experiment was defined (RQ2, Task 3). This provided a means to define the specific area of focus while allowing the experiment to be tailoring to the specific needs of the HMLV manufacturing environment.

Throughput

Over the 3-month period that the experiment took place, the work centers in the production line where the production components were monitored for throughput. An average of the number of parts per hour that each work center completed was determined. Those work centers and their corresponding throughput values in number of components per hour are listed in Table 8.

Table 8: Work center average parts per hour produced over the 3-month experimentation period (Ex 1)

Work Center (WC)	PPH
0003	28.32
0009	4.52
0043	5.57
0062	1.80
0065	17.16
0071	1.74
0101	23.97
0104	9.06
0215	2.81
0219	0.29
0222	4.65
0223	3.25
0224	3.51
0228	1.93
0226	4.16
0502	7.42

Inventory

There were multiple contributors to inventory during this experiment. For each work center, the inventory value waiting to be processed was determined at 5 intervals during the 3-month period. The data for this is shown in Table 9.

Table 9: Inventory Value (USD) waiting to be processed at Each Work Center at Each Measurement Interval during the 3 Month Experiment (EX 1)

	Inventory (WIP, USD)				
Work Center (WC)	**12/23/2022**	**1/12/2022**	**2/12/2022**	**3/2/2022**	**3/20/2022**
0003	1663.35	2661.17	1198.92	1830.93	1415.33
0009	726.82	1111.77	941.32	458.69	234.61
0043	1205.62	827.37	565.94	1219.02	749.80
0062	220.25	932.70	1134.76	448.16	181.94
0065	101.51	412.73	1716.98	619.57	259.51
0071	0.00	78.52	119.70	0.00	0.00
0101	8577.22	6475.29	9764.65	5084.86	734.48
0104	1061.02	662.66	687.56	317.92	127.36
0215	3601.53	6637.13	4905.78	6565.31	4521.79
0219	1676.76	2665.00	3378.41	2838.33	2080.86
0222	33748.70	25393.64	17674.42	25403.21	5340.54
0223	9759.86	14222.28	13208.18	11177.11	12249.62
0224	24812.37	11666.44	18511.37	22473.91	1110.82
0228	14897.38	18133.11	16329.95	14470.29	430.92
0226	23806.89	16233.24	18106.30	23631.65	10061.50
0502	12715.97	10005.96	13544.29	14575.63	830.24

Cost

The overall cost for the baseline scenario was determined using Equation [1]. This is illustrated in Table 9.

4.6. Experimental Measurements:

Having determined the baseline measurements for the experiment, changes were made to the manufacturing process in accordance with TOC and adjusted to the HMLV manufacturing environment (RQ2, Task 4). Once implemented, the metrics and their components were measured to determine how the application of TOC principles impacted the metrics (RQ2, Task 5).

For the experiment, Equation [2] was used where the LV cell value was added to the value of the main production line. The LV cell manufactured additional components outside of the main production line as well as allowing the main production line to manufacture additional components per hour by reducing setup time.

Table 10 shows all calculated values for the metrics that comprise Equations [1] (for the baseline) and [2] (for the experiment). From these metrics, the overall value creation[2] can be seen for the baseline ($6,203,742.88) and the experiment ($6,480,817.71).

Table 10: Calculated values for contributors to overall value, translated into USD for the baseline and experimental data (EX 1)

Baseline Metrics					
Description	+		**Description**	-	
Part Value Created MP	$PPH_{MP}*H*M*PV_{MP}$	$6,503,711.91	Operator Wage MP	OW_{MP}	$217,875.84
			Overhead MP	OH_{MP}	$76,017.12
			Inventory Cost MP	IW_{MP}	$6,076.07
	Sum of Benefits	$6,503,711.91		Sum of Costs	$299,969.03
				Total Value	**$6,203,742.88**
Experiment Metrics					
Description	+		**Description**	-	

[2] A major contributor to overall value creation (profit margin) was downstream operational efficiencies. An overall assessment was done to determine which percentage of components would ultimately be sold as parts (60%) and which would be used to assemble a finished product (40%). A multiplier was then used to account for downstream operation efficiency to determine actual value of the components as part of the overall business.

Part Value Created MP	PPH_{MP}*H *M*PV_{MP}	$6,503,711.91	Operator Wage MP	OW_{MP}	$217,875.84
Part Value Created LV	PPH_{LV}*H *M*PV_{LV}	$170,956.99	Operator Wage LV	OW_{LV}	$14,133.24
Production Gain MP	Gain PPH_{MP}	$156,082.64	Overhead MP	OH_{MP}	$76,017.12
			Overhead LV[3]	OH_{LV}	$35,402.76
			Inventory Cost MP	IW_{MP}	$6,076.07
			Inventory Cost LV	IW_{LV}	$428.81
Sum of Benefits		$6,830,751.54	Sum of Costs		$349,933.84
Total Value[4]					**$6,480,817.71**

4.7. Reflection

Comparing the baseline and the experimental measurement, correlations between the applications of TOC and the metrics were determined (RQ2, Task 6). These correlations began to define an applicable model for best practices in improving the metrics for HMLV manufacturing using TOC (RQ2, Task 7).

The overall cost to operate the LV cell during the 3-month experimental period was approximately $50,000 which includes labor and overhead. The value that the LV cell added was approximately $327,000. As shown in Figure 6, the LV cell, combined with the operating costs and value creation of the main production line, along with the additional time available for the

[3] The overhead for the LV cell was difficult to determine. This manufacturer had some unique building features that changed the cost for the location of the LV cell compared to the cost to construct the building in the main production area. Other considerations include power usage per machine, skill level needed to operate the machine, operator wage, and the overall production flow that contributed to unlevel machine loading and WIP values between operations.

[4] Cost to implement the LV cell can also be determined by summing the operator wage (OW_{LV}), the overhead (OH_{LV}) and the cost of WIP (IW_{LV}).

main production line to produce parts when offloaded to the LV cell, the overall production gain was approximately 4.5%.

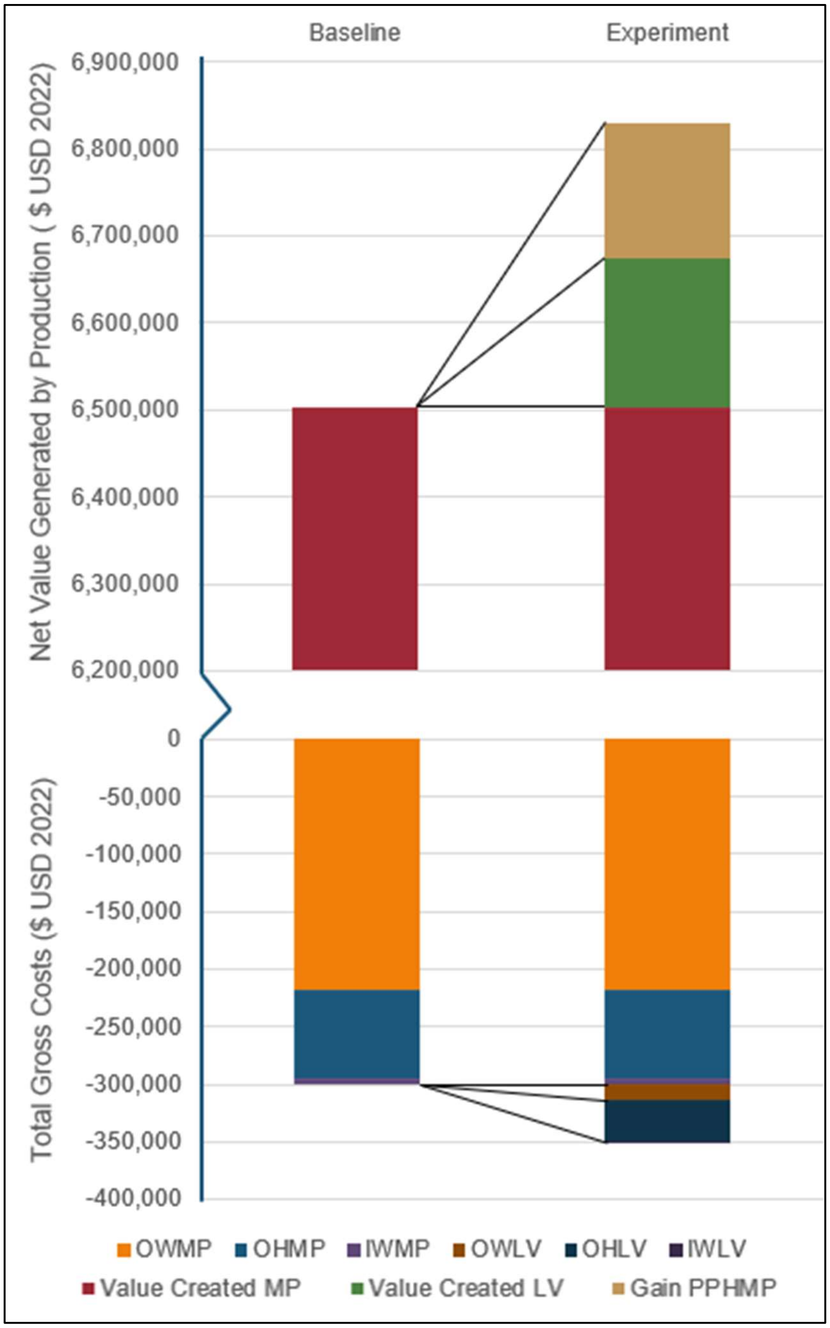


Figure 6: Cost to implement LV Cell compared to Value created vs Cost and Value Without LV Cell (Ex 1)

If standard cost accounting methods were used to determine the effectiveness of implementing the LV cell, the per component cost would be significantly higher due to the time to manufacture the component with semi-automated equipment. The added cost, when considered as part of the overall value is, however, offset with the gain in production in the main production line.

In summary, the addition of the LV manufacturing cell improved the performance of the main production line. Even considering the costs associated with operating the LV cell, plant-level productivity improved by 4.5, and a net benefit of $277,074.82.

4.8. Experiment Conclusions

This experiment provides evidence that TOC is a viable means to improve the metrics of throughput, inventory, and cost in HMLV manufacturing environments. Within the given experimental period, value produced exceeded the cost and increased the overall value creation.

The LV cell relieved some of the production constraints, and the low value return batch sizes in the main production line and, therefore, the main production line was able to gain efficiencies in the number of parts produced per hour. The LV cell was also an addition to production where parts were manufactured outside of the main production line. Based on the defined metrics, the process used could be used on additional ultra-low volume components for this manufacturer. There are over 700 components that would fall into this category.

There is an opportunity to continue to monitor the success of the LV cell over a longer period. This would determine if the experimental results could be shifted by increasing the volume of components and, therefore, potentially increasing the amount of WIP that would detract from the value created. It is also important to note that, during the 3-month experimental period, the production demand (levels and variation) was unpredictable and presented no discernible pattern. This was compared to a longer baseline period, using 10 years of production data and it was found that the same chaotic demand was present over a longer period of time. Although it was determined that the experimental period was, therefore, representative of "normal demand conditions", the specific manufacturer where the experiment took place did not offer the opportunity to test the experiment parameters in conditions of more predictable or leveled demand.

In this experiment, a suitable solution to the production constraint was found by offloading the main production line. However, there were notable scenarios that would have potentially provided a different outcome. For instance, the processes needed to manufacture the components from the main production line in the LV cell were scalable so that the implementation cost (cost of equipment) was not substantial compared to adding addition production equipment. The workflow was also, as noted, consistent with "normal production" during the experiment period. This contributed to the confidence level of implementing the LV such that it would not be overwhelmed with production and become a new bottleneck.

Chapter V: Experiment 2: Increase Operational Flexibility Using Adaptable Machining Fixture Methods

This experiment is the second of (5) that will seek to answer the following research question (Research Question 2):

Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?

This experiment expands the scope of paradigm application through the inspiration of multiple paradigms at the same time. This experiment was designed to exploit the similarities in these paradigms to achieve the goal of improving the metrics of cost, throughput, and flexibility. The four paradigms chosen provide a common emphasis on continuous improvement through the entire manufacturing life cycle, have a focus on customer needs and expectations, emphasize the elimination of waste in all forms, use data to drive decision making, and emphasize standardization as a means to improve quality.

For an illustration of the experimental design for Experiment 2, see Appendix E, Figure 35.

5.1. Description:

To evaluate the effectiveness of Total Quality Management (TQM), Total Productive Maintenance (TPM), Lean Manufacturing (Lean), and Quick Response Manufacturing (QRM), an experiment was conducted to determine if machine changeover times could be reduced in a

HMLV manufacturing environment using modular fixturing techniques. This experiment focused on component families that were machined in batches per component on a CNC mill (machining center). This machining center will be referred to as WC215.

In HMLV manufacturing, setup reduction is a focus but must be looked at differently than in LMHV manufacturing. When setups are reduced in variety, as they are in LMHV manufacturing, then the cost allowable to develop that setup can be greater, as it can spread that cost across a large volume of manufactured items. In LMHV operations, setup change times are typically measured in minutes or seconds, and this is done by creating highly specialized equipment or processes for the specific component. In HMLV operations, there is a much greater need for flexibility in the setups, so that they may be used for a larger variety of components. This leads to setup times that are longer than in LMHV operations and the setup time for a batch is converted to cost and spread across a much lower quantity of components. This indicates that there is a need to understand how the above-mentioned paradigms, which largely focus on quality and reduction of setup time might be applied in HMLV manufacturing to provide a cost-benefit that is a balance between reduction in setup time and the cost required to provide that reduction.

Another major difference in HMLV manufacturing compared to LMHV manufacturing is how equipment uptime should be measured. In LMHV, operations are typically continuous. Machines run unattended for longer periods, and uptime is measured against available hours in a day. In HMLV manufacturing, there is a need for greater consideration for flexibility which often means that operator availability is a stronger indication of uptime than machine availability because of the constant shifting demand that causes labor resources to be frequently reallocated. To accommodate this, this experiment utilized the definition of uptime that is defined by QRM where the available machine time is the time that an operator is available to operate that machine [67].

5.2. Paradigm(s):

This experiment is motivated by multiple paradigms that, together, provide similar but more collectively comprehensive metrics for manufacturing. In HMLV environments, TQM, TPM, Lean, and QRM can be more difficult to incorporate due to the lack of repeatability of processes from a component level that comes with higher volume production. The specific manufacturing environment where this experiment focuses has opportunities to reduce WIP between operations for all work centers but the main constraints in manufacturing exist in the milling work centers. For these work centers, the component cycle time is typically much higher than for other types of machines and the setup of the machines takes longer. These factors make these work centers the ideal area of focus to apply these paradigms that focus on improved throughput while maintaining high levels of quality. This experiment will focus on improving the setup time and the flexibility of a single work center, WC215.

5.3. Bounds:

This experiment focused on specific components that were manufactured in the WC215 area. These components belonged to multiple families of similar components and had comparable features and characteristics for component locating that allowed them to be fixtured inside of the machine in a similar way. Consideration was given to the volume of each component to be machined to determine if changing from the dedicated fixture to a modular one would provide a cost benefit (suitable return on investment) if it were to be the process used for new fixture creation going forward. The large number of dedicated fixtures that could only be used for small part groups also had inherent inefficiencies driven by the need keep the cost of manufacturing the fixtures low. These inefficiencies were addressed as part of the experiment through the application of the stated paradigms.

5.4. Metrics:

To effectively assess the impact of the application of the defined paradigms, we can define the metrics and the specific measurement methods for this experiment (RQ2, Task 1).

The metrics for this experiment were determined based on the metrics used under TQM, TPM, Lean Manufacturing, and QRM application. Each of these required further definition so that they could be applied in the HMLV manufacturing environment. These specific metrics, grouped by paradigm are shown in Table 11.

Table 11: Traditional metrics for TQM, TPM, Lean Manufacturing, and QRM defined for specific experimental application (Ex 2)

Metric	Paradigm	Units	Definition
Accuracy (A)	TQM	% P	This is a measure of quality or scrap rate and is determined based on the number of parts scrapped versus the number of parts successfully completed. This value also includes parts that are reworked, or do not positively contribute to first pass yield (FPY).
Cost (C_P)	TQM	USD ($)	This is a measure of the total process cost that includes any costs incurred from the time that the material is allocated to the job to the time that the job is completed (parts logged into stock).
Process Variation (σ)	TQM	σ	This is a measure of the process that represents the variation in set up times that changes the ability of the process to meet the expected completion to stock time.
Parts Per Hour (PPH)	QRM	P	This is a measure of throughput and indicates how many parts per hour a process is able to produce. For this experiment, "process" is synonymous with work center.

Reliability (H_R)	TQM	R	This is a measure of how consistent the process is using variables of time that represent total time on the job versus time the machine is not running (setup, adjustments, etc.)
Labor Hours (H_L)	Lean	H	This is a measure of labor input to the process. This is a combined value for all labor applied whether direct or indirect labor.
Setup Reduction (C_{SR})	Lean	USD ($)	Setup reduction is a measure of time that is converted to cost where the time saved is assumed to provide operator (and machine) availability to produce other components that have a defined value (PV).
Uptime (H_U)	TPM / QRM	% T	This is a measure of machine availability compared to machine usage. For this experiment, the QRM definition of uptime is used where machine availability is based on operator availability to operate the machine.

5.5. Experimental Design:

This experiment was designed to improve the change over time for a critical work center by reducing the time to change between similar, but different components that were manufactured by this work center. To do this, a tombstone style fixture was used. This type of fixture was historically used as a single part fixture. For this experiment, the tombstone was fitted with “mini plates” that could be installed quickly and interchangeable pilot rings that could be used for a wide variety of parts. Figure 7 shows the fixtures before any changes for this experiment, illustrating the set 3 fixtures that are mountable to a conventional 3 jaw chuck. Figure 8 shows the tombstone fixture with a mini plate installed.

Figure 7: Fixtures used for process prior to changes for experimentation (Ex 2)

Figure 8: Tombstone style fixture with mini plate installed using self-centering pins (Ex 2)

The creation of this fixture was completed after a review of the part families that were machined on the chosen work center (WC215). Although the levels and patterns of production demand are difficult to predict in HMLV manufacturing environments, it was determined that this type of tombstone fixturing would allow for the fastest changeover of fixtures between both similar parts and dis-similar parts because of the ability to attach various fixtures to each of the 4 sides. The main tombstone could then be left in the machine and rarely changed. Example components for this experiment are shown in Figure 9 with the pilot diameter surfaces highlighted. This experiment included the manufacture of 35 different suction head part numbers and 17 different inboard head part numbers, all with geometry similar to the components illustrated in Figure 9.

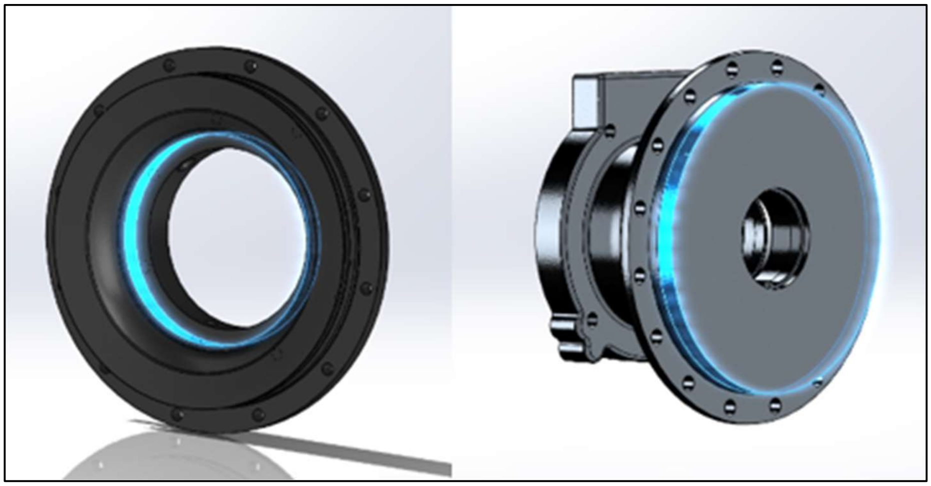


Figure 9: Example Suction Head (left) and Inboard Head (right) with fixture pilot diameters highlighted (Ex 2)

Table 12 defines the variables that were measured during the experiment to calculate the traditional metrics for the applied paradigms.

Table 12: Variables used to calculate defined metrics (Ex 2)

Variable	Definition	Measurement Method
μ	Population mean	Mean of the measured setup times
C_E	Cost of engineering	T_E * Cost per Hour
C_F	Cost of fixtures and components	$C_M + (T_F(OW_F+OH_{WC}))$
C_M	Cost of material	Measured in USD
C_{PR}	Cost of programming	T_P * Cost per hour
C_S	Cost of space	$Ft^2/(\$/Ft^2)$
C_T	Cost of Training	H * Cost per Hour
IW	Inventory value in WIP	Average over experimental period
M_S	Machine Setup Time	Measured in hours
N	Size of populations	Number of values (setup time)
OH_{EX}	Overhead multiplier for the experiment period	Overhead multiplier over experimental period
OH_{WC}	Overhead for work cell	Overhead constant for the work center
OW_{WC}	Operator wage	Operator wage per hour
OW_F	Operator wage for fixture making	Operator wage per hour

Q_B	Quantity of components in batch	Set value per job
Q_S	Quantity of components scrapped in batch	Measured in number of parts not completed from a batch due to quality
T_A	Machine Adjustments	Measured in hours used to make adjustments during machining process
T_E	Labor time for engineering	Hours of labor applied to engineering
T_F	Labor time applied for fixture making	Hours of labor applied for fixture making
T_{IN}	Labor time for inventory	Hours of labor applied to inventory management
T_J	Time operator is on specific job	Hours operator is clocked into a job
T_M	Labor time for material handling	Hours of labor applied to material handling
T_O	Labor time for operator	Hours of labor operator applies
T_{OM}	Time operator is assigned to machine	Hours operator is assigned to a machine
T_G	Machine time spent on good parts	Hours operator is machining (cycle time) parts that are good
T_P	Labor time for programming	Hours of labor applied to programming
T_S	Machine time spent on scrap parts	Hours operator is machining (cycle time) parts that are scrap

Using these variables, the following formulas were used to measure the defined metrics for the baseline and the experiment:

[1] Accuracy $(A) = (Q_B - Q_S)/Q_B$

[2] Cost $(C_P) = C_E(T_E) + C_{PR}(T_P) + OW_F(T_F) + C_M + (IW)(OH_{EX}) + OW_{WC}(T_O) + C_T + C_S + C_F$

[3] Process Variation $(\sigma) = \sqrt{(\Sigma(x_i - \mu)^2/N)}$

[4] Parts Per Hour $(PPH) = Q_B / T_J$

[5] Reliability $(H_R) = 1 - (T_A + T_S) / T_J$

[6] Labor Hours $(H_L) = T_E + T_P + T_F + T_O + T_M + T_{IN}$

[7] Setup Reduction $(C_{SR}) = C_E + C_{PR} + C_T + C_M + C_F$

[8] Uptime $(H_U) = (T_{OM} - (T_J - M_S))/T_{OM}$

5.5.1. Variable Measurements:

To effectively assess the impact of the application of the defined paradigms, the metrics and the specific measurement method have been defined for this experiment (RQ2, Task 1).

To evaluate the impact of the defined paradigms, it was necessary to establish a baseline measurement for each metric. The baseline was used to provide a starting point from which to assess the effectiveness of each paradigm and draw meaningful conclusions about their potential for improving the defined metrics (RQ2, Task 2).

As part of the baseline definition, the scope for the experiment was defined (RQ2, Task 3). This provided a means to define the specific area of focus while allowing the experiment to be tailoring to the specific needs of the HMLV manufacturing environment.

Having determined the baseline measurements for the experiment, changes were made to the manufacturing process in accordance with TQM, TPM, Lean, and QRM and adjusted to the HMLV manufacturing environment (RQ2, Task 4). Once implemented, the metrics and their components were measured to determine how the application of TQM, TPM, Lean, and QRM principles impacted the metrics (RQ2, Task 5).

The 5-month experimental period involved the manufacture of 17 inboard head part numbers, 8 suction head part numbers, and 5 inboard head part numbers. For the components that were manufactured, Table 13 shows the set of baseline measurements prior to the experimental period, and the measurements during the experimental period.

Table 13: Baseline variable measurements (prior to experimental period) for components that were manufactured in the experimental period (of the 35 identified for the new fixture process), and experimental variable measurements (Ex 2)

Variable	Definition	Measurement Method	Baseline	Experiment

μ	Population mean	Mean of the measured setup times	2.17	1.98
C_E	Cost of engineering	T_E * Cost per Hour	$984.00	$156.00
C_F	Cost of fixtures and components	$C_M + (T_F(OW_F+OH_{WC}))$	$5,073.85	$903.67
C_M	Cost of material	Measured in USD	$623.00	$235.00
C_P	Cost of programming	T_P * Cost per hour	$1,440.00	$1,080.00
C_S	Cost of space	Ft^2 * [$250/ sq ft]	$53,750.00	$27,000.00
C_T	Cost of Training	H * Cost per Hour	$420.00	$26.25
IW	Inventory value in WIP	Average over experimental period	$17,885.70	$7,064.23
M_S	Machine Setup Time	Measured in hours	2.17	1.98
N	Size of populations	Number of values (setup time)	19	25
OH_{EX}	Overhead multiplier for the experiment period	Overhead multiplier over experimental period	0.10	0.10
OH_{WC}	Overhead for work cell	Overhead constant for the work center	$77.23	$77.23
OW_{WC}	Operator wage	Operator wage per hour	$26.25	$26.25
OW_F	Operator wage for fixture making	Operator wage per hour	$27.25	$27.25
Q_B	Quantity of components in batch	Set value per job	7.76	7.58
Q_S	Quantity of components scrapped in batch	Measured in number of parts not completed from a batch due to quality	0.08	0.06
T_A	Machine Adjustments	Measured in hours used to make adjustments during machining process	1.2	0.8
T_E	Labor time for engineering	Hours of labor applied to engineering	8.2	1.3
T_F	Labor time applied for fixture making	Hours of labor applied for fixture making	42.6	6.4
T_I	Labor time for inventory	Hours of labor applied to inventory management	1.30	0.60
T_J	Time operator is on specific job	Hours operator is clocked into a job	3.75	3.39
T_M	Labor time for material handling	Hours of labor applied to material handling	6.00	2.40
T_O	Labor time for operator	Hours of labor operator applies	4.08	3.40

T_{OM}	Time operator is assigned to machine	Hours operator is assigned to a machine	9.93	9.56
T_G	Machine time spent on good parts	Hours operator is machining (cycle time) parts that are good	4.97	5.14
T_P	Labor time for programming	Hours of labor applied to programming	12.00	9.00
T_S	Machine time spent on scrap parts	Hours operator is machining (cycle time) parts that are scrap	0.62	0.45

Using the variables from Table 13, the following metrics can be calculated as shown in Table 14:

Table 14: Baseline and experimental metrics calculated using measured variables (Ex 2)

Eq #	Metric	Units	Baseline	Experiment
1	Accuracy (A)	% P	0.990	0.992
2	Cost (C_P)	USD ($)	$65,421.93	$30,400.41
3	Process Variation (σ)	σ	0.69	1.18
4	Parts Per Hour (PPH)	P	2.07	2.24
5	Reliability (H_R)	R	0.51	0.63
6	Labor Hours (H_L)	H	74.18	23.10
7	Initial Setup Cost (C_{SR})	USD ($)	$8,540.85	$2,400.92
8	Uptime (H_U)	% T	0.841	0.853

Based on the metrics, each of which can be distilled to cost as common unit of measure, the total value creation for the baseline and the experiment were determined as shown in Table 15:

Table 15: Comparison of value created during the baseline and the experimental period (Ex 2)

Component of Value	Baseline	Experiment
Total Cost of Parts X Accuracy X 5 Months	-$18,519.10	-$16,236.17
Total Cost of Parts including indirect labor	-$65,421.93	-$30,400.41
Cost of inventory holding between operations	-$4,678.00	-$39,277.81
Hours in 5 months * PPH * average part value	$900,576.76	$972,795.31
Initial cost of setup X Number of setups in period	-$162,276.11	-$60,023.05
Total Value	**$649,681.61**	**$826,857.87**

5.6. Reflection:

As illustrated in Figure 10, the initial cost of setting up the experimental fixture included the tombstone which was higher cost than the baseline fixture plate but could be used for multiple mini-plates and multiple part numbers. The high cost of the tombstone was spread across the total number of mini plate fixtures that would be able to be used with it. This flexibility enabled by the tombstone reduced the overall cost, improved the time to set up each job, and improved the time to train the operator. This reduction in down time for set up improved the uptime for the work center from 84.3% to 85.3%. Because downtime is measured against the time that an operator is available, this small increase, although positive, does not represent the additional time that was made available for the operator to run other machines or other jobs. There was an average difference of 11.4 minutes less to run each of the measured jobs during the experiment.

The experiment also showed improved reliability in the process from 0.51 during the baseline to 0.63 during the experiment. This reflects an improvement in scrap rate and reduction in operator adjustments during the job. However, there is also an increase in the standard deviation of these measurements that would suggest that the process is less in control during the experimental period than during the baseline.

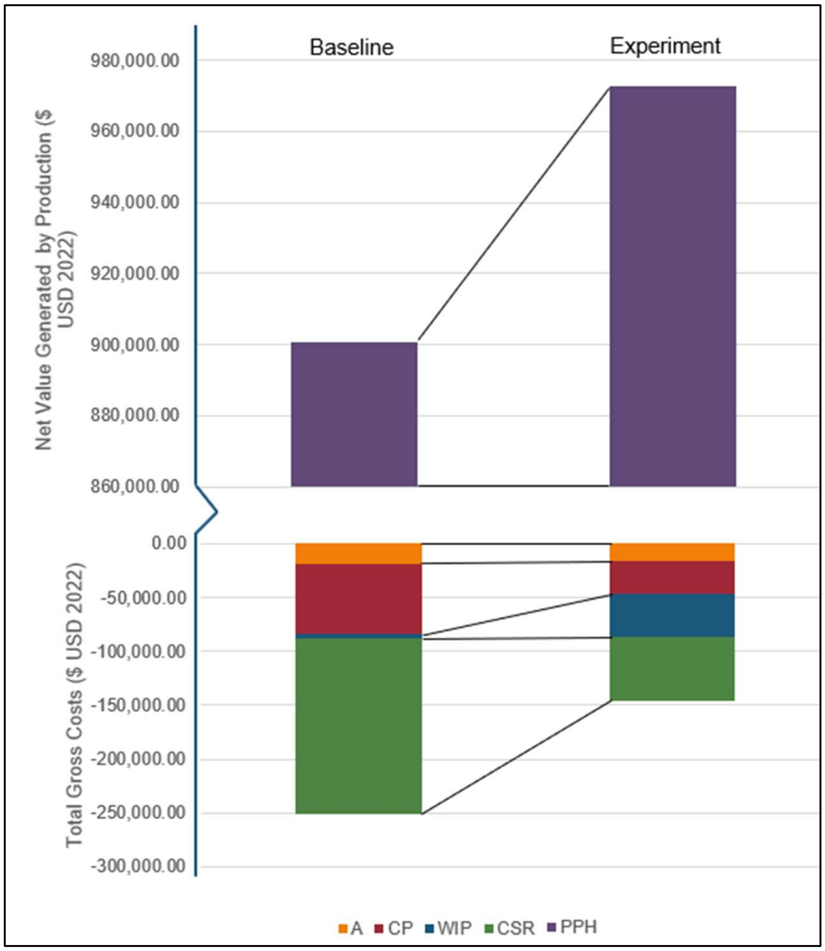


Figure 10: Cost to manufacture components vs. value created where A = Accuracy, CP = Cost (total cost of parts including indirect labor), WIP = Work in Process, CSR = Initial Setup Cost, PPH = Parts Per Hour (Ex 2)

5.7. Experiment Conclusions:

Comparing the baseline and the experimental measurement, correlations between the applications of paradigms and the metrics were determined (RQ2, Task 6). The experiment revealed noteworthy improvements in accuracy (A), uptime (H_U), labor hours (H_L), and parts per hour (PPH). These metrics were used to measure the efficacy of QRM, TPM, Lean, and QRM. Specifically, the experiment showed an increased in accuracy from 0.990 to 0.992 (QRM), an increase in uptime from 0.841 to 0.853 (TPM), a decrease in labor hours (Lean) from 74.18 to 23.10, and an increase in parts per hour (QRM) from 2.07 to 2.24.

These observed correlations began to outline a feasible model of best practices for HMLV manufacturing utilizing TQM, TPM, Lean, and QRM techniques (RQ2, Task 7). This experiment provides evidence that TQM, TPM, Lean, and QRM can be applied in HMLV manufacturing environments as a means to improve the metrics of accuracy, cost, PPH, reliability, labor hours applied, initial set up costs and uptime. However, the experiment did show an increase in process variation.

This variation could be an indication of many factors such as operator uncertainty or trust in the process, multiple other components that did not use the tombstone style fixture and required that the tombstone be sometimes unloaded from the machine (a labor-intensive process), or the length of the experimental period given the infrequency with which components are manufactured. All of these causes for variation could be resolved over time and by increasing the number the components (part numbers) that could be manufactured with the mini-plate style fixtures.

The small change in uptime during the experiment was also of note. Measuring operating time against the time that an operator is available, as is suggested by QRM makes sense in HMLV environments. However, unless this is measured as a whole (all work centers), it appears to not account for the increase in overall productivity that is gained by making the operator available elsewhere. A future experiment should consider machine time compared to the number of operators available for the entire facility to better understand the impact of these experimental changes in process. If we consider the savings of 11.4 minutes per job and the experimental period including 25 different jobs, this was an overall time savings of 4.75 hours where the operator was available to run other machines or jobs.

Another observation was that, during the experiment, the operator was highly engaged in the process change for the new fixture. Although this is desirable when creating an initial set up process, it can have negative impacts to creating a process that remains consistent over time. This could suggest that another approach to improving sources of variation could be to use an operator with a lower skill level. In HMLV manufacturing, there is a balance between highly skilled labor that is assumed to be critical to account for the large variation of components, and lower-skilled labor that reduces the operators comfort level with the process and reduces the operators comfort level in adjusting the process.

Chapter VI: Experiment 3: Standardization with Machining Process Flow

This experiment is the third of (5) that will seek to answer the following research question (Research Question 2):

> *Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?*

This experiment continues to expand the complexity of paradigm application through the implementation of multiple paradigms at the same time. This experiment was designed to exploit the similarities in these paradigms to achieve the goal of improving the metrics of cost, throughput, and flexibility. The six paradigms chosen provide a common emphasis on continuous improvement, have an underlying philosophy of waste elimination, use data-driven decision making, strongly emphasize standardization for quality, have a focus on customer needs and expectations, and include employee involvement to foster a culture of continuous learning and adapting.

For an illustration of the experimental design for Experiment 3, see Appendix E, Figure 36.

6.1. Description:

As a means to evaluate the effectiveness of philosophies attributable to Just in Time (JIT), Overall Equipment Effectiveness (OEE), Total Productive Maintenance, (TPM), Lean Manufacturing (Lean), Six Sigma (6σ), and Quick Response Manufacturing (QRM), an experiment was conducted to determine if there was a cost benefit to manufacturing components complete on one work center or using cellular manufacturing processes. This experiment focused on the manufacturing processes for a single part number that was manufactured using both processes.

The specific HMLV manufacturer where this study was conducted had multiple CNC turning centers. The number of operators available was less than the number of turning centers available. In LMHV manufacturing, long runs (quantity) of components enables operators to run multiple machines where they focus on loading and unloading materials to keep production continuous. Change overs between components are in infrequent and, depending on volume, may be unnecessary [64]. To do this, highly specialized and oftentimes automated equipment is used. This is a large capital investment that improves productivity but reduces flexibility.

The need for flexibility in HMLV manufacturing can have a direct negative impact to equipment uptime because it adds to operational complexity. To improve equipment uptime, specialized equipment and techniques are used. However, with the large variety of components, this becomes impractical from a capital investment standpoint. The potential answer to this is to focus on less specialized operations that can be used for multiple components by reducing them to their basic functions and creating efficiency at that level.

For this experiment, both highly specialized manufacturing processes that are refined for the specific component, and more basic manufacturing techniques that are refined at the process level were compared. A single part number, representative of many similar components was chosen for experimentation. The specific operations to complete this component included turning, grinding, and hobbing.

6.2. Paradigm(s):

This experiment utilized the metrics provided by multiple paradigms that represent overall cost reduction while maintaining or improving quality. In HMLV environments, JIT, OEE, TPM, Lean, 6σ, and QRM can be difficult to incorporate, and it can be difficult to measure effectiveness. Basing measurements on specific components does not represent the overall system in the same way that is possible in LMHV operations where a single production line can be focused on a single component or product. The specific manufacturing environment where this experiment focuses provides evidence of process control that contributes to a high level of quality as measured by a less than 1% scrap rate for any given operation. This, in additional to labor resources less than one to one for machines, made it an ideal environment to determine if single machines performing multiple operations to manufacture a complete part or processes reduced to single operations and manufacturing a component in a cellular environment was more beneficial.

6.3. Bounds:

This experiment focused on a specific component that was manufactured using turning, grinding, and hobbing processes. This component was chosen because the processes to manufacture it were the same as many other, similar components. Consideration was also given to the volume and frequency of manufacturing where this component has relatively higher volume and frequency than other components and provided the best opportunity for experimentation without creating unnecessary production. Before the experiment, the component was manufactured in multiple operations that were used in many value streams. The scheduling of multiple value streams created WIP between operations. This WIP, as part of the overall cost to manufacture, was addressed in the experiment using both single machine manufacturing and cellular manufacturing.

6.4. Metrics:

To effectively assess the impact of the application of the defined paradigms, the metrics and the specific measurement method have been defined for this experiment (RQ2, Task 1).

The metrics for this experiment were based on the metrics used under JIT, OEE, TPM, Lean, 6σ, and QRM. Each of these is further defined for applicability in HMLV environments in Table 16.

Table 16: Traditional metrics for JIT, OEE, TPM, Lean, 6σ, and QRM defined for specific experimental application (Ex 3)

Metric	Paradigm	Units	Definition
WIP	JIT	USD ($)	This is a measure of throughput and indicates how many parts per hour a process is able to produce. For this experiment, “process” is synonymous with work center.
On Time Delivery (OTD)	JIT	% OT	This is a measure of the percentage of parts that are completed (logged into stock for this experiment) by the date, with the lead time that has been defined for them.
Performance (H_C)	OEE	Hours	Performance is a measure of the average cycle time for manufactured components.
Effectiveness (E)	OEE	% Parts	This is a measure of quality or scrap rate and is determined based on the number of parts that are completed that conform to the quality standard defined.
Uptime (H_U)	TPM/ QRM	Hours	This is a measure of machine availability compared to machine usage. For this experiment, the QRM definition of uptime is used where machine availability is based on operator availability to operate the machine.

Lead Time (H)	6σ	Hours	For this experiment, this is a measure of the time from when a component starts its first operation to the time when the component is logged into stock.
Process Variability (Cpk)	6σ	Cpk	Cpk is the process capability ratio or index. It is a statistical measure of process capability.
Parts Per Hour (PPH)	JIT/ QRM	PPH	This is a measure of throughput and indicates how many parts per hour a process is able to produce. For this experiment, "process" is synonymous with work center.
Cost (C_P)	All	USD ($)	This is a measure of the total process cost for a single part that includes any costs incurred from the time that the material is allocated to the job to the time that the job is completed (parts logged into stock).

6.5. Experimental Design:

This experiment was designed to determine the effectiveness of cellular manufacturing and single machine manufacturing compared to the baseline of mixed value stream manufacturing. To do this, a single component was chosen that required multiple processes to manufacture, including turning, grinding, and hobbing. These operations were each performed at separate work centers that also processed many other components (mixed value streams). This type of processing required that workflow was scheduled for each operation separately. This mixed value stream method was used as the baseline.

The component was then manufactured in a single work center where all operations were combined to manufacture a complete part. This type of processing is typical in LMHV environments where dedicated equipment can be used for single components or component families.

The second method of processing for this component was a work cell where the operations remained separate, but the workflow was only scheduled at the first operation. This was a combination of 3 machines and a pull system was implemented between them. Cellular manufacturing is used in many Lean Manufacturing implementations as a means to reduce WIP and produce a complete component in a single work cell comprised of multiple pieces of manufacturing equipment. As shown in Figure 10, both methods of manufacturing had to include turning, grinding, and hobbing to manufacture the component.

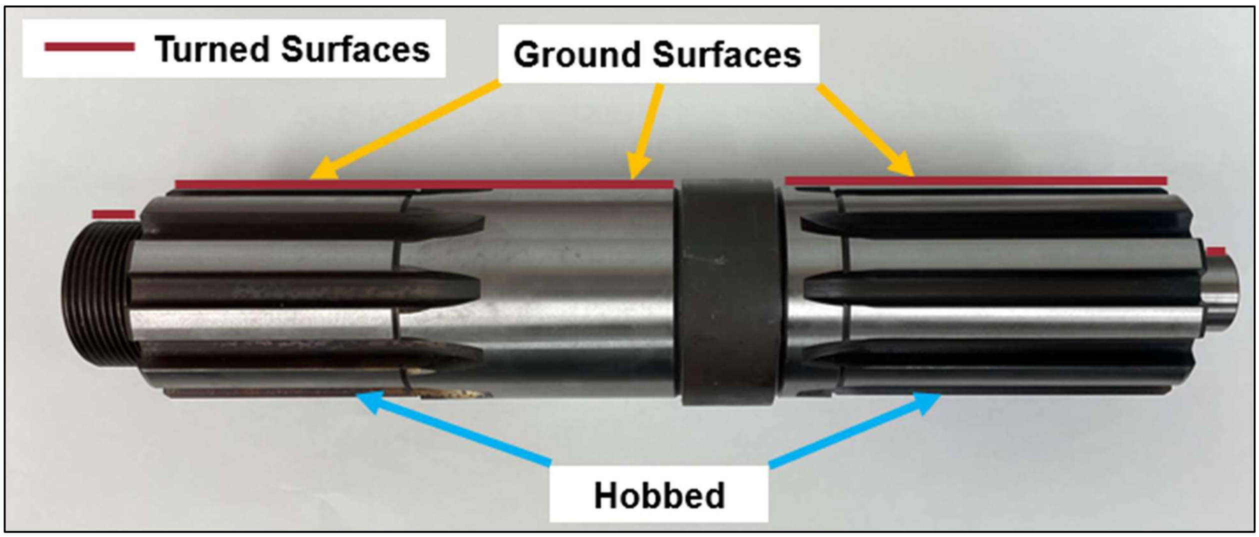


Figure 11: Shaft used for experimentation with operations performed (Ex 3)

For the baseline, the shaft was manufactured on three separate machines, a lathe, a plunge grinder, and a hob. These machines each operated at separate work centers. To perform these operations on a single machine, some processing modifications were made that performed the same operations but in a different way. The lathe turning operation remained the same. The grinding operation on the lathe was performed by turning the ground surface finish. The hob operation was incorporated into the lathe using a single tooth cutter and live tooling. For each of these methods of manufacturing, the variables in Table 17 were measured.

Table 17: Variables measured for each of the manufacturing methods defined (Ex 3)

Variable	Definition	Measurement Method
C_S	Cost of space	$Ft^2 * (\$/Ft^2)$
D	Defects	Scrap or Rework Rate
IW	Inventory value in WIP	Average over experimental period
M_S	Machine Setup Time	Measured in hours
OH_{EX}	Overhead multiplier for the experiment period	Overhead multiplier over experimental period
OH_{WC}	Overhead for the parts produced (3 months)	Overhead constant for the work center
OW_{WC}	Operator wage	Operator wage per hour
Q_B	Quantity of components in batch	Set value per job
Q_S	Quantity of components scrapped in batch	Measured in number of parts not completed from a batch due to quality
σ	Standard Deviation	For this experiment, this is the standard deviation of the lead time in hours
T_C	Cycle Time (per part)	Average over experimental period
T_J	Time operator is on specific job	Hours operator is clocked into a job
T_O	Labor time for operator	Hours of labor operator applies
T_P	Planned production time	Based on the routed time
X-bar	Mean or average change in process over time	For this experiment, this is the mean or average of the lead time in hours

6.5.1. Baseline Measurements:

To effectively evaluate the impact of the defined paradigms, it was necessary to establish a baseline measurement for each metric. The baseline was used to measure the improvement in effectiveness attributable to each paradigm and to draw meaningful conclusions about their potential for improving the defined metrics (RQ2, Task 2).

As part of the baseline definition, the scope for the experiment was defined (RQ2, Task 3). This provided a means to define the specific area of focus while allowing the experiment to be tailoring to the specific needs of the HMLV manufacturing environment.

The baseline measurements were recorded before any changes were made to processing. The baseline included 3 separate work centers, as seen in Figure 11, operating independent of each other. Each work center had a separate area for WIP, which added to the amount of space that this method occupied compared to the others.

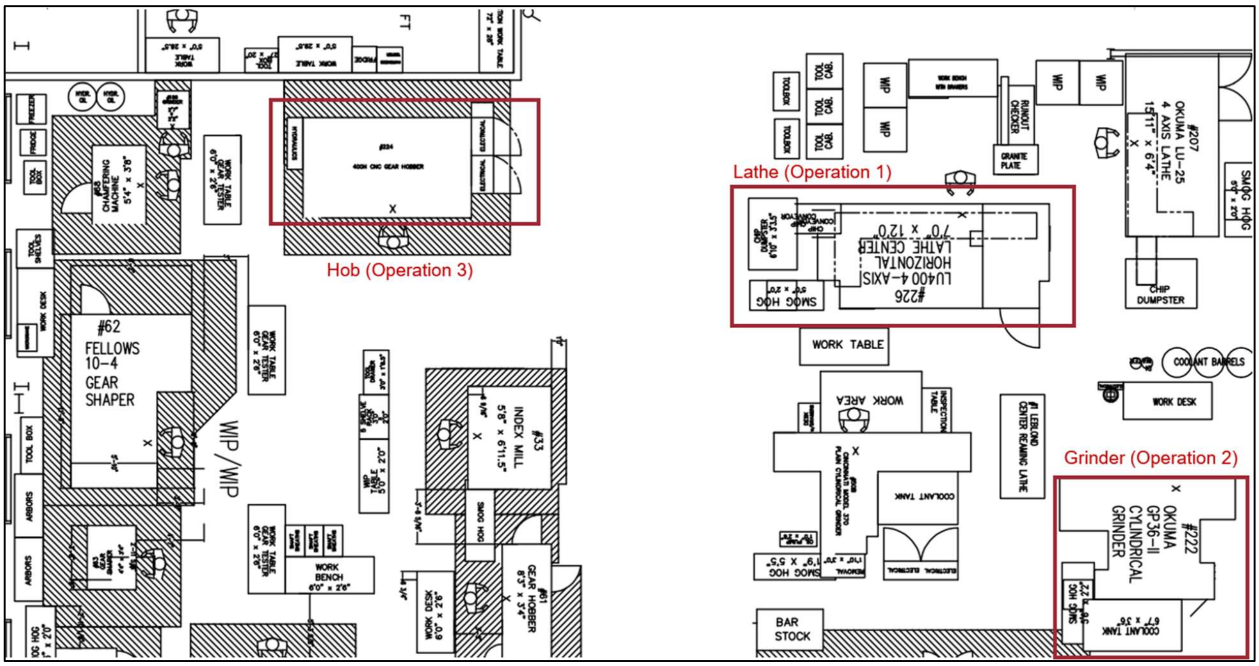


Figure 12: Baseline layout of machining operations performed to manufacture component (Ex 3)

This experimental baseline was a typical machine arrangement in HMLV operations where the need to contribute to multiple value streams dictated the machine placement and the work scheduling method of each machine scheduled separately. It is also important to note that these machines do not include many additional options beyond the base operations that they performed. For instance, the lathe did not include live tooling as is typically used when operations beyond turning are performed. This contributed to the length of setup time for each machine by providing relative simplicity in the setups.

Variable measurements for the baseline were measured, as shown in Table 18.

Table 18: Variable measurements for baseline processing using separate machines that were part of the larger system of mixed value streams (Ex 3)

Variable	Definition	Baseline
C_S	Cost of space	$112,500.00
D	Defects	0.12%
IW	Inventory value in WIP	$73,193.99
M_S	Machine Setup Time	3.38
OH_{EX}	Overhead multiplier for the experiment period	0.10
OH_{WC}	Overhead for the parts produced (3 months)	$77.23
OW_{WC}	Operator wage	$26.25
Q_B	Quantity of components in batch	58
Q_S	Quantity of components scrapped in batch	0.07
σ	Standard Deviation	851.14
T_C	Cycle Time (per part)	0.59
T_J	Time operator is on specific job	11.97
T_O	Labor time for operator	11.97
T_P	Planned production time	9.86
X-bar	Mean or average change in process over time	768.83

Using the baseline measurements, the process is described in Figure 12 using Value Stream Mapping to represent the critical path to manufacture the component. With the work centers acting as separate entities and as part of a larger system of mixed value streams, work starting goes into que at each machine for processing. Batch processing also dictated that a batch of components is complete before any single component is considered complete and logged into stock. As shown in Figure 12, this means that a new job or work packet will be in que for 67.32 hours before it begins to process in the first operation. The critical path for this processing method, for a batch to be completed, was 253.61 hours. The uptime for this method is 14.76% of the total processing time with wait time in staging providing the most significant portion of downtime.

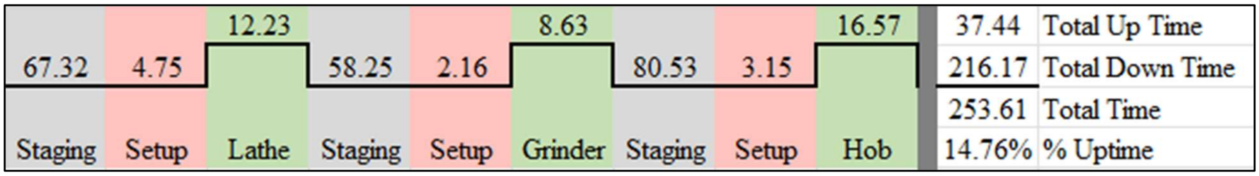


Figure 13: Value Stream Map of baseline processing with machines working separately in mixed value streams (all values in hours)

6.5.2. Experimental Measurements:

Having determined the baseline measurements for the experiment, changes were made to the manufacturing process in accordance with JIT, OEE, TPM, Lean, 6σ, and QRM and adjusted to the HMLV manufacturing environment (RQ2, Task 4). Once implemented, the metrics and their components were measured to determine how the application of JIT, OEE, TPM, Lean, 6σ, and QRM principles impacted the metrics (RQ2, Task 5).

The experimental measurements were recorded for 2 different processing methods. The first was using the same machines as the baseline but as a cellular workflow where the que for work existing in front of the first operation and then components flowed through the work cell to the second and third operations, as shown in Figure 13.

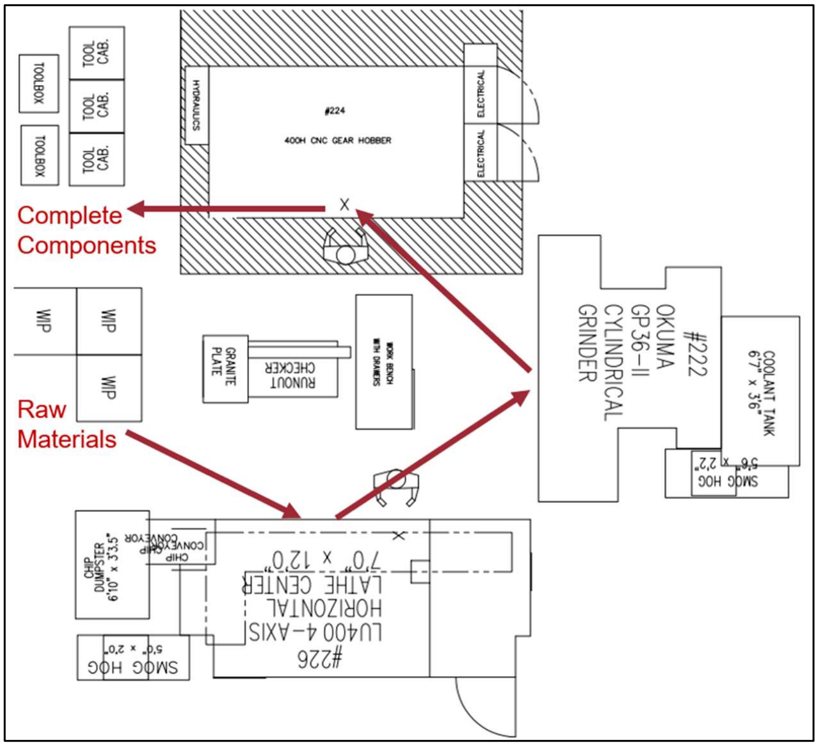


Figure 14: Cellular workflow layout of machining operations performed to manufacture components (Ex 3)

Processes for the cellular workflow were completed in fewer total hours, as seen in Figure 14, compared to the baseline given the reduced time in staging, or wait time. The critical path was reduced to 109.51 hours. This method also allowed batch processing to be reduced and, within the work cell, single piece workflow was achieved. These changed increased the uptime to 34.19% of the total time to complete the batch. With no changes made to the batch size, compared to the baseline, the last operation (hob) remained the pace setter for takt time.

		12.23				
67.32	4.75				37.44	Total Up Time
		Lathe	8.63		72.074	Total Down Time
Staging	Setup	2.16			109.51	Total Time
			Grinder	16.57	34.19%	% Uptime
		Setup	3.15			
				Hob		
			Setup			

Figure 15: Value Stream Map of cellular workflow processing with machines working as a single work cell (all values in hours) (Ex 3)

The second experimental processing method that was used was a single machine making the component complete. There were many considerations to do this that required some changes in processing methods to machine the component to the same specifications as with multiple machines. For instance, plunge grinding was not an option inside of the lathe without additional machine modification and reduction in machine and tool life due to abrasives used, and therefore increased the processing time to turn the required surface finish. Hob operations were performed using a single tooth cutter in live tooling.

As shown in Figure 15, the wait time in staging was more than the wait time in the cellular processing method but less than the total wait time for the baseline processing method. The reduction in total wait time in staging, compared to the baseline, increased the uptime compared to the baseline. However, the processing time for the lathe to perform the 3 required operations increased. The critical path for this processing method was 210.13 hours to complete the job.

		39.44	39.44	Total Up Time
162.64	8.05		170.69	Total Down Time
			210.13	Total Time
Staging	Setup	Lathe	18.77%	% Uptime

Figure 16: Value Stream Map of single machine processing (all values in hours) (Ex 3)

The measured variables for both experimental methods can be seen in Table 19. As shown, the space required for single machine processing was less the cellular processing method. When compared to the baseline, the cellular processing method was less space because of the reduction in staging space needed and the ability to overlap operator work envelopes between machines.

Table 19: Variable measurements for single machine (WC) processing and cellular processing (Ex 3)

Variable	Definition	Single WC	Cellular
C_S	Cost of space	\$37,500.00	\$60,000.00
D	Defects	0.26%	0.10%
IW	Inventory value in WIP	\$44,609.36	\$11,820.80
M_S	Machine Setup Time	6.11	2.84
OH_{EX}	Overhead multiplier for the experiment period	0.10	0.10
OH_{WC}	Overhead for the parts produced (3 months)	\$77.23	\$77.23
OW_{WC}	Operator wage	\$26.25	\$26.25
Q_B	Quantity of components in batch	58	58
Q_S	Quantity of components scrapped in batch	0.15	0.06
σ	Standard Deviation	412.02	361.73
T_C	Cycle Time (per part)	1.63	0.59
T_J	Time operator is on specific job	47.49	9.85
T_O	Labor time for operator	29.34	9.85
T_P	Planned production time	9.44	8.14
X-bar	Mean or average change in process over time	1047.87	548.84

Using the measured variables for all 3 processing methods, the metrics were calculated as show in Table 20 using the following equations:

[1] Work In Process (WIP) = $IW * OH_{EX}$

[2] On Time Delivery (OTD) = Quantity Batches Completed on Time/ Total Batches

[3] Performance (H_C) = T_C / Q_B

[4] Effectiveness (E) = $(((Q_B - Q_S) * T_P) / T_O) / 100$

[5] Uptime (H_U) = $(T_C * Q_B) / T_J$

[6] Lead Time (LT) = Average Hours Per Batch

[7] Process Variability (Cpk) = $\bar{x} / \sigma$

[8] Parts Per Hour (PPH) = Q_B / T_J

[9] Total Cost (C_P) = (T_C + (M_S / Q_B)) * (OW_{WC} + OH_{WC})

Table 20: Calculated metrics for the 3 processing methods for the component (Ex 3)

Eq #	Metric	Variable	Units	Baseline	Single WC	Cellular
1	WIP	**WIP**	USD ($)	$7,624.37	$4,646.81	$1,231.33
2	On Time Delivery	**OTD**	%	33.33%	85.71%	33.33%
3	Performance	$\mathbf{H_C}$	Hours	0.36	0.40	0.36
4	Effectiveness	**E**	%	47.68%	18.65%	47.74%
5	Uptime	$\mathbf{H_U}$	Hours	14.76%	18.77%	34.19%
6	Lead Time	**LT**	Hours	768.83	1047.87	548.84
7	Process Variability	**Cpk**	Cpk	1.21	0.76	1.38
8	Parts Per Hour	**PPH**	Parts	0.19	0.83	0.79
9	Total Cost (per part)	$\mathbf{C_P}$	USD ($)	$66.69	$76.00	$64.81

6.6. Reflection:

The baseline processing method requires additional floor space for each machine to have an operator envelope to work in and have a staging area for WIP prior to processing. The wait time in staging is a significant contributor to critical path. The setup time for each machine is also performed externally (not internally to another run) and this adds additional time to the critical path. Not represented well in the variable measurements is that this process also requires that 3 operators are used, working consecutively.

Cellular processing methods reduced the floor space requirement by overlapping operator work envelopes. The time to set up the second and third machining operations was able to be done internally to the cycle time of the previous operation which, in addition to one-piece-flow for components, reduced the critical path. This method provided an additional benefit by only requiring 1 machine operator to run all 3 machines. Quality also improved (0.06 scrap rate) compared to the baseline (0.07 scrap rate) because of the operator's ability to impact all machining operations as necessary to improve the next operation.

Single machine processing methods increased the time it took to setup the machine because of the complexity needed to perform all the operations in the same machine. This complexity also contributed to an increase in component scrap rate. The wait time in staging (compared to the baseline of ~206 hours total) was reduced during the experimental period but this may not be an accurate representation of processing given that the machine used was more caught up on work than the machines used for the baseline.

6.7. Experiment Conclusions:

Comparing the baseline and the experimental measurement, correlations between the applications of JIT, OEE, TPM, Lean, 6σ, QRM and the metrics were determined (RQ2, Task 6). These correlations began to define an applicable model for best practices in improving the metrics for HMLV manufacturing using JIT, OEE, TPM, Lean, 6σ, and QRM (RQ2, Task 7).

This experiment provides evidence of beneficial applicability of both single machine and cellular processing in HMLV manufacturing. Both provided improvements in cost, parts per hour, and WIP compared to the baseline. Cellular processing provided a larger benefit in each category in addition to improved overall lead time and quality. The complexity of the setup for single machine processing and the added cycle time to perform all of the operations negatively impacted these metrics compared to cellular processing.

During the experimental period, there were also auxiliary factors that effected the measurements. The main impact came from supply chain challenges that disrupted the material availability and changed the lead times where some work packets were completed well in advance of their due date and others were rushed through once materials were available.

Single machine processing, if done with multiple machines that used a single operator could potentially provide a larger benefit over cellular processing. This would also represent a much larger capital investment as multi-functional equipment, such as a lathe with live tooling, is a larger cost than a simplified, single process machine. This could be beneficial, however, in either production environments more similar to a job shop where a single operator is running multiple machines with multiple different components, or in a LMHV environment where the setup quantity can be significantly reduced.

Chapter VII: Experiment 4: Reducing Change Over Times Using Adjusted Process Flow and Internalized Operations

This experiment is the fourth of (5) that will seek to answer the following research question (Research Question 2):

> *Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?*

This experiment expands the complexity of paradigm application through the inspiration of multiple paradigms at the same time. This experiment was designed to exploit the similarities in these paradigms to achieve the goal of improving the metrics of cost, throughput, and flexibility. The six paradigms chosen to provide a common emphasis on continuous improvement, have an underlying philosophy of waste elimination, use a data-driven approach, emphasize standardization to improve quality, focus on customer needs and expectations, and require employee involvement to continuously learn and adapt the manufacturing environment.

For an illustration of the experimental design for Experiment 4, see Appendix E, Figure 37.

7.1. Description:

As a means to evaluate the effectiveness of philosophies attributable to Just in Time (JIT), Theory of Constraints (TOC), Overall Equipment Effectiveness (OEE), Total Productive Maintenance (TPM), Lean Manufacturing (Lean), Six Sigma (6σ), and Quick Response

Manufacturing (QRM), changes to processing order and resource allocation (with the same number of resources) were made to determine if throughput and cost could be improved. This experiment focused on evaluating processes for testing highly configured products.

The HMLV test environment required highly skilled labor. This increased the cost of the test operations [62]. In many LMHV environments, operations are pre-engineered to reduce the labor input. For this HMLV environment, the manufacturer where this study was conducted required that flexibility in product offerings remained as a core market strategy. This flexibility allowed thousands of different configurations of each of the 62 top level products that represented the midship or PTO style fire pumps.

Test operations involved preparation and setup for testing in the setup area illustrated in Figure 17. This included adding oil to the transmission, preparing any inlet or outlet flanges to be connected to testing equipment, and adding manifolding as needed. The pump was then connected to a test station through the installation of a driveshaft between the test motor and the pump, safety guarding for all rotating components, and connection of inlet (suction) and outlet (discharge) hoses to allow the flow of water through the product. An illustration of a pump in staging can be seen in Figure 18 and a photograph of the same pump setup in the test station can be seen in Figure 19.

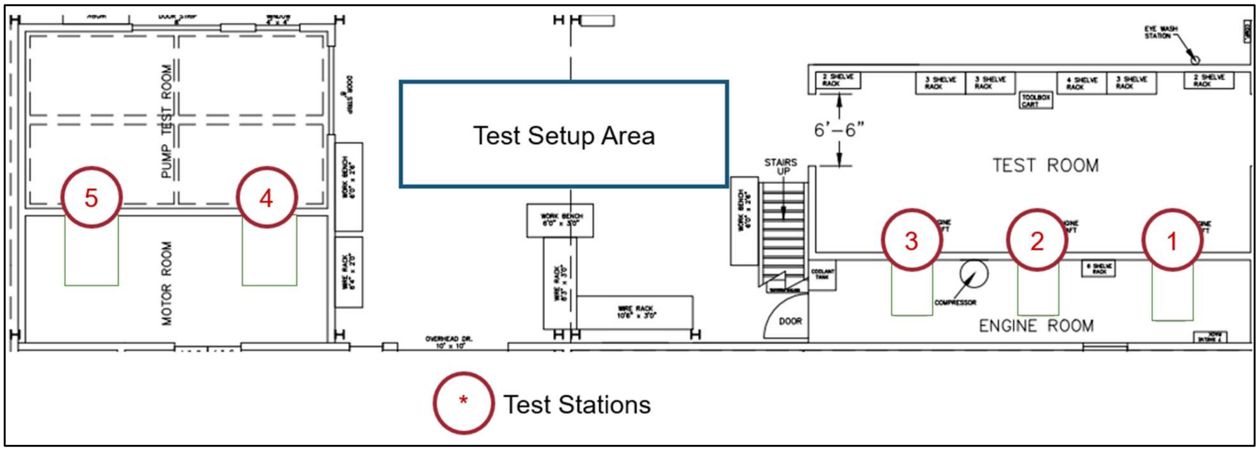


Figure 17: Floor layout of test operations with setup area and each of the 5 test stations

Figure 18: Fire Pump as Retrieved from Staging After Assembly and Prior to Test Operations (Ex 4)

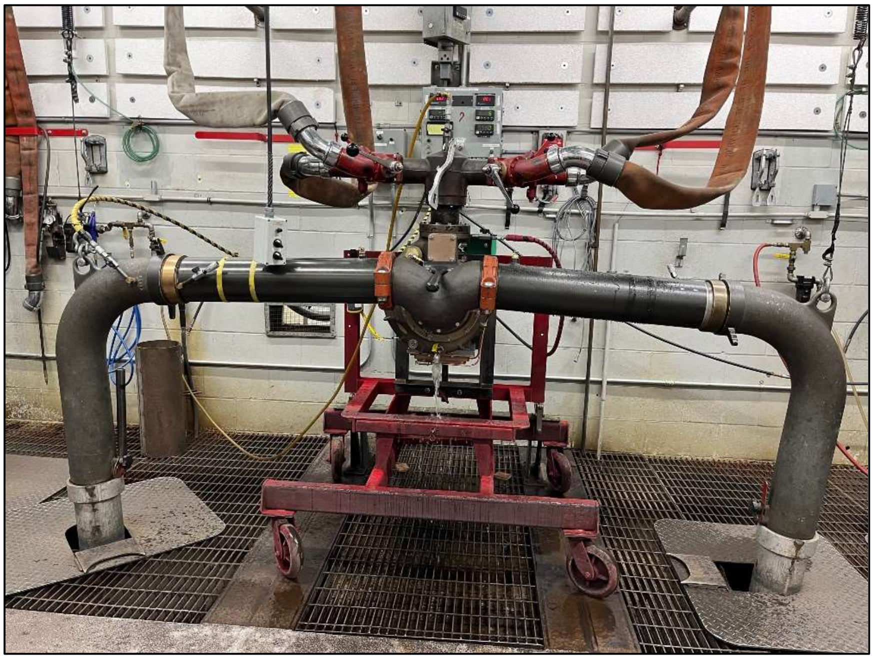


Figure 19: Example test setup of fire pump in test station as viewed from the suction side of the pump (Ex 4)

7.2. Paradigm(s):

The test process is the first process in the manufacture of the product that does not allow batch processing to be easily achieved. Because of this, the test process is typically a pacesetter for all operations in production. To improve, this experiment utilized the metrics classically used for multiple paradigms that focus on throughput as a top-level measurement.

Additional limitations existed in the manufacturing environment that required leveling the workload. These included power limitations for the five test motors where the highest power draw test points could not be reached for more than two test motors simultaneously, requiring the staggering of test processes. The other major limitation was the quantity of test fittings and equipment that, if attempting to batch set up product, there would be a shortage of these items. Working within these limitations provided an ideal environment for pure paradigm application where the workflow was the main focus.

7.3. Bounds:

The product test area was composed of five motors or test stations. The test area was staffed with four labor resources per shift (two shifts). The test cycle time was, on average, 1.5 hours to run the required set of test points that were specified by flow (GPM) and pressure (PSI) for each test point and a required duration of run for each point. The test duration was not changed during the experiment (NFPA).

The product tested consisted of 63 parent level assemblies, each with thousands of different potential configurations. In general, these can be categorized further into 2 distinct types, PTO driven and Midship. The configuration changes that most impacted the test set up included the type of gearcase (2 gear, 3 gear, auxiliary, or none), and the manifolding assembled on the pump (full manifolding or none).

To effectively assess the impact of the application of the defined paradigms, the metrics and the specific measurement method have been defined for this experiment (RQ2, Task 1).

The metrics shown in Table 21 were measured as a baseline and used to determine the effectiveness of applying the paradigms for the experiment.

Table 21: Traditional metrics of performance for JIT, TOC, OEE, TPM, Lean, 6σ, and QRM for specific experimental application (Ex 4)

Metric	Paradigm	Units	Definition
WIP (WIP)	JIT	USD ($)	This is a measure of process wait time (by dollar value) and indicates the value of work waiting to be processed.
Performance (H_C)	OEE	%	Performance is a measure of the average cycle time for manufactured components.

Effectiveness (E)	OEE	%	This is a measure of quality or scrap rate and is determined based on the number of parts that are completed that conform to the quality standard defined.
Uptime (H_U)	TPM	%	This is a measure of machine availability compared to machine usage. For this experiment, the QRM definition of uptime is used where machine availability is based on operator availability to operate the machine.
Process Time per Unit (H_P)	Lean	Hours	This is the number of hours the process takes to complete one unit.
Lead Time (LT)	6σ	Hours	This is the time (in hours) that a unit takes to be completed from the first step to the last step of the manufacturing process. This value includes wait time, or time in que to be processed.
PPH (PPH)	TOC/QRM	Parts	This is a measure of throughput and indicates how many parts per hour a process can produce. For this experiment, "process" is synonymous with test station.
Total Cost (C_P)	All	USD ($)	This is the total cost for the process of testing a unit.

7.5. Experimental Design:

To effectively evaluate the impact of the defined paradigms, it was necessary to establish a baseline measurement for each metric. The baseline was used to provide a starting point from which to assess the effectiveness of each paradigm and draw meaningful conclusions about their potential for improving the defined metrics (RQ2, Task 2).

As part of the baseline definition, the scope for the experiment was defined (RQ2, Task 3). This provided a means to define the specific area of focus while allowing the experiment to be tailoring to the specific needs of the HMLV manufacturing environment.

The baseline for this experiment was the manufacturing flow that already existed for test processes. This flow included product staging before test processes and individual scheduling for each test technician where a list of product, in order of priority and based on the technicians skill level or product familiarity, was provided at the beginning of each shift. Each test technician would retrieve the product that was on the scheduled list for them to test from the staging area. The product was then brought to the test setup area where fittings and manifolding (where required) was assembled onto the product. The test technician would then fill the gearcase (if applicable) with oil and move the product into their designated test station (dependent on technician preference and power required for the product to be tested).

Once in the test station, the product was connected to the test motor with a drive shaft and safety guarding was added. The technician then connected the inlet (suction) and outlet (discharge) plumbing. Before testing, the product was filled with water and pressurized to meet a hydrostatic pressure requirement that was based on the specific product performance rating. Once the product passed the hydrostatic pressure test, the test motor was started, and the technician ran the specified performance points to meet NFPA requirements. Once complete, the product was disconnected from the test motor and moved back to the setup area to remove the test fittings and any manifolding added for the test. Four test techs performed these operations on individual stations with individual scheduled work.

The experimental changes for the test process included reallocating one of the four test technicians to perform the product setup and tear down operations. This person ensured that each product was readied to the point that it could be moved to the test station. After the test was performed, this person removed any test fittings and manifolding assembled for the test process, drained fluids, and moved the product to staging for the paint process (if required).

The three test technicians were provided a single schedule based only on product due date and whether or not the product was available from the previous assembly operation. During the experimental period, there were two instances where the list could not be followed in completely sequential order due to limitations in available test fittings where there were too many products that needed the same fittings. To maintain product flow, these instances were remedied by moving test technicians to the next product on the schedule while one technician continued to test the batch or similar product that wasn't batched. The variables are defined in Table 22.

Table 22: Variables measured for the baseline and experimental period to calculate metrics (Ex 4)

Variable	Definition	Measurement Method
FPY	First Pass Yield over experiment period	Quantity of defects / Quantity of products tested
H_T	Total process hours	Measured from job punches
H_U	Hours of time producing product	Measured in payroll hours over period
IW	Inventory value in WIP	Measured value of product waiting for processing
LT	Lead Time Average over time period (days)	Measured from job punches
OH_{EX}	Overhead multiplier for the experiment period (3 weeks)	Calculated based on 25% per year adjusted for period
OH_{WC}	Overhead for the parts produced	Constant
OW_{WC}	Operator wage	Constant
Q_B	Production quantity over time period	Measured in job punches
Q_S	Quantity of Non-Conforming Product	Measured in non-conformity reports
T_C	Cycle time per product (actual average over time period)	Measured in job punches
T_I	Ideal Cycle Time (Avg from St Rtg)	Determined based on standard routing times
T_J	Time operator is on specific job	Measured in job punches
T_O	Labor time for operator	Measured in job punches
T_P	Planned production time	Determined based on standard routing times

T_S[5]	Setup Time Average over time period	Measured in job punches

Using the variables shown in Table 21, the following equations were used to calculate the metrics for the baseline and for the experiment:

[1] Work In Process (WIP) = IW * OH

[2] Performance (H_C) = T_C / Q_B

[3] Effectiveness (E) = $(((Q_B - Q_S) * T_P) / T_O) / 100$

[4] Uptime (H_U) = $(T_C * Q_B) / T_J$

[5] Process Time Per Unit (H_P) = $T_C + T_S$

[6] Lead Time (LT) = Average Hours Per Unit

[7] Parts Per Hour (PPH) = Q_B / T_J

[8] Total Cost (C_P) =

C_P Baseline = $T_C * (OH_{WC} + OW_{WC})$

C_P Experiment[6] = $T_C * ((OH_{WC} + OW_{WC})1.33)$

7.5.1. Baseline Measurements:

Variables were measured for a 3-week period of production prior to paradigm application for the experiment. These measurements are shown in Table 23. Using the variables measured, the metrics were calculated (Table 23).

Table 23: Variable Measurements for Baseline 3 Week Production Period (Ex 4)

Variable	Definition	Baseline
FPY	First Pass Yield over experiment period	0.74
H_T	Total process hours	323.72
H_U	Hours of time producing product	960
IW	Inventory value in WIP	$261,858.12
LT	Lead Time Average over time period (days)	65.48
OH_{EX}	Overhead multiplier for the experiment period (3 weeks)	0.014
OH_{WC}	Overhead for the parts produced	$77.23
OW_{WC}	Operator wage	$26.25

[5] Setup Time includes the time to setup the pump to go to the test operation and the time to tear down the pump for completion.

[6] During the experimental period, the labor units increase from 1 per product to 1.33 per product while 1 labor unit is used for setup and teardown operations for the other 3.

Q_P	Production quantity over time period	185
Q_S	Quantity of Non-Conforming Product	49
T_C	Cycle time per product (actual average over time period)	4.44
T_I	Ideal Cycle Time (Avg from St Rtg)	2.33
T_J	Time operator is on specific job	2.70
T_O	Labor time for operator	2.70
T_P	Planned production time	2.33
T_S	Setup Time Average over time period	0.75

During the baseline period, 185 fire pumps were tested. The total labor hours for resources allocated to test operations was 960 hours. Total hours applied to the test process, however, was 323.72 hours. Resources were not re-allocated to other production operations during this time. Figure 20 is a graphical view of the process sequencing for a single technician for 3 total fire pumps tested.

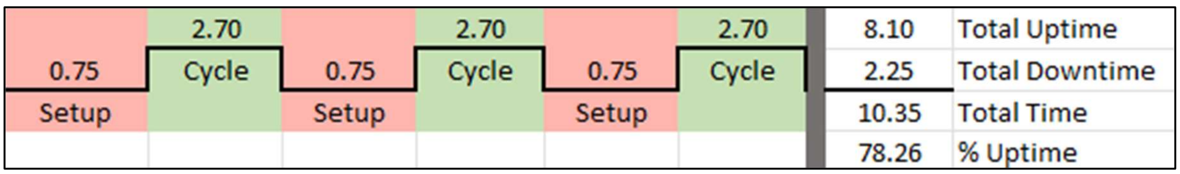


Figure 20: Value Stream Map of Single Technician Testing 3 Fire Pumps (Approximately 1 Day of Production for that Technician) (Ex 4)

Using the variable measurements for the baseline, the metrics were calculated as shown in Table 24.

Table 24: Metrics of Performance Calculations for the Baseline 3 Week Production Period (Ex 4)

Eq #	Metric	Variable	Baseline
1	WIP (WIP)[7]	WIP	$3,776.80
2	Performance (H_C)	H_C	1.46
3	Effectiveness (E)	E	0.33%
4	Uptime (H_U)	H_U	52.04%
5	Process Time per Unit (H_P)	H_P	4.44
6	Lead Time (LT)	LT	65.48
7	PPH (PPH)	PPH	0.77
8	Total Cost (C_P)	C_P	$459.37

[7] Total WIP value is adjusted for the time of the production period (3 weeks)

7.5.2. Experimental Measurements:

Having determined the baseline measurements for the experiment, changes were made to the manufacturing process in accordance with the principles of JIT, TOC, OEE, TPM, Lean, 6σ, and QRM and adjusted to the HMLV manufacturing environment (RQ2, Task 4). Once implemented, the metrics and their components were measured to determine how the application of JIT, TOC, OEE, TPM, Lean, 6σ, and QRM principles impacted the metrics (RQ2, Task 5).

Variables were measured for the 3-week period of production after paradigm application for the experiment. These measurements are shown in Table 25.

Table 25: Variable Measurements for Experimental 3 Week Production Period (Ex 4)

Variable	Definition	Experiment
FPY	First Pass Yield over experiment period	0.89
H_T	Total process hours	684.04
H_U	Hours of time producing product	960
IW	Inventory value in WIP	$736,126.23
LT	Lead Time Average over time period (days)	123.00
OH_{EX}	Overhead multiplier for the experiment period (3 weeks)	0.014
OH_{WC}	Overhead for the parts produced	$77.23
OW_{WC}	Operator wage	$26.25
Q_P	Production quantity over time period	299
Q_S	Quantity of Non-Conforming Product	35
T_C	Cycle time per product (actual average over time period)	2.46
T_I	Ideal Cycle Time (Avg from St Rtg)	2.85
T_J	Time operator is on specific job	3.01
T_O	Labor time for operator	2.70
T_P	Planned production time	2.33
T_S	Setup Time Average over time period	0.75

During the experimental period, 299 fire pumps were tested. The total labor hours for resources allocated to test operations was 960 hours. Total hours applied to the test process was 684.04 hours. Resources were not re-allocated to other production operations during this time.

Figure 21 is a graphical view of the process sequencing for a single test technician where another technician was performing setup and teardown operations.

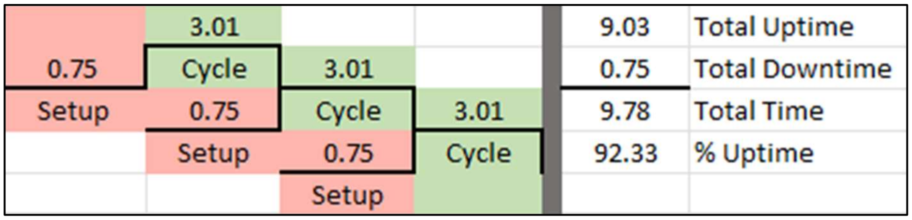


Figure 21: Value Stream Map of a Single Technician Testing 3 Fire Pumps with Another Technician Performing Setup and Teardown Operations (1/3 Labor Resource Allocated) (Ex 4)

Using the variable measurements for the experiment, the metrics were calculated as shown in Table 26.

Table 26: Metrics of Performance Calculations for the Experimental 3 Week Production Period (Ex 4)

Eq #	Metric	Variable	Experiment
1	WIP (WIP)[8]	WIP	$10,617.21
2	Performance (H_C)	H_C	1.01
3	Effectiveness (E)	E	0.99%
4	Uptime (H_U)	H_U	93.77%
5	Process Time per Unit (H_P)	H_P	2.46
6	Lead Time (LT)	LT	123.00
7	PPH (PPH)	PPH	1.25
8	Total Cost (C_P)	C_P	$338.66

During the experimental period, there was an increase in lead time compared to the baseline (65.48 hours to 123.00 hours). This was measured by job completions from the previous operation (assembly) to completion in test. This measure, in addition to the increase in WIP was a strong indication of the test process reducing its backlog.

[8] Total WIP value is adjusted for the time of the production period (3 weeks)

7.6. Reflection:

There was a significant improvement in throughput from the baseline to the experiment. During both production periods, the test operation was the pacesetter for the entire system (component allocation to shipping). This would indicate that the increase in WIP prior to the test operation is not indicative of an increase in available work improving throughput for test operations. The increase in WIP prior to test operations for the experimental period (from $3,776.80 to $10,617.21) does, however, represent the unlevel demand patterns typical of HMLV manufacturing operations. This is also an indication of the higher number of products being processed in test. There were also economic considerations associated with this change where the external supply change challenges resulted in large "slugs" of work available. In many cases, raw material availability in upstream operations created even large demand imbalances than is typical in HMLV manufacturing operations.

These phenomena of upstream batch production and supply chain challenges may also help to describe the change in lead time from the baseline period (65.48 days) to the experimental period (123 days). This lead time is indicative of the entire process from order entry to completion and is subject to significant changes based on many external factors that also include customer need.

There was also an unexpected improvement in quality as indicated in the change in first pass yield between the baseline of 75% to the experimental period of 89%. To better understand this, additional experiments should be conducted to track changes in the quantity of upstream batching for operations. It could mean that the experimental period had more batched product from upstream operations that changed the effectiveness of the operation (more repeatability leading to fewer defects). This could have also been impacted based on repeatability where the same technician was performing the same operation multiple times consecutively (setup and tear down).

The baseline period had a product cycle time (average over the production) of 2.33 hours. The experimental period had a product cycle time (average over the production) of 2.85 hours. This is indicative of product complexity where the set standard to complete the test operation is on average greater during the experimental period than the baseline period. Although increased cycle time was expected for each pump in the experimental period, the technician, without setup and teardown operations, improved throughput where the baseline was 3 pumps tested in 10.35 hours and the experimental period was 3 pumps tested in 9.78 hours.

7.7. Experiment Conclusions:

Comparing the baseline and the experimental measurement, correlations between the applications of JIT, TOC, OEE, TPM, Lean, 6σ, and QRM and the metrics were determined (RQ2, Task 6). These correlations began to define an applicable model for best practices in improving the metrics for HMLV manufacturing using JIT, TOC, OEE, TPM, Lean, 6σ, and QRM (RQ2, Task 7).

This experiment provided evidence of the applicability of JIT, TOC, OEE, TPM, Lean, 6σ, and QRM in HMLV manufacturing operations. All of the metrics that were controlled within the bounds of this experiment showed positive improvements with the applied paradigms. The variables that were subject to strong influence from either external or upstream operations such as inventory in WIP prior to test operations and, in many cases, failures that contributed to first pass yield reduction should be further examined.

It should also be noted that there is a need for further experimentation to better understand capacity for both upstream and test operations. It is not completely clear from the measurements if the capacity used was sufficient to meet production demands given the inverse relationship between WIP and effectiveness (WIP being a negative value add).

Lastly, although the experimental period provided more favorable results, it is clear that there is a labor absorption issue for test operations. This could indicate that there is low-capacity utilization overall or that the standard routed times are in need of review.

Chapter VIII: Experiment 5: Load Leveling Operations to Optimize Flexibility, Balance Throughput, and Improve Quality

This experiment is the fifth of (5) that will seek to answer the following research question (Research Question 2):

> *Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?*

This experiment expands the complexity of paradigm application through the implementation of multiple paradigms at the same time. This experiment was designed to exploit the similarities in these paradigms to achieve the goal of improving the metrics of cost, throughput, and flexibility. The four paradigms chosen provide a common emphasis on continuous improvement, an underlying philosophy of waste reduction, data as a means to measure performance, standardization to improve quality, focus on customer needs and expectations, and employee involvement to continuous learn and improve manufacturing processes.

For an illustration of the experimental design for Experiment 1, see Appendix E, Figure 38.

8.1. Description:

As a means to evaluate the effectiveness of philosophies attributable to Just in Time (JIT), Theory of Constraints (TOC), Overall Equipment Effectiveness (OEE), Lean

Manufacturing (Lean), and Quick Response Manufacturing (QRM), an experiment was conducted in a HMLV manufacturing environment. The intent was to understand production flow and impacts to other Key Performance Indicators (KPI's), including quality, when changes were made to scheduling processes. These changes focused on a work cell that contained 2 milling machines connected by a pallet changing system.

For this specific HMLV manufacturer, this work cell provided a unique opportunity to understand the use of production equipment intended for high volume production. The 12-pallet changer offered an opportunity to load the machine with several different fixtures at the same time, in turn allowing several parts to be fixtured at the same time. The operator had 2 unloading/ loading stations for the pallet changer system. This type of machine setup is more typical for higher volume production or production where the operator is used in other areas and the machine is unattended, while the 12 pallets of components are machined.

8.2. Paradigm(s):

This experiment was motivated by multiple paradigms, including JIT, TOC, OEE, Lean, and QRM that were first implemented (baseline) based on component cost level measurements. The intent of this work cell was to provide the major components for a single product in one machining cycle. This meant that each pallet would have a different major component and the end of a cycle provided components to assemble a single product. However, this work cell represented a large portion of the reported non-conforming product due to quality in the machine shop. For this reason, TQM was also considered a critical paradigm to implement and measure during the experiment.

8.3. Bounds:

This experiment focused on a single work cell because the components machined had no secondary operations. This work cell also machined a very limited variety of part numbers that were considered to be "higher volume" in the HMLV manufacturing environment. The components were all large and complex castings that required hours of machine time to be completed and WIP in front of the machine therefore represented a large portion of production floor space.

8.4. Metrics:

To effectively assess the impact of the application of the defined paradigms, the metrics and the specific measurement method have been defined for this experiment (RQ2, Task 1).

The metrics for this experiment were based on the metrics typically used under JIT, TOC, OEE, Lean, QRM, and TQM. Each of these was adjusted for applicability in the HMLV manufacturing environment as shown in Table 27.

Table 27: Traditional metrics for JIT, TOC, OEE, Lean, QRM, and TQM defined for specific experimental application (Ex 5)

Metric	Paradigm	Units	Definition
Total Cost (C_P)	All	USD ($)	This is a measure of the total process cost for a single part that includes any costs incurred from the time that the material is allocated to the job to the time that the job is completed (parts logged into stock).
Value Created (V_C)	All	USD ($)	This is the total value that the process produces.
Value (Profit) (V_P)	All	USD ($)	This is the actual value of the process (Value created - Cost)
Work In Process (WIP)	JIT	USD ($)	This is a measure of process wait time (by dollar value) and indicates the value of work waiting to be processed.

Parts Per Hour (PPH)	TOC/QRM	Parts	This is a measure of throughput and indicates how many parts per hour a process can produce.
Process Time Per Unit (H_P)	Lean	Hours	This is the number of hours that the batch is undergoing a process
Uptime (H_U)	OEE	%	This is a measure of machine availability compared to machine usage. For this experiment, the QRM definition of uptime is used where machine availability is based on operator availability to operate the machine.
Effectiveness (E)	OEE	%	This is a measure of parts produced that are within specifications compared to the time the operator is allocated to the job.
Performance (H_C)	OEE	%	Performance is a measure of the average cycle time for manufactured components.
Accuracy (A)	TQM	%	This is a quality measure of how effectively the process produces parts that are within specifications.
Lead Time (LT)	Lean	Hours	For this experiment, this is a measure of the time from when a component starts its first operation to the time when the component is logged into stock.
Reliability (H_R)	OEE	%	This is a measure of process repeatability based on the time to make adjustments.
Process Variation (σ)	Lean	Cpk	This is a measure of variation in component cost.

8.4.1. Experimental Design:

This experiment was designed to understand the overall cost of processing all of the major components for a single product through both one piece flow (12 pallet with all different components) and small batching (5 of each component at a time). The work cell layout (as shown in Figure 22) proved the operator with 2 loading/ unloading stations (LS 1 and LS 2) for raw materials, a 12 pallet pallet-changer, and 2 machining centers (M1 and M2) that shared the pallet changer.

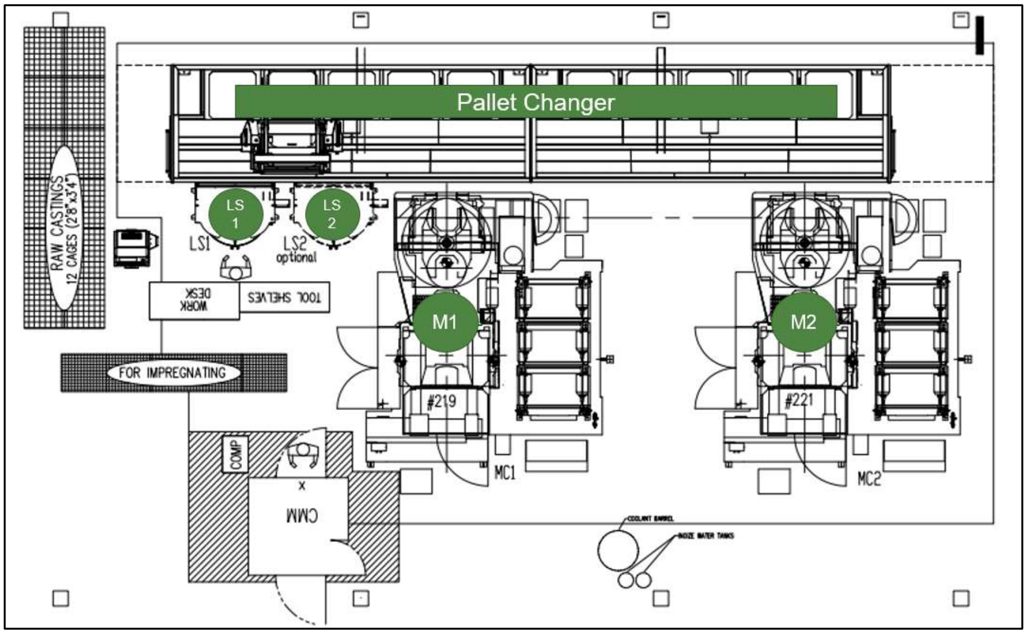


Figure 22: Work cell layout for baseline and experiment (Ex 5)

Using the pallet changer (Figure 23) and a shared toolbelt between the two machines, both the baseline and the experiment had no setup recorded as external to the job.

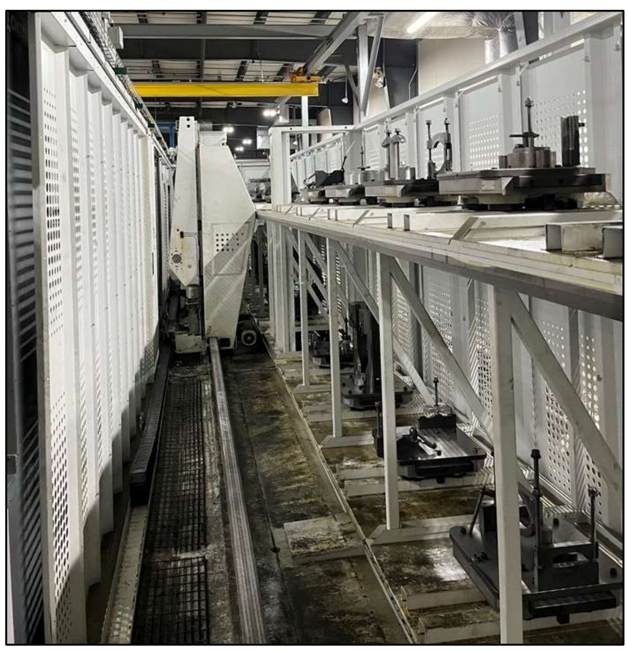


Figure 23: Pallet changer internal view with machine fixtures shown (Ex 5)

The baseline processing method included the use of 5 of these pallets setup to machine each of the 5 major components for a single product. The operator ran all 5 of these components in batches with one each in the machine at any given time (Figures 24 and 25).

	Pallet				
Component	1	2	3	4	5
A	X				
B		X			
C			X		
D				X	
E					X

Figure 24: Component pallet loading for baseline (Ex 5)

Machine 1	B	D	A	C	E	B	D	A	C	E	B	D	
Machine 2	A	C	E	B	D	A	C	E	B	D	A	C	E

Figure 25: Machine processing timeline for baseline (Ex 5)

The experiment processing method was to change the component batch to 5 and run 5 of each component before machining the next batch of 5 (Figures 26 and 27).

	Pallet																								
Component	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
A	X	X	X	X	X																				
B						X	X	X	X	X															
C											X	X	X	X	X										
D																X	X	X	X	X					
E																					X	X	X	X	X

Figure 26: Component pallet loading for experiment (Ex 5)

Machine 1	A	A	A	B	B	C	C	C	D	D	E	E	E
Machine 2	A	A	B	B	B	C	C	D	D	D	E	E	

Figure 27: Machine processing timeline for experiment (Ex 5)

For this experiment, the variables to calculate each metric were defined (Table 28).

Table 28: Variables measured for baseline and experiment period to calculate metrics (Ex 5)

Variable	Definition	Measurement Method
μ	Average Value from Population	Average cycle time based on job punches
C_M	Cost of Material	$(T_C*(OH_{WC}+OW_{WC})+(T_A/(Q_B-Q_S)-P_C)/5$

H	Hours	Average processing hours based on job punches
IW_{WC}	Inventory in WIP Value	Measured value based on WIP in front of machine
LT	Lead Time	Averge hours based on job punches
M	Number of Machines	Constant (2)
M_S	Machine Setup Time	Average hours based on job punches
N	Number of Values in Population	Number of batches over each 3 month period
OH_{EX}	Overhead multiplier for the experiment period (3 months)	Multipler based on 3 month period
OH_{WC}	Overhead for Work Center	Constant
OW_{WC}	Operator Wage for Work Center	Constant
P_C	Part Cost Average	T_C*(OH_{WC}+OW_{WC})+(T_A/(Q_B-Q_S)+C_M
PPH_{WC}	Parts Per Hour Produced for Work Center	Calculated based on parts produced over time
PV	Part Value	Avergae of selling price
Q_B	Number of Components in Batch	Average over time period
Q_S	Number of Components Scrapped in Batch	Components identified as non-conforming (average per batch)
T_A	Time for Machine Adjustments	Measure value based on job punches (all internal)
T_C	Cycle time per component (actual average over time period)	Average based on job punches
T_I	Ideal Cycle Time (Routed)	Average base on standard routings
T_J	Time Operator is on Specific Job	Average per job based on job punches
T_O	Labor Time for Operator	Average per job based on job punches
T_P	Planned Production Time (Routed)	Average based on standard routings
T_S	Machine Time Spent on Scrap Parts	Measured value of components identified as non-conforming
σ	Standard Deviation	Standard deviation of measured lead time

Using the variables shown in Table 28, the following equations were used to calculate the metrics for the baseline and for the experiment:

[1] Total Cost (C_P) = $((P_C*(Q_B-Q_S))+IW_{WC}(OH_{EX}))*Q_W$

[2] Value Created (V_C) = $((PV-P_C)(Q_B-Q_S))*Q_W$

[3] Value (Profit) (V_P) = $V_C-C_P= ((PV-P_C)(Q_B-Q_S))*Q_W-((P_C*(Q_B-Q_S))+IW_{WC}(OH_{EX}))*Q_W$

[4] Work in Process (WIP) = $I_W * OH_{WC}*OH_{EX}$

[5] Parts Per Hour (PPH) = Q_B / T_J

[6] Process Time Per Unit (H_P) = Measured Value

[7] Uptime (H_U) = T_C / T_O

[8] Effectiveness (E) = $(((Q_B - Q_S) * T_P) / T_O) / 100$

[9] Performance (H_C) = T_C / Q_B

[10] Accuracy (A) = $(Q_S/Q_B)*100$

[11] Lead Time (LT) = Measured Value

[12] Reliability (H_R) = $1 - (T_A + T_S) / T_J$

[13] Process Variation (σ) = $\sigma(\Sigma(x_i - \mu)^2/N)$

8.4.2. Baseline Measurements:

To effectively evaluate the impact of the defined paradigms, it was necessary to establish a baseline measurement for each metric. The baseline was used to provide a starting point from which to assess the effectiveness of each paradigm and draw meaningful conclusions about their potential for improving the defined metrics (RQ2, Task 2).

As part of the baseline definition, the scope for the experiment was defined (RQ2, Task 3). This provided a means to define the specific area of focus while allowing the experiment to be tailoring to the specific needs of the HMLV manufacturing environment.

Variables were measured for a 3-month period of production prior to paradigm application for the experiment. These measurements are shown in Table 29.

Table 29: Variable measurements for baseline 3-month production period (Ex 5)

Variable	Definition	Baseline
μ	Average Value from Population	83.07
C_M	Cost of Material	$285.35
H	Hours	299.33
IW_{WC}	Inventory in WIP Value	$62,547.92

LT	Lead Time	171.72
M	Number of Machines	2
M_S	Machine Setup Time[9]	1.90
N	Number of Values in Population	35
OH_{EX}	Overhead multiplier for the experiment period (3 months)	0.0625
OH_{WC}	Overhead for Work Center	$77.63
OW_{WC}	Operator Wage for Work Center	$26.25
P_C	Part Cost Average	$334.64
PPH_{WC}	Parts Per Hour Produced for Work Center	3.84
PV	Part Value	1031.35
Q_B	Number of Components in Batch	21.66
Q_S	Number of Components Scrapped in Batch	20.45%
T_A	Time for Machine Adjustments	1.90
T_C	Cycle time per component (actual average over time period)	13.73
T_I	Ideal Cycle Time (Routed)	3.73
T_J	Time Operator is on Specific Job	299.33
T_O	Labor Time for Operator	299.33
T_P	Planned Production Time (Routed)	82.62
T_S	Machine Time Spent on Scrap Parts	4.43
σ	Standard Deviation	53.44

During the baseline period, 35 batches of components were machined with an average batch size of 21.66 components, or 758 total components over the period. During this time, there were 72 non-conformity reports (NCR's) generated by the operator that effected 155 components and resulted in a non-conformity rate of 20.45%. These non-conformities required additional operations to be performed to correct their quality issues or, in some cases, the components were considered scrap. For the purposed of this experiment, these components are denoted by Quantity Scrap (Q_S) to indicate that the process yield was affected, resulting in fewer "complete" components at the end of the process.

Using the variables, the metrics were calculated (Table 30).

[9] Machine setup time was done completely internal to all operations and therefore is not part of the critical path.

Table 30: Metric calculations for the baseline 3 month production period (Ex 5)

EQ#	Metric	Variable	Baseline
1	**Total Cost (C_P)**	C_P	$338,608.88
2	**Value Created (V_C)**	V_C	$420,119.88
3	**Value (Profit) (V_P)**	V_P	$81,511.00
4	**Work In Process (WIP)**	WIP	$3,909.25
5	**Parts Per Hour (PPH)**	PPH	0.07
6	**Process Time Per Unit (H_P)**	H_P	1.28
7	**Uptime (H_U)**	H_U	0.05
8	**Effectiveness (E)**	E	0.21
9	**Performance (H_C)**	H_C	0.63
10	**Accuracy (A)**	A	0.94
11	**Lead Time (LT)**	LT	299.33
12	**Reliability (H_R)**	H_R	0.98
13	**Process Variation (σ)**	σ	1.31

Over the 3 month baseline period, the average time required to complete a component (considering the batch size) was 13.73 hours. For comparison to the experimental period that studied the production of 5 of each of the 5 components required for a complete product, the total time, as shown in Figure 26, to complete 5 of each component was 178.54 hours.

	13.73	13.73	13.73	13.73	13.73	13.73	13.73	13.73	13.73	13.73	13.73	13.73	13.73	**178.54**
Machine 1	B	D	A	C	E	B	D	A	C	E	B	D		**Hours**
Machine 2	A	C	E	B	D	A	C	E	B	D	A	C	E	

Figure 28: Timeline to complete 5 of each of the 5 components required during the 3-month baseline period (Ex 5)

8.5. Experimental Measurements:

Having determined the baseline measurements for the experiment, changes were made to the manufacturing process in accordance with JIT, TOC, OEE, Lean, and QRM and adjusted to the HMLV manufacturing environment (RQ2, Task 4). Once implemented, the metrics and their components were measured to determine how the application of JIT, TOC, OEE, Lean, and QRM principles impacted the metrics (RQ2, Task 5).

During the 3-month experimental period, the production processing method was changed to machine 5 of a single component at a time until all 5 of the component numbers were machined. This represented the addition of TQM to the process as a driver of total cost. The variables were recorded as shown in Table 31.

Table 31: Variable measurements for experimental 3-month production period (Ex 5)

Variable	Definition	Experiment
μ	Average Value from Population	155.09
C_M	Cost of Material	$183.82
H	Hours	181.92
IW_{WC}	Inventory in WIP Value	$9,363.73
LT	Lead Time	194.71
M	Number of Machines	2
M_S	Machine Setup Time	2.02
N	Number of Values in Population	27
OH_{EX}	Overhead multiplier for the experiment period (3 months)	0.0625
OH_{WC}	Overhead for Work Center	$77.63
OW_{WC}	Operator Wage for Work Center	$26.25
P_C	Part Cost Average	$335.48
PPH_{WC}	Parts Per Hour Produced for Work Center	7.61
PV	Part Value	980.93
Q_B	Number of Components in Batch	20.37
Q_S	Number of Components Scrapped in Batch	6.91%
T_A	Time for Machine Adjustments	1.71
T_C	Cycle time per component (actual average over time period)	8.85
T_I	Ideal Cycle Time (Routed)	3.72
T_J	Time Operator is on Specific Job	181.92
T_O	Labor Time for Operator	181.92
T_P	Planned Production Time (Routed)	77.89
T_S	Machine Time Spent on Scrap Parts	1.41
σ	Standard Deviation	62.83

During the experimental period, 27 batches of components were machined with an average batch size of 20.37 components, or 550 total components over the period. During this time, there were 23 NCR's generated by the operator that effected 38 components and resulted in a non-conformity rate of 6.91%.

Using the variables, the metrics were calculated (Table 32)

Table 32: Metric calculations for the experiment 3-month production period (Ex 5)

EQ#	Metric	Variable	Experiment
1	**Total Cost (C_P)**	C_P	$187,568.01
2	**Value Created (V_C)**	V_C	$330,471.29
3	**Value (Profit) (V_P)**	V_P	$142,903.28
4	**Work In Process (WIP)**	WIP	$585.23
5	**Parts Per Hour (PPH)**	PPH	0.11
6	**Process Time Per Unit (H_P)**	H_P	2.54
7	**Uptime (H_U)**	H_U	0.05
8	**Effectiveness (E)**	E	0.20
9	**Performance (H_C)**	H_C	0.43
10	**Accuracy (A)**	A	0.34
11	**Lead Time (LT)**	LT	181.92
12	**Reliability (H_R)**	H_R	0.98
13	**Process Variation (σ)**	σ	0.73

Over the 3-month experiment period, the average time required to complete a component (considering the batch size) was 8.85 hours. Figure 29 is a graphical timeline of the completion of 5 of each of the 5 components in a total of 115.01 hours.

	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	115.01
Machine 1	A	A	A	B	B	C	C	C	D	D	E	E	E	Hours
Machine 2	A	A	B	B	B	C	C	D	D	D	E	E		

Figure 29: Timeline to complete 5 of each of the 5 components required during the 3-month experimental period (Ex 5)

8.6. Reflection:

There was a significant reduction in non-conformity rate from the baseline (20.45%) to the experiment (6.91%). Component complexity did not significantly change between the 2 periods. This reduction in non-conformity rate significantly improved the process yield such that, although the experiment period produced 37.81% (758 during the baseline and 550 during the experiment) fewer components, the number of conforming components compared to the baseline was only 17.78% less (603 during the baseline and 512 during the experiment).

The total value (profit) during the experimental period was almost 43% greater than the baseline ($142,903.28 compared to $81,511.00 for the baseline). Process yield was a major contributor to this change in addition to the reduced number of each component the operator was logged into labor tracking for (complete 5 and record instead of complete the batch and record). This also resulted in improved process flexibility where components were able to be logged into stock in lower quantities (5 each instead of 5 batches of 21.66 components each).

8.7. Experiment Conclusions:

Comparing the baseline and the experimental measurement, correlations between the applications of JIT, TOC, OEE, Lean, and QRM and the metrics were determined (RQ2, Task 6). These correlations began to define an applicable model for best practices in improving the metrics for HMLV manufacturing using JIT, TOC, OEE, Lean, and QRM (RQ2, Task 7).

The improved quality and reduced time during the experiment required further understanding of the process issues that the operator was addressing. The operator indicated that the complexity of machining 5 different components at the same time added a high degree of difficulty to the process. For instance, given that the tool belt is shared between machines and components, any tool adjustment now had to be tracked over 5 different components. This was difficult for the operator to keep track of and created many opportunities for human-error that contributed to the high level of non-conformities during the baseline.

In addition to the complexity of tracking tool adjustments over all of the components, there was a reduction in confidence when loading each of the 5 components when loading 5 of the same one at a time compared to 5 different components at the same time. Further studies could determine the optimal “batch” sizing to reduce operator fatigue while ensuring that on time delivery is adequate for downstream processes such as assembly.

It was also found during the experiment that reasons for the non-conformities generated was consistent with the baseline period. In most cases, dimensions outside of the allowed tolerance range resulted in the non-conformities. This resulted in mixed normal distributions (Figure 28) for dimensions and indicated that there was a significant amount of adjustment taking place during the machining of various batches. Further investigation is needed to determine if the high non-conformity rate (for both the baseline and the experiment) could be further improved with a review of required tolerances and machine capability.

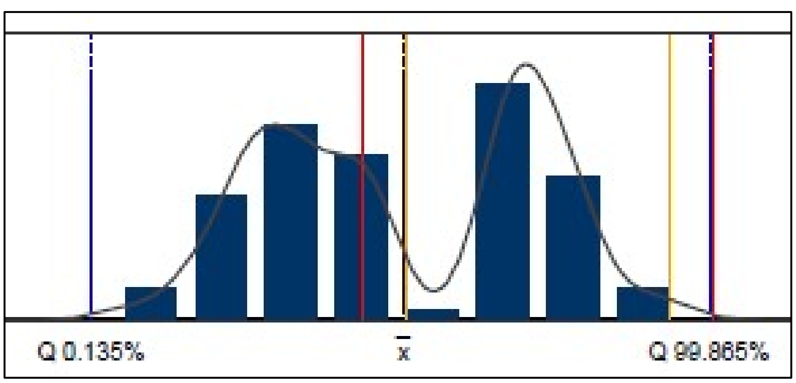


*Figure 30**:** Mixed normal distribution of machined feature representative of the non-conformities during both the baseline and the experimental period (specific chart is during the experimental period) (Ex 5)*

Chapter IX: Presentation of Research (Results)

The State of the Art, Implications, and Applications

Research Question 1 aimed to investigate the various manufacturing paradigms that have been used in LMHV manufacturing environments to determine their potential for experimental application in HMLV manufacturing:

> *Using a literature review method, what are the comprehensive set of manufacturing philosophies that have been considered in managing, optimizing, and enabling HMLV, and what is the consensus in the field on their application and success?*

The survey of existing literature for industrial paradigm application in HMLV manufacturing (RQ1, Task 1) revealed that many of the paradigms were specifically designed and validated in the context of LMHV manufacturing. The existing literature was limited in describing how these paradigms could be adjusted or adapted to provide similar benefits in HMLV manufacturing environments. The paradigms, however, could be grouped into categories based on the metrics and competitive advantages they were developed to address (RQ1, Task 2). These categories were compared to a needs analysis (Appendix A) conducted for a subject manufacturer and prioritized based on the correlations in intent. The specific method used can be seen in Appendix B, but the categorization resulted in the framework shown in Table 33 for research, where the paradigms are grouped by the requirements in HMLV manufacturing.

Table 33: Industrial paradigm applications compared to requirements defined by needs analysis

Paradigms	JIT	TQM	TOC	OEE	TPM	Lean	6σ	QRM
Improve Throughput								
Minimize purchased goods lead time	X		X					

Minimize manufacturing flow time	X	X	X	X	X	X	X	X
Improve Flexibility								
Maintain legacy product support	X		X			X		X
Maintain customized product	X		X					X
Maximize operational flexibility	X		X			X		X
Reduce Cost								
Minimize Costs	X	X	X	X	X	X	X	X

Experimental Design, Implementation, and Outcomes

Research Question 2 aimed to implement the various manufacturing paradigms that have been used in LMHV manufacturing environments to determine through experimentation their cost and benefits in HMLV manufacturing environments.

> *Using experiments conducted within a real-world manufacturing system, based on the application of industrial paradigms suggested in existing literature, which paradigms provide the strongest potential for improving competitive advantage for high-mix low-volume manufacturers and therefore warrant inclusion in a potential framework for application outside of the subject manufacturer?*

Using the metrics derived from RQ1, the variable measurement methods were determined for each of the experiments (RQ2, Task 1). All variables that were determined to not be constants were measured in real time based on job punches or in situ observation.

With the measurement methods defined, each experiment began with documenting a baseline period (RQ2, Task 2). The baseline period was determined by how long the measured process would take, how dynamic the process was, and how stable the process was. These determinations were made based on practical knowledge of the processes.

Through the baseline documentation process, the application scope was further refined based on anomalies or other factors that were determined to not be representative of typical manufacturing in this HMLV setting (RQ2, Task 3). Once the scope was refined and the baseline documented, the defined paradigms were implemented as documented in the experiment detail (RQ2, Task 4). Outputs from the experimental period were then measured (RQ2, Task 5).

Each of the following 5 experiments followed the tasks outline in RQ2 (Tasks 1 – 5).

Experiment 1: Hybrid Dynamic Manufacturing as a Theory of Constraints Application Method

Experiment 1 employed the use of Theory of Constraints principles to offload the main production line. Using a technique referred to as Hybrid Dynamic (HD) manufacturing. HD manufacturing attempts to combine the benefits of traditional and advanced manufacturing systems. In HD manufacturing, traditional systems such as manual machining or, in this case, semi-manual machining, are integrated with more advanced manufacturing technologies such as automation using CNC machines. The premise is that this combination of technologies is more flexible and adaptive as a manufacturing system and can quickly respond to changes in market demand and production requirements. HD seeks to achieve efficiency, scalability, and consistency while maintaining agility and reducing costs.

The results of Experiment 1 provided strong evidence that the use of HD manufacturing, in the form of a low volume cell (LV), could be used in HMLV manufacturing to successfully implement TOC principles and processes. TOC posits that the following series of steps can be followed to reduce constraints within a system:

1) Identify the constraint: For this experiment, the constraint was identified as a machining center that was part of the main production system. This was identified by the amount of WIP waiting for processing in front of this machining center ($494,997 at baseline conditions).
2) Manage the constraint: Measurement of the baseline metrics revealed that the machining center provided a constraint to the production system's performance. The baseline measurements provided further evidence of the constraint that this machining center imposed on the production system.
3) Improve the constraint: It was determined that the constraint could be primarily alleviated by reducing the number of machine changeovers as compared to run time for the machine, thereby increasing uptime. This prompted the implementation of the HD cell to offload the main production equipment of the ultra-low volume components.
4) Elevate the constraint: The HD cell was successful in offloading the machining center and provided a means to ensure that the machining center would not have the same constraint in the future with ultra-low volume production increasing the number of machine setups.
5) Repeat the process: The HD cell now includes capacity to allow other production equipment to offload ultra-low volume production in the future.

A crucial component to measuring the success of this experiment was using a system-level viewpoint to understand the impact to cost that the LV cell had overall. If the cell were measured individually, the cost of manufacturing the components compared to the main production machining center was significantly higher per component. The processing time in the LV cell was longer for every component than it would have been on the main production equipment. However, the increased uptime that offloading to this LV cell gave to the main production equipment, in addition to the comparatively low implementation costs considering the much less expensive equipment used in this cell, provided a significant increase in the overall (system level) value created.

In addition to the benefit of overall value creation, the LV cell also provided a much more flexible manufacturing process than the main production machining center. The machining center required large, expensive, and complex machine fixturing in addition to more expensive tooling. The LV cell was able to use “low-tech” fixturing that was adaptable to many different part geometries. The cost of the equipment and tooling in the LV cell was, as a result, significantly less than the main production machining center and was able to be used without modifications to accommodate varying geometry. The operator in this cell was able to adapt the process as necessary to machine each component.

The cost to add the LV cell was 16.7%. However, the result of this experiment was that value created when the LV cell was added was 4.5% higher than the value created without. If traditional cost accounting methods were used for the components produced, the benefit of implementing the LV cell would not have been apparent.

Experiment 2: Increasing Operational Flexibility Using Adaptable Machining Fixture Methods

Experiment 2 tests the use of multiple paradigms that were combined based on the similarity in their intent. Operational flexibility in HMLV manufacturing is a key concept that drives competitive advantage through adaptable processes that allow for quick responses to rapidly changing customer needs. The paradigms of TQM, QRM, and Lean all intend to provide the benefit of flexibility and TPM adds cost and throughput as additional metrics. When implemented together, we can test whether all three of the metrics (flexibility, cost, and throughput) could be optimized.

This experiment was conducted using a single machining center where a large variety of components with long setup times were being manufactured. The components that were chosen all included a similar prior lathe operation that provided an opportunity to capitalize on the use of this type of feature for fixturing. The fixtures in use for the machining center operation were large plate style fixtures that were heavy and difficult to move in and out of the machining center. Each component had its own unique fixture which required changing the fixture during each setup and allowing storage space for the large number of fixtures.

Traditional TQM metrics of accuracy, cost, and process variation (as a means to reduce costs) were used. These metrics were chosen as a representation of all of the traditional TQM metrics while still adapting to the specific experiment and the availability of data or ability to measure the data.

Traditional QRM metrics of reliability and uptime were used. Also traditionally used for TPM, QRM uptime was used because of its ability to adapt to a manufacturing environment where flexibility means that machine may be left idle while operators perform other operations. Reliability was related to this definition of uptime and was also a metric chosen for its traditional application within the TQM paradigm.

Traditional Lean metrics related to cost were tracked along with the other metrics to ensure that the experimental changes did not improve the metrics of throughput and flexibility by increasing costs (which is often a concern in HMLV manufacturing). The Lean principle of standardization wherever possible was also applied cautiously to not reduce flexibility.

The results of this experiment provide evidence that adaptable fixture techniques could provide an overall cost benefit in HMLV manufacturing. It was found that the overall cost to both produce and use the adaptable fixtures was significantly less than the baseline. The experimental changes provide an increase in parts produced during the experimental period of 8% and, when considering the initial cost to manufacture, the cost to store the fixtures, and the time to change between parts, the total benefit of the adaptable fixturing process was approximately 21.4% more. This also included a key quality metric improvement of approximately 37.8% which represented the reduced amount of machine time used making non-conforming parts.

This experiment provided evidence that the paradigms could be combined and adapted to the HMLV environment in a way that would provide a benefit beyond single paradigm application.

Experiment 3: Standardization with Machining Process Flow

Experiment 3 employed the use of multiple paradigms that were combined based on the similarity in their intent. Standardization in HMLV manufacturing is difficult to achieve at a product-level while maintaining the ability to respond to the customer demand for customization. For this experiment, the paradigms chosen were JIT, OEE, TPM, Lean, 6σ, and QRM. The intent was to use the waste reduction methods of JIT, OEE, TPM, and Lean combined with the quality focus of 6σ and the adaptability of QRM to determine if a benefit would result from processing changes. In this experiment, two different scenarios were tested: single machine manufacturing (as used in LMHV operations), and cellular manufacturing (as suggested by QRM).

When attempting to achieve standardization at a process level with a wide variety of components, it is important to understand the manufacturing environment from a system-level. This experiment focused on the manufacturing processes needed to manufacture shafts. Although the experiment was focused on optimization for a single part number, it is important to note that this part is representative of hundreds of different components that could all be manufactured through the same processes and materials.

Traditional metrics for each paradigm were reviewed and it was determined that cost would be a measure of both waste in the process, and quality. For this reason, WIP and on time delivery (JIT), performance and effectiveness (OEE), uptime (TPM and QRM), lead time and process variability (6σ), and throughput in parts per hour (JIT and QRM) were calculated in addition to the overall process cost.

The results of this experiment provided evidence that both of the experimental processing methods had benefits beyond the baseline. For instance, the measured on-time delivery (as measured by job punches compared to job due dates) increased from the baseline of 33.3% to 85.7% for single machine processing. The cellular processing method saw no change from the baseline. The cellular processing method did, however, provide an improvement in uptime because the majority of the machine downtime in setup became internal to other processes. This was an increase to 34.19% compared to the baseline of 14.76% and single machine processing of 18.77%. For the baseline and single machine processing, the largest contributor to decreased uptime was the wait time before processing.

Despite the overall benefits from each of the experimental processing methods, when looking at the entire manufacturing process for the shaft, there was little improvement to the total cost. The cellular process showed a cost benefit of 2.9% compared to the baseline. The single machine processing method increased overall cost by approximately 14%.

Experiment 4: Reducing Change Over Times Using Adjusted Process Flow and Internalized Operations

Experiment 4 employed the use of multiple paradigms including JIT, TOC, OEE, TPM, Lean, 6σ, and QRM applied to a testing and validation process. Similar to experiment 1, the process used for this experiment was identified as a constraint in the overall production system. The initial impression of this constraint was that labor could be allocated to elevate the constraint without any other changes being made to the process. However, this would have represented a higher cost and would not have been aligned with the combined metrics of cost reduction with improved throughput and flexibility. Each of the paradigms were chosen based on the premise that they would impact these metrics.

For this experiment, the labor resources remained constant, and the processing method was changed. The baseline employed 4 test technicians who would retrieve product from a staging area, prepare the product for testing, connect the product to one of the test cells, and then test the product based on a pre-defined standard. This was changed to 3 test technicians connecting product to one of the test cells (each) and testing the product while 1 test technician performed setup and teardown operations for the 3 test technicians. This effectively made downtime from setup and teardown internal to test operations.

The result of this experiment was a wait time reduction for testing. This wait time was the time for setup and teardown operations that accounted for the process downtime for each technician. Although the number of technicians performing the direct labor process of “testing” was reduced by 25%, the result was a production increase of approximately 38% (299 products tested during the experiment compared to the baseline of 185 products). In addition to this improvement, the first pass yield for the test process also improved from 74% to 89% in the experimental period. This improvement was attributed to the improved repeatability in processes where no technician was changing between the mechanical operations of setup and teardown to the process operation of testing.

These findings provided strong evidence for the applicability of JIT, TOC, OEE, TPM, Lean, 6σ, and QRM to HMLV manufacturing product test operations. This particular experiment also provides promising evidence that similar processing changes could be used in other areas of manufacturing. For instance, this method could also benefit machining center operations where operators run component machining cycles while a secondary party provides setup and teardown operations. This is especially applicable in HMLV manufacturing where machines are sometimes intentionally not used because other operations that require the labor resource take precedence.

Experiment 5: Load Leveling Operations to Optimize Flexibility, Balance Throughput, and Improve Quality

Experiment 5 employed the use of multiple paradigms including JIT, TOC, OEE, Lean, TQM, and QRM. For this experiment, a work cell consisting of two machining centers linked with shared pallets and tooling represented a constraint in production operations. This constraint was exacerbated by significant quality issues that required rework that was often performed in the LV cell set up in Experiment 1.

This machining cell was intended to provide all of the major components for a single product by utilizing the multiple pallet system to load one of each of the main components into the machine at the same time. The intent was to then offload the components into a single basket to be moved directly to assembly. This was done in component batches averaging about 22 components (times five different components). This method was the baseline before the implementation of the paradigms for the experiment.

During the baseline measurements, the process yield was approximately 80% (4.43 components per 21.66 component batch were non-conforming). It was suspected that this low process yield, compared to other machining centers in the same HMLV manufacturing environment, was the result of primarily human error. In most cases the components were reworked rather than scrapped due to material defects. This indicated that the process itself was not in control. The operator was experiencing difficulty in remembering every tool adjustment that was made and relating that to how it affected the quality for the rest of the components that used the same tool for machining.

The experimental treatment consisted of a process to load five of the same component at a time, machine those, and then load five of the next components, and so on. Although this change might reduce operator error, it also has the effect of increasing lead time. This resulted in a quality improvement to 96% process yield (1.41 components per 20.37 component batch were non-conforming). Despite a batch lead time increase of approximately 13% (from a baseline of 171.72 hours to the experimental measure of 194.71 hours), the overall cost to produce five of each of the five components drastically improved. Expanded over the experimental period, this resulted in an increase value (profit) of over 75%.

This experiment provided evidence of both the need for a system level viewpoint to understand the full impact of poor process yield (where the rework was done at another work center), and the need to consider how human factors impact quality. Without understanding the specific reasoning that the operator was having difficulty, changing the processing method would not have made sense.

9.1. Paradigm Discussion and Assessment

Next, the paradigms were compared across all of the experiments to determine correlations in methods and metrics, if there were areas where they were more or less effective than others (RQ2, Task 6):

Just in Time (JIT)

JIT is a method to control inventory and production systems to minimize waste and improve efficiency by producing goods as they are needed. The intended benefits to this paradigm include reduced inventory costs, reduced cost of quality defects (because of low inventory), increased flexibility, reduced lead times, improved productivity through waste elimination, and increased collaboration and communication at all levels of the supply chain.

Table 34 compares the benefits and detriments to each of the metrics for the experiments where JIT methodology was applied. Each value represents a comparison between the experimental data and the baseline for each experiment where benefits are displayed in green, and detriments are displayed in red.

JIT methods are aligned with the interventions used in experiments 3, 4, and 5. JIT application is associated with no effect on the metric of Reliability (H_R). The largest effects appeared to be in increased PPH with an average of 245% gain for all experiments and Total Cost (C_P) with an average cost decrease of 24.57%.

JIT methods are associated negatively with the metrics of Performance (HC) and WIP for experiments 4 and 5 while providing a benefit in experiment 3. Experiment 3 did not include TOC or lean methodology application whereas 4 and 5 did. All 3 experiments included (in addition to JIT), OEE and QRM methodology.

Table 34: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with JIT methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 3 (Cell)		2.82%	181.58%		0.00%		100.00%				231.64%	71.39%	100.00%	415.79%	16.15%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%
Ex 5	36.17%	44.61%	55.73%		95.24%		68.25%		198.44%	0.00%	0.00%	113.39%		157.14%	85.03%

<u>Theory of Constraints (TOC)</u>

TOC is a management philosophy that seeks to optimize the performance of an organization by identifying, addressing, and eliminating constraints. The intended benefits of

TOC include improved resource utilization, increased throughput, reduced lead time, increased flexibility, and improved employee engagement.

TOC methodology was used in experiments 1, 4, and 5. TOC application appeared to have no effect on the metric of Reliability (R). TOC application appeared to have a detrimental effect on WIP in experiments 1 and 4 with a marginal increase of 0.5% in experiment 1 and an increase of 281.12% in experiment 4.

All 3 of the experiments where TOC methodology was applied realized a benefit in total cost with an average improvement of 44.5%. This is largely attributable with to the improvement in PPH with an average improvement of 44.2%.

Table 35 compares the benefits and detriments to each of the metrics for the experiments where the intervention can be associated with TOC.

Table 35: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with TOC methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 1		95.53%			95.53%	113.05%						99.49%		113.05%	100.50%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%
Ex 5	36.17%	44.61%	55.73%		95.24%		68.25%		198.44%	0.00%	0.00%	113.39%		157.14%	85.03%

Total Quality Management (TQM)

TQM is an approach used to optimize the quality of products by involving the entire supply chain (internal and external) in the process. The intended benefits of this paradigm include improved customer satisfaction, increased efficiency, employee involvement, decision making based on data, increased flexibility (because of reduced rework), and improved safety.

TQM methodology was used in experiment 2. The largest detrimental effects appeared to be an increase in process variation (σ) of 171.01% and an increase in WIP of 839.63%. Despite these effects, the PPH increase of 108.21% appeared to provide a large enough benefit to result in a total cost reduction for the experimental process of 53.53%.

Experiment 2 may have been largely impacted by human factors such as process familiarity and measurements should be retaken after a longer period of time after the implementation of the experimental changes to determine if the same benefits and detriments are still apparent.

Table 36 illustrates the benefits and detriments to each metric where the intervention can be associated with TQM.

Table 36: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with TQM methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 2	100.20%	53.53%	171.01%	71.89%				68.86%		123.53%	101.43%			108.21%	839.63%

Overall Equipment Effectiveness (OEE)

OEE is a paradigm centered around performance metrics that provide a comprehensive assessment of efficiency and effectiveness of the manufacturing equipment. Benefits of OEE include improved equipment utilization (uptime), reduced downtime, improved product quality, data driven decision making, increased throughput, and improved employee engagement.

OEE methodology was used in experiments 3, 4, and 5. OEE application appeared to have no effect on the metric of Reliability (R). The largest effects of OEE application appeared to be an improvement in PPH averaging 245.09% and a total cost improvement of 24.57%. The metric that appeared to have the most detrimental effect was Performance (H_C) with an average decrease of 20.86%.

Table 37 compares the benefits and detriments to each of the metrics for the experiments where the intervention can be associated with OEE.

Table 37: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with OEE methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 3 (Cell)		97.18%	181.58%		0.00%		100.00%				231.64%	71.39%	100.00%	415.79%	16.15%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%
Ex 5	36.17%	44.61%	55.73%		95.24%		68.25%		198.44%	0.00%	0.00%	113.39%		157.14%	85.03%

<u>Total Productive Maintenance (TPM)</u>

TPM is maintenance strategy that seeks to optimize the performance of equipment and processes. The benefits of TPM include improved equipment performance, increased equipment reliability, improved product quality, reduced maintenance costs, improved safety, and increased employee engagement.

TPM methodology was used in experiments 2, 3, and 4. The largest effects of TPM application appeared to be an overall cost improvement averaging 59.00% and an average uptime increase of 171.08%. The metrics that appeared to have the most detrimental effects were Process Variation (σ) with an increase of 176.30% and WIP with an increase of 378.98%.

Table 38 compares the benefits and detriments to each of the metrics for the experiments where the intervention can be associated with TPM.

Table 38: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with TPM methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 2	100.20%	53.53%	171.01%	71.89%				68.86%		123.53%	101.43%			108.21%	839.63%
Ex 3 (Cell)		97.18%	181.58%		0.00%		100.00%				231.64%	71.39%	100.00%	415.79%	16.15%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%

Lean Manufacturing (Lean)

Lean is a production philosophy that seeks to minimize waste and maximize value by continuously improving manufacturing processes. Benefits of lean include improved process efficiency, increased customer satisfaction, improved product quality, reduced costs, increased flexibility (through process standardization), and improved employee engagement.

Lean methodology was used in experiments 2, 4, and 5. The largest effects of Lean application appeared to be cost improvements averaging 58.53% and PPH increases averaging 142.56%. The metrics that appeared to have the most detrimental effect were Performance (HC) with a decrease averaging 31.28%, and WIP with a benefit of 14.97% for experiment 5 but a detriment of increased WIP by 560.37% for experiments 2 and 4. Experiments 2 and 4 also had TPM methodology applied, whereas Experiment 5 did not.

Table 39 compares the benefits and detriments to each of the metrics for the experiments where the intervention can be associated with Lean.

Table 39: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with Lean methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 2	100.20%	53.53%	171.01%	71.89%				68.86%		123.53%	101.43%			108.21%	839.63%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%
Ex 5	36.17%	44.61%	55.73%		95.24%		68.25%		198.44%	0.00%	0.00%	113.39%		157.14%	85.03%

Six Sigma (6σ)

6σ is a quality management approach that seeks to minimize defects and variability in processed and products using data-driven decision making. The benefits of 6σ include improved quality, increased efficiency, reduced cost, data-drive decision making, improved customer satisfaction, improved business performance, and improved employee engagement.

6σ methodology was used in experiments 3 and 4. The largest effects of 6σ application appeared to be cost improvements of 14.55%, uptime improvements of 205.91%, and PPH improvements of 289.06%. The metric that appeared to have the most detriment was Process

Variation (σ) with an increase of 181.58%. It is important to note that experiment 3 measured process variation but did not seek to control it through standardization.

Table 40 compares the benefits and detriments to each of the metrics for the experiments where the intervention can be associated with 6σ.

Table 40: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with 6σ methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 3 (Cell)		97.18%	181.58%		0.00%		100.00%				231.64%	71.39%	100.00%	415.79%	16.15%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%

Quick Response Manufacturing (QRM)

QRM is a production philosophy that seeks to minimize lead times and maximize customer satisfaction through improved production flow with reduced set up times. The benefits of QRM include reduced lead times, increased customer satisfaction, improved flexibility, increased productivity, improved quality, increased employee engagement, and overall improved business performance.

QRM methodology was used in experiments 2, 3, 4, and 5. The largest effects of QRM application appeared to be improvements in overall cost of 68.19%, improvements in uptime of 171.08%, and improvements in PPH of 210.87%. The metrics that appeared to have the most detrimental effects were Process Variation (σ) with an increase averaging 136.11%, Effectiveness (E) with decrease averaging 6.75%, and Performance (H_C) with a decrease averaging 20.86%.

Table 41 compares the benefits and detriments to each of the metrics for the experiments where the intervention can be associated with QRM.

Table 41: Comparison of baseline to experimental data with benefits and detriments defined for each experiment with QRM methodology used

	Accuracy (A)	Total Cost (C_P)/ Value	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 2	100.20%	53.53%	171.01%	71.89%				68.86%		123.53%	101.43%			108.21%	839.63%
Ex 3 (Cell)		97.18%	181.58%		0.00%		100.00%				231.64%	71.39%	100.00%	415.79%	16.15%
Ex 4		26.28%			225.00%		69.18%		44.59%		180.19%	187.84%		162.34%	281.12%
Ex 5	36.17%	44.61%	55.73%		95.24%		68.25%		198.44%	0.00%	0.00%	113.39%		157.14%	85.03%

RQ2, Task 7 seeks to begin articulating an applicable model for paradigm implementation for HMLV manufacturing.

9.2. Summary and Conclusions

Each of these paradigms provides a potential benefit for HMLV manufacturers to improve their costs, throughput, and flexibility. However, implementation of the methods in the HMLV environment is challenging for many reasons. In HMLV manufacturing, the process and product complexity make it difficult to standardize and optimize processes for efficiency and quality. HMLV manufacturing also has a general lack of data large enough to provide statistically significant sample sizes, making the traditional way that LMHV manufacturers use data to drive decisions more difficult. In many cases, there is not enough data to determine whether paradigm application has been successful without expanding the types of data to be considered.

Another key learning is in regard to HMLV manufacturers typically use highly skilled labor for production operations. This is intended to offset the large number of resources it would take to fully document processes based on the large variety and complexity of products and processes. However, this type of workforce is also more resistant to change and relies more heavily on performing production processes in the exact same ways that have been shown to work in the past. In this environment, the ability to adapt to change is stifled and can take a much greater amount of time, making experimentation and adaptation based on the results a much longer learning cycle than LMHV operations.

Finally, the learnings from such experiments are subject to change and uncertainty. When changes are made in HMLV manufacturing, the variety of products and processes effected is very high given that processes are set up to be adaptable to many different products. This means that change integration involves nearly every functional area to communicate in a high level of detail that is often difficult to achieve. In addition to internal processes, the product complexity also creates a highly complex supply chain that requires significant resource allocation to coordinate and synchronize processes with suppliers and customers.

Chapter X: Summary, Implications, Conclusions (Discussion)

The needs analysis conducted for this specific HMLV manufacturer provided crucial information to determine the unique requirements of this type of environment. These needs were distilled into three requirements: throughput, cost, and flexibility. In many cases, flexibility proves to be a detriment to optimizing throughput and cost. Flexibility in manufacturing is complex and time consuming. The use of existing industrial paradigms in this environment is also complex and requires a systems-level viewpoint to successfully realize the benefits that LMHV manufacturers achieve with these paradigms.

Research Question 3 seeks to determine which existing industrial paradigms have the greatest potential to improve the metrics defined in the needs analysis for a HMLV manufacturer.

> *Using a needs analysis to determine specific requirements and applying existing industrial paradigms in a real-world setting based on the potential to satisfy those needs determined, what paradigms provide promising results for further research?*

Each implemented paradigm represented an approach or methodology that included a new manufacturing process, a new management strategy, or a new application of an existing approach. Research Question 3, Task 1 involved documenting the correlations that have been determined between metric outputs and the implemented paradigm(s) for each experiment.

Correlations Between Experiments

The objective of Research Question 3, Task 1 is to document and examine the correlation between implementation methods and metrics in a HMLV manufacturing environment. The metrics calculated for each experiment were designed to quantify performance and assess the efficacy of the implementation of industrial paradigms. Through the identification of beneficial and hindering practices within the HMLV context, a relevant model can be developed. The ultimate goal of this analysis is to establish an understanding of the relationship between the implementation methods and the performance metrics for the HMLV manufacturing environment.

Table 42 presents a comparative analysis of the experiments, the implemented paradigms, and the metrics used to assess the paradigm performance. This comparison was conducted to determine the effect of each paradigm on the metrics with the results classified into three categories: beneficial (+), detrimental (-), or having no impact (0). The purpose of this analysis is to provide a clear and concise evaluation of the relationship between the paradigms and the metrics, which will facilitate the development of a relevant model for paradigm application in HMLV manufacturing environments.

Table 42: Comparison of experiments and implemented paradigms to determine impact to metrics[10]

	Paradigms								**Metrics**														
	JIT	TQM	TOC	OEE	TPM	Lean	6σ	QRM	Accuracy (A)	Total Cost (C_P)	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)
Ex 1			X							+			+	+						+		+	-
Ex 2		X			X	X		X	+	+	-	+				+		+	+			+	+

[10] Experiment 3 included two different applications of the paradigms. One was a single machine manufacturing process and the other was a cellular process. For the purpose of comparison, the cellular process is used as it was determined that process provided more overall benefits than the single machine process or the baseline.

Ex 3 (Cell)	X			X	X		X	X		+	-		0		+				+	+	+	+	+
Ex 4	X		X	X	X	X	X	X		+			+		-		+		+	-		+	-
Ex 5	X		X	X		X		X	-	+	+		-		-		-	0	0	+		+	+

Using the information from Table 42, a mathematical comparison can be made to determine the correlations between the experiments and the paradigms. Each (-) was assigned a value of (-1) and each (+) was assigned a valued of (1). The values were then normalized based on the number of times that each of the paradigms was used for each of the five experiments. Table 43 presents a ranking of the paradigms utilized within the five experimental applications in the specific HMLV manufacturing environment.

Table 43: Mathematical comparison of benefits and detriments each paradigm provided, adjusted by number of uses to determine overall score for each paradigm

	Metrics																
Paradigm	Accuracy (A)	Total Cost (C_P)	Process Variation (σ)	Initial Setup Cost (C_{SR})	Effectiveness (E)	Throughput	Performance (H_C)	Labor Hours (H_L)	Process Time per Unit (H_P)	Reliability (H_R)	Uptime (H_U)	Lead Time (LT)	On Time Delivery	Parts Per Hour (PPH)	WIP (WIP)	**Totals**	**Normalized Totals**
JIT	-1	3	0	0	0	0	-1	0	0	0	2	1	1	3	1	**9**	**3**
TQM	1	1	-1	1	0	0	0	1	0	1	1	0	0	1	1	**7**	**7**
TOC	-1	3	1	0	1	1	-2	0	0	0	1	1	0	3	-1	**7**	**2**
OEE	-1	3	0	0	0	0	-1	0	0	0	2	1	1	3	1	**9**	**3**
TPM	1	3	-2	1	1	0	0	1	1	1	3	0	1	3	2	**16**	**5**
Lean	0	3	0	1	0	0	-2	1	0	1	2	0	0	3	1	**10**	**3**
6σ	0	2	-1	0	1	0	0	0	1	0	2	0	1	2	0	**8**	**4**
QRM	0	4	-1	1	0	0	-1	1	0	1	3	1	1	4	3	**17**	**4**

The results indicate that TQM has proven to be the most advantageous paradigm for this particular environment, receiving a score of 7. This observation aligns with the challenges of controlling quality in a flexible manufacturing environment such as HMLV. On the other hand, the TOC paradigm demonstrated the least benefit, with a score of 2. Despite its low overall score, the data suggests that TOC plays a significant role in HMLV manufacturing operations and contributes to favorable outcomes in the metrics that it does impact such as high scores in total cost benefits and throughput as measured by PPH.

All of the experiments provided strong evidence that a holistic approach to understanding overall cost, in addition to value creation is beneficial in paradigm application in HMLV manufacturing. This approach provides a more comprehensive view of the cost structure of the manufacturing processes as a system rather than a series of isolated events and focuses on understanding the interactions between the components and how they affect the overall performance of the system.

This result supports the premise that HMLV manufacturing environments must be treated as an entire system in order to understand how changes can impact the overall system (manufacturing environment) performance. Similar to any complex mechanical system, the HMLV manufacturing environment presents interdependence of components including the supply of raw materials, equipment, labor, and management processes. A change to one component of the system can have a ripple effect on other components and the overall system performance. By treating the HMLV manufacturing environment as an entire system, it is possible to identify the interdependencies between these components and attempt to control and measure them for requirements (needs) optimization.

The HMLV manufacturing environment also includes complex interactions between components. Without a holistic view of this environment, it is difficult to understand and anticipate what outcomes there will be and where they will happen when changes are made to any component in the system. This viewpoint allows for the avoidance of unintended negative consequences while prioritizing changes that will provide an overall benefit.

The outcomes of all of the experiments were influenced by the utilization of highly skilled labor in the HMLV manufacturing environment. The presence of highly skilled labor is a common requirement in complex manufacturing environments, as it is perceived to minimize the upfront costs of detailed documentation. However, previous research has shown that the use of highly skilled labor can also negatively affect the flexibility of manufacturing operations [22]. This is due to the skillsets of these workers that are often tailored to specific applications, making it challenging to adapt to changes. Additionally, the labor resources are not easily transferred between different operations, further reducing the overall flexibility of the manufacturing environment. When making process changes, it is crucial to consider both employee satisfaction and engagement as well as standardization. Failure to balance these factors can result in frustration among employees, who are unable to utilize their skills to their full potential. This can lead to decreased collaboration, resistance to mentoring, and negative impacts on team dynamics and communication.

Given these considerations, it is essential to consider the human factors involved in the design of a system that improves the metrics of flexibility, throughput, and cost while also preserving employee engagement within the HMLV manufacturing environment. This represents a unique challenge in HMLV manufacturing, as it requires a constant balancing act between transitioning highly skilled labor from performing tasks to designing tasks that maximize their skill utilization. The goal of this effort is to create a system that effectively leverages the skills and knowledge of highly skilled workers while also promoting their engagement, satisfaction, and collaboration to improve the metrics of flexibility, throughput, and cost.

The overall approach to determining the specific experiments that should be conducted was beneficial. The process of first determining the requirements for the specific HMLV manufacturing environment and then matching those requirements to the traditionally accepted paradigm benefits provided a roadmap for experimental design and implementation.

For each of these experiments to be successful, the first step was using a systems level view to determine interactions between each of the system components. This included an understanding of human factors that balanced the core principle of usability with engagement.

<u>“Best Case” Application of Paradigms and Scalability</u>

RQ3, Task 2 seeks to determine the “best case” application of traditional industrial paradigms for HMLV manufacturing environments. The goal of this task is to identify how these traditional paradigms can be adapted or modified to best suit the needs of HMLV manufacturing, and to determine the potential benefits and drawbacks of doing so. By understanding the “best case" application, HMLV manufacturers can improve their production processes while meeting the unique demands of their customers.

Upon analyzing the data collected from the five experiments, it was found that the strongest positive correlations between the paradigms and metrics existed between Total Cost (C_P) and Parts Per Hour (PPH) with JIT, TOC, OEE, TPM, Lean, and QRM. Notwithstanding, TQM appeared to exert the most significant impact when considering all of the metrics. Given that cost is a pivotal performance indicator in the manufacturing industry, and throughput as measured by PPH serves as a scaling factor for profitability, these correlations are easily understood. Furthermore, the Five Forces Analysis revealed that the manufacturer in this study did not compromise overall quality and placed higher value on a low scrap rate compared to high rework rate, which drove the strong scores for TQM application in this particular business strategy.

The strongest negative correlations between the paradigms and metrics existed between Performance (H_C), TOC, and Lean as well as Process Variation (σ) and TPM. There are many reasons that could have caused these negative correlations. For example, HMLV manufacturing requires significant flexibility in production processes, which may lead to increased process variation. This variability can negatively impact performance, which may explain the negative correlation between Performance (H_C) and TOC and Lean. At the same time, TPM focuses on reducing process variability and improving OEE, which could explain the negative correlation between Process Variation (σ) and TPM.

This section seeks to examine the measured results of the experimental interventions to draw comparisons between the manufacturing paradigms. These comparisons reveal correlations that could provide insights into how HMLV manufacturers might adapt their practices through a combined application of these paradigms. These comparisons are presented first in Table 44. Table 44 presents the fractional changes in each of a set of metrics measured between the baseline and the experimental conditions. A value of 0.72 indicates that the experimental value was measured to be 72% of the baseline value. For example, the results of experiment 5 are that the Accuracy of production was reduced relative to the baseline conditions. The ratio of the accuracy under the experimental treatment to the accuracy measured under baseline conditions is 0.36. This cell is colored red, indicating that this reduction in accuracy is a detrimental change to the performance of the manufacturing system.

Table 44: Fractional changes in results relative to the baseline for each experiment, metrics, and the paradigm(s) the metrics represent. Values are color coded: Green = positive change, Red = detrimental change, Yellow = neutral

Metric	Paradigm	Ex 1	Ex 2	Ex 3 (Cell)	Ex 4	Ex 5
Accuracy (A)	TQM		1.00			0.36
Total Cost (C_P)/ Value	TOC	0.96	0.54	0.03	0.26	0.45
Process Variation (σ)	6σ		1.71	1.82		0.56
Initial Setup Cost (C_{SR})	TOC		0.72			
Effectiveness (E)	OEE	0.96		0.00	2.25	0.95
Throughput	TOC	1.13				
Performance (H_C)	OEE			1.00	0.69	0.68
Labor Hours (H_L)	Lean		0.69			
Process Time per Unit (H_P)	Lean				0.45	1.98
Reliability (H_R)	TQM		1.24			0.00
Uptime (H_U)	TPM		1.01	2.32	1.80	0.00
Lead Time (LT)	6σ	0.99		0.71	1.88	1.13
On Time Delivery	JIT			1.00		
Parts Per Hour (PPH)	QRM	1.13	1.08	4.16	1.62	1.57

WIP (WIP)	JIT	1.00	8.40	0.16	2.81	0.85

Variation and Results

In the context of highly dynamic and low volume (HMLV) environments, traditional parametric statistical tools cannot be defensibly applied due to their inherent assumptions of large sample sizes and stable data distributions. These tools rely on the Central Limit Theorem, which assumes that as sample sizes increase, the distribution of sample means becomes approximately normal, leading to defensible inferences [33].

In HMLV settings, data is sparse and non-stationary, rendering these assumptions invalid. Under these conditions, treating the data with n=1, where each experiment point is considered independently and uniquely, becomes imperative to gain a more accurate and comprehensive understanding of the environment. Under these conditions, treating the data with n=1, where each experiment's resulting value is the integrated result over the entire time of the experiment. This method provides a means to gain a more accurate and comprehensive understanding of the HMLV performance in practice, including variability and non-stationarity of the system under test. Embracing the normal and expected variability in HMLV settings allows us to recognize and account for the inherent fluctuations and uncertainties without assuming that the variability changes over time. In such contexts, n=1 approaches can provide valuable insights that better align with the dynamic nature of the environment, enabling more informed decision-making processes.

The benefits of this approach are illustrated with a scatter plot analysis from Experiment 5's data, as shown in Figure 3. Within the baseline results, we can observe substantial variation between lead time and completion date. This variation reflects the constantly shifting priorities and intricacies of value streams in the HMLV setting, even under baseline conditions. The trendline plotted for the baseline results illustrates the absence of a clear dependency between lead time and completion date in Experiment 5. Outliers such as those shown in Figure 31 are not a result of aleatory uncertainty, these were orders created for components to build safety stock, but they were not prioritized because they were not immediately needed. This type of demand unpredictability is common in HMLV environments. These types of challenges highlight the ineffectiveness of relying solely on large sample size assumptions and stable data distributions.

The n=1 approach, which treats the entire 3-week experiment as a single sample enables us to accept the inherent variability and complexities of HMLV environment, by presenting each experiment and each intervention as a single evaluation, integrated over the entire period of the experiment. The result of this experiment is therefore presented as the two average Lead Times for the entire period of the baseline (171, days) and the experimental treatment (192 days).

Embracing this approach, we gain a more comprehensive picture of the environment, allowing for more informed decision-making processes that better account for the normal and expected fluctuations over time. This reinforces the importance of recognizing the unique nature of HMLV environments and adapting our analytical methods accordingly to gain insight in such dynamic manufacturing environment.

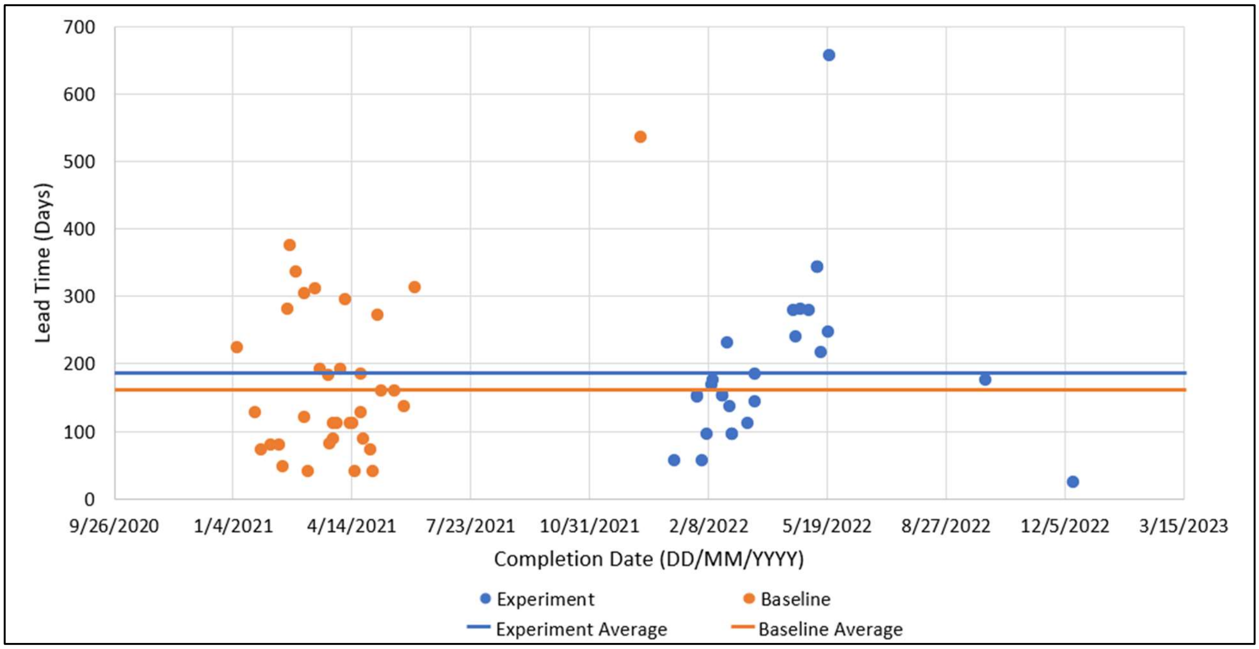


Figure 31: Lead Time (Days) Compared to Completion Dates per Batch for Experiment 5 Baseline and Experimental Period

Upon examination of the data from Table 44, several correlations between paradigms can be determined as shown in Table 45:

Table 45: Correlation matrix comparing paradigms to each other based on metric measurements from all (5) experiments[11]

	JIT	TQM	TOC	OEE	TPM	Lean	6σ	QRM
JIT	1.00							
TQM	1.00	1.00						
TOC	0.00	1.00	1.00					
OEE	0.15	0.00	-0.38	1.00				
TPM	-0.15	1.00	-0.81	0.28	1.00			
Lean	-1.00	0.00	1.00	-1.00	-1.00	1.00		
6σ	0.65	1.00	-0.24	0.12	0.62	-1.00	1.00	
QRM	-0.49	-1.00	0.00	0.16	0.67	-1.00	0.05	1.00

[11] This correlation matrix combines the paradigms to simplify the correlations. As shown in Table 45, there are multiple instances where the same paradigms are correlated and areas where the same paradigms presented different correlations (strong positive in one instance and strong negative in another) are described in the text following Table 45.

Understanding the Strong Positive Correlations

TQM and TPM (1.00)

- Both TQM and TPM aim to improve overall efficiency and effectiveness of the manufacturing process.
- Both rely heavily on data analysis and measurement.
- Both emphasize the importance of employee involvement to create a culture of continuous improvement.
- Both emphasize the importance of preventative maintenance and proactive problem-solving.

In HMLV manufacturing environments, the high degree of product and process variation and complexity make it more difficult to maintain quality and efficiency compared to LMHV manufacturing environments. Using TQM and TPM in HMLV manufacturing environments can be particularly effective for this reason.

TQM and JIT (1.00)

- Both emphasize the importance of reducing waste.
- Both require high level coordination and communication to streamline processes.
- Both emphasize the importance of continuous improvement.
- Both emphasize the importance of customer satisfaction.

In HMLV manufacturing environments, the need for customization creates complexity and variation in products and processes. This can lead to longer lead times and higher inventory levels when maintaining high quality standards. TQM can help identify and address quality issues while JIT helps to reduce the amount of inventory. Together, these paradigms are able to maintain the requirement of quality while reducing costs in HMLV environments, whereas the repeatability of LMHV manufacturing may only require JIT to improve flow and reduce costs.

TOC and Lean (1.00)

- Both aim to improve efficiency in production processes.
- Both rely on data analysis to identify areas of improvement.
- Both emphasize the importance of continuous improvement.
- Both emphasize the importance of involving employees in the process of identifying and implementing improvements.

TOC helps to identify bottlenecks in production processes that can be difficult to identify in the complexity of HMLV environments and seeks to prioritize improvement efforts to them. Lean methods are used to improve the entire manufacturing system through waste elimination that can also identify bottlenecks based on the presence of WIP. Together, these approaches work well in HMLV manufacturing spaces because they are able to consider the entire system without narrowing the focus like would be done in LMHV manufacturing.

6σ and TQM (1.00)

- Both aim to improve the quality of the production process.
- Both rely on data analysis to identify areas for improvement.
- Both emphasize the importance of continuous improvement.
- Both prioritize customer satisfaction.

6σ and TQM both aim to improve quality, reduce defects, and increase customer satisfaction. In HMLV manufacturing, these paradigms work well together because TQM focuses on quality while 6σ seeks to identify and reduce the sources of variation that may be the cause of defects. These paradigms are also effective together in LMHV manufacturing. However, in LMHV manufacturing, there may be less emphasis on TQM once a systems is streamlined and more focus on 6σ as a means to maintain the system. In HMLV manufacturing, these paradigms are equally applied due to the high level of complexity and variation with change overs.

Understanding the Strong Negative Correlations

TQM and QRM (-1.00)

- QRM focuses on speed, TQM focuses on quality.
- QRM focuses on flexibility, TQM focuses on standardization.
- Both require significant resource allocation making it difficult to implement both at the same time.

In LMHV manufacturing, TQM and QRM can work well together because production processes are more often standardized and repetitive. This makes it easier to identify and eliminate sources of inefficiency and waste while improving quality. However, in HMLV manufacturing, the focus on customization and product complexity can make it challenging to apply standardization principles that are often used in QRM. Moreover, the focus on flexibility in QRM can sometimes come at the expense of quality control which is a key component of TQM.

OEE and Lean (-1.00)

- OEE focuses on efficiency, Lean focuses on value through waste elimination. It is possible to achieve a high OEE score without adding value to the customer.
- OEE is narrowly focuses on single pieces of equipment. Lean is broadly focused on the entire manufacturing process. OEE doesn't consider the effect of improved machine effectiveness on the entire system.
- OEE relies on performance metrics and data analysis. Lean relies on tools like value stream mapping to eliminate waste.

OEE and Lean work well together in environments where processes are standardized and repetitive, such as LMHV manufacturing. However, the focus on customization and product complexity in HMLV manufacturing make it difficult to apply standardization principles, such as Lean focuses on, while also maximizing machine utilization, which is a key component of OEE. OEE can also reduce flexibility, making it difficult to respond to the changing demand patterns that are typical of HMLV manufacturing.

Lean and TPM (-1.00)

- TPM focuses on equipment. Lean focuses on value and uses a broader perspective.

The combination of Lean and TPM works best in environments where there is a high degree of standardization and repetition. The focus on customization and complexity in HMLV manufacturing reduces the effectiveness of this combination of paradigms. Lean and TPM can also be direct competitors in this type of environment where Lean requires a combination of standardization and flexibility that can be effective but the complexity of this makes the TPM components of reliability and availability more difficult.

Lean and 6σ (-1.00)

- 6σ focuses on quality improvement. Lean focuses on maximizing value to the customer through waste elimination.
- 6σ focuses on individual processes or components. Lean is a broader perspective and considers the entire manufacturing process. 6σ doesn't always consider the impact of individual areas of performance on the entire system.

In HMLV manufacturing environments, the need to support complex and customized products makes it difficult to apply standardization principles that both Lean and 6σ focus on. Although these paradigms are often successfully used in combination in LMHV manufacturing environments, in HMLV environments, it is more difficult to identify sources of variation using 6σ techniques that rely on large amounts of repeatable data. Separately, these paradigms can be effective in small areas or when combined with different paradigms but, together the focus becomes too narrow to effectively implement these paradigms on a large scale in HMLV environments.

Lean and QRM (-1.00)

- QRM focuses on agility and responsiveness. Lean focuses on waste elimination to improve efficiency.
- QRM is focused on a short-term perspective. Lean focuses on a long-term perspective to make sustainable improvements.

In HMLV manufacturing environments, QRM attempts to improve flexibility by changing over work centers or work cells more quickly to adapt to changing demand patterns.

This is often done successfully in LMHV environments where the number of changeovers is relatively small compared to HMLV environments. The extreme levels of product complexity and lack of significant repeatability creates instability in HMLV environments when attempting to apply QRM. This instability directly negatively impacts the application of Lean principles that focus on standardization.

Lean and JIT (-1.00)

- JIT primarily focuses on minimizing inventory levels and associated costs. Lean focuses on maximizing value to the customer through waste elimination and improved efficiency.
- JIT is typically based on demand forecasting to make sure products arrive only when they need to for different processes. Lean sees to create a pull system to drive production.

In LMHV manufacturing, JIT and Lean can work well together because of more standardized and repetitive production processes. In HMLV environments, this combination of paradigms can be difficult because the JIT focus of reducing inventory and the standardization focus of Lean can come at the expense of flexibility. This can make it more difficult to respond to changing demand patterns that are typical in HMLV environments.

<u>Understanding the Strong Positive and Negative Correlations Depending on Application</u>

6σ and OEE (1.00, -1.00, -0.41, 0.87)

- OEE and 6σ are different approaches to measuring and improving manufacturing performance. OEE is focused on equipment availability, performance, and quality, whereas 6σ is focused on using a data-driven approach to eliminate defects and reduce variation in the manufacturing process.
- OEE is a single metric that combines availability, performance, and quality. 6σ uses multiple metrics such as defects and process capability to measure and improves process quality and reducing defects.
- OEE aims to maximize equipment effectiveness and improve production efficiency. 6σ seeks to reduce defects and improve product quality. These don't always align with each other.

The successful application of OEE and 6σ in HMLV manufacturing depends on the specific characteristics of the production process that they are applied to. HMLV environments are complex and variable which can make it more difficult to obtain consistent sample sizes for statistical analysis if applied to the wrong part of the manufacturing system. If applied together at a process rather than a product level, where there may be more statistical sample sizes available, these approaches in combination can work well in HMLV manufacturing.

Research Process Conclusions

In consideration of the research process taken, a promising potential application roadmap for future experiments has emerged. This roadmap enables the assessment of specific needs through a needs analysis, which can then be mapped to the relevant industrial paradigms as illustrated in Figure 31. Consequently, the more promising potential paradigms can be identified and applied to the manufacturing process.

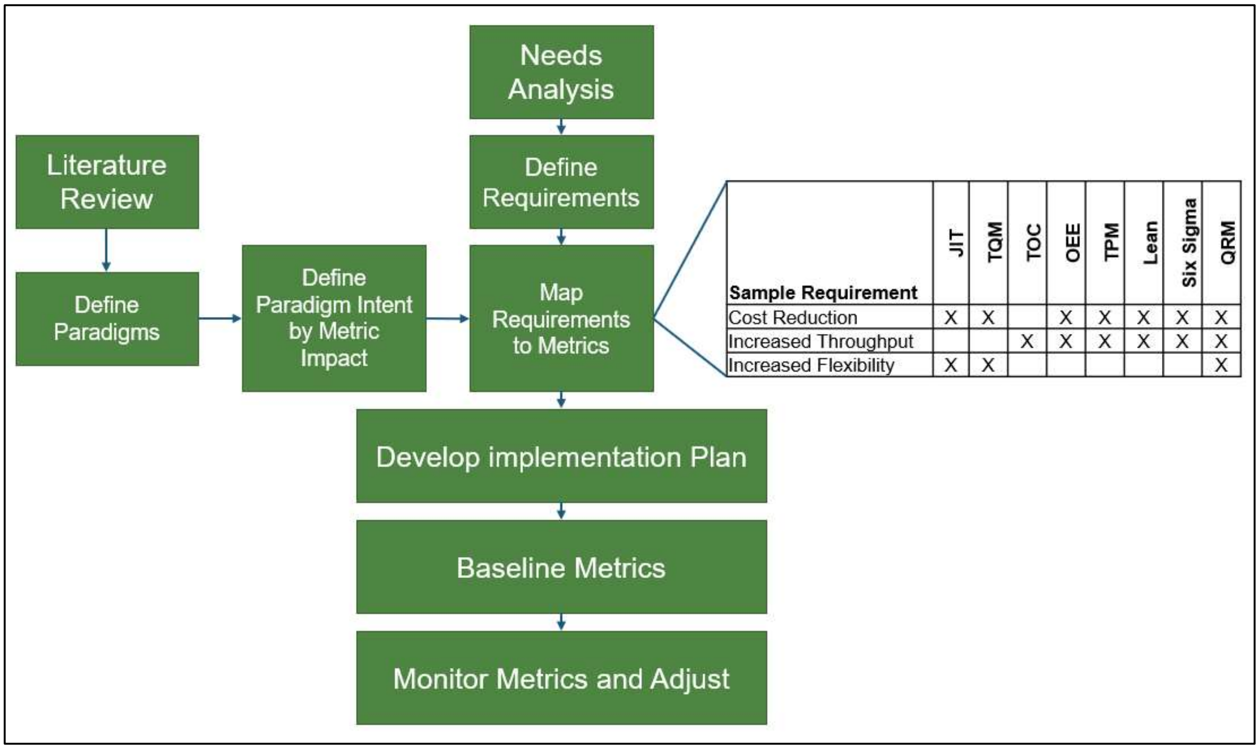


Figure 32: Determination of paradigm applications through comparison of paradigm intent and metrics defined in the needs analysis

RQ3, Task 3 seeks to determine the scalability of applying the industrial paradigms for HMLV manufacturing outside of the subject manufacturer. This task entails identifying the potential barriers that may hinder the successful application of these paradigms, considering the potential differences between manufacturers within the classification of HMLV manufacturing. In essence, the goal is to assess the transferability of these paradigms to other HMLV manufacturing settings, and to identify any factors that may limit their effectiveness in different contexts.

Utilizing the model outlined in Figure 31, the scalability of the identified industrial paradigms can be determined. It is important to note that each HMLV manufacturer will have a specific competitive advantage that it seeks to exploit, which typically encompasses flexibility, cost, and throughput. However, if a manufacturer's strategy does not prioritize quality, the results of the paradigm application could differ from this research. The crucial steps that a manufacturer should take involve identifying their specific needs and aligning them with the relevant industrial paradigms. For the subject manufacturer, this process resulted in multiple potential experimental applications, with the experiments chosen for this research aimed at determining paradigm applicability, rather than being selected based on the known benefits of the experimental application. Therefore, it is recommended that this process be conducted after the implementation of "best practices", such as reducing waste, minimizing downtime through setup reductions, and standardizing operations as much as possible while still maintaining the business model.

Limitations

Although these specific correlations were determined from the five experiments, they may not be generalizable to all HMLV manufacturing environments, as each manufacturing process is unique and may require specific strategies and approaches to optimize performance and reduce process variation. It is therefore crucial to conduct further research and analysis to determine the factors driving these correlations in each HMLV manufacturing setting and identify the most effective strategies to optimize performance and reduce process variation within the correct context.

Suggested Application Model

The last task for this research (RQ3, Task 4) seeks to define a suggested application model for further implementation in HMLV manufacturing environments. This application model seeks to outline the steps and necessary processes for successful implementation of relevant industrial paradigms. The model also seeks to consider the specific needs and competitive advantages of the manufacturer, align them with the relevant industrial paradigms, and suggest experimental applications for the most promising paradigms. The goal of this model is to provide a roadmap for HMLV manufacturers to confidently implement changes in their manufacturing process to realize the benefits of industrial paradigm application that best align with their specific business needs.

To successfully implement the existing industrial paradigms, first determine whether the HMLV manufacturing environment has the same requirements as the one used for these experiments. These included, flexibility, cost reduction, and throughput, while maintaining an emphasis on quality. If these requirements are different, determine which paradigms most closely mirror the requirements of the specific manufacturing environment.

Next, consider areas where standardization is possible in the HMLV environment. With the dynamic nature of HMLV environment, in most cases, this will be at a process rather than a product level where the complexity of the final product has a lesser effect. This approach will allow the application of Lean principles to the extent that they are relevant in this type of environment, limiting the application to avoid a negative impact to flexibility.

Once standardization efforts are complete wherever apparent, consider the entire manufacturing system and determine interdependencies and interactions between components of the system. This will allow for a holistic approach to measuring overall benefits from paradigm application. It is important to also consider all of the potential measurement areas and methods that need to be included to understand overall benefits to implementing the industrial paradigms. Given the potential for strong positive correlations between some of the paradigms, first consider areas where the following paradigm combinations could be used:

TQM and TPM (1.00)

This combination is most effective when implemented in systems where it is possible to standardize processes to reduce errors and improve quality while increasing efficiency and reducing waste. This could include:

- The optimization of equipment maintenance (including machines, tools, fixtures, etc.) to create process repeatability.
- Continuous improvement efforts that seek to eliminate waste through improved quality and increased efficiency.
- Employee training and empowerment programs that include operator-led maintenance to reduce errors and improve quality.
- Supply chain optimization efforts to reduce lead times, increase flexibility, and improve overall quality through supplier quality management.

TQM and JIT (1.00)

This combination is most effective when implemented in systems where the number of interactions between subsystems is easily determined. This could include:

- Optimizing production scheduling using pull-based systems wherever possible (such as Kanban).

- Improving quality through process mapping, root cause analysis, and continuous improvement efforts.
- Supplier management and partnerships to reduce lead times and increase flexibility, including supplier development and supplier quality management.
- Employee training and empowerment programs, including cross-training and employee skill expansion (multi-skilling).

TOC and Lean (1.00)

This combination is most effective when a system constraint can be identified, and interactions and interdependencies of that constraint can be documented. This could include:

- Value stream mapping events to help identify and improve bottlenecks by increasing flow with TOC practices (manage the constraint).
- Constraint management through waste reduction with Lean principles.
- Continuous improvement programs to reduce waste throughout the entire system.
- Employee training and empowerment programs provide a means to empower the employees who are part of the constraint team to improve quality, reduce errors, and improve efficiency.

6σ and TQM (1.00)

This combination is most effective when variation and quality concerns are apparent in the process. There should also be an opportunity to measure the sources of variation in the system in order to reduce them. Application of this combination could include:

- Process mapping (TQM) that is integrated with 6σ data analysis to eliminate sources of variation.
- Implementing statistical process control (SPC) in areas where there is sufficient data to understand and document processes. This could then be improved through TQM processes such as root cause analysis.
- Areas where Design of Experiments (DOE) can be implemented to improve quality while using TQM practices to ensure the process is capable of meeting customer needs.
- Quality improvement projects where quality can easily be identified as a contributor to process constraints.

6σ and JIT (0.95)

This combination is most effective in areas where process variation negatively impacts throughput. Application of this combination could include:

- Value stream mapping to improve flow through waste, in the form of WIP and process yield, elimination.
- Areas where flow can be metered through kanban systems while maintaining quality and reducing variation.
- Error-proofing projects that seek to improve first-pass-yield in processes where quality defects are identified as an impediment to flow.
- Continuous improvement projects where sources of variation can be identified and reduced to improve process flow.

Starting with the implementation of the proposed combinations of quality paradigms, HMLV manufacturers can adopt a systems approach towards their manufacturing environments. This approach entails considering the overall impacts of the paradigm application, facilitating the realization of the benefits that LMHV manufacturers have traditionally enjoyed. Such a holistic approach enables manufacturers to view their HMLV manufacturing systems as an interconnected whole, as opposed to a collection of isolated components. By adopting this perspective, manufacturers can leverage the synergies that exist among the various paradigms to improve manufacturing processes holistically. This strategic approach to paradigm implementation has the potential to enhance efficiency, flexibility, and throughput within HMLV manufacturing environments to enable them to remain competitive in a dynamic marketplace.

Contributions to the State of the Art

A comparison of the results of the experiments and the existing literature reveals some marked differences. The most profound of these differences are described below.

Lean and Six Sigma

Existing literature suggests that Lean Manufacturing and Six Sigma work well together in most manufacturing environments [81]. The premise is that they complement each other with Lean focusing on reducing waste and maximizing efficiency through improved processes and flow, and 6σ using data-driven decision making to reduce variation in processes to create more predictable outcomes [43]. Lean and Six Sigma evolved together as extensions of the TQM paradigm. Together, they are meant to facilitate the achievement of zero defects (six sigma) through the reduction of waste (Lean) [46].

However, it was found in the subject HMLV manufacturer's environment that this was not the case. Lean and 6σ had one of the strongest negative correlations in this environment for the experiments where they were implemented in parallel (Ex. 4). If we consider conventional Lean Six Sigma (LSS) philosophies for Experiment 4, we might consider the baseline wasteful and inefficient. The baseline measured as having significant added costs due to WIP between operations. This resulted in a relatively long wait time, and large overall time required to produce the components.

Both the Cellular Manufacturing method, and the Single Machine method would be considered promising LSS interventions in a LMHV manufacturing environment, relative to the baseline, because of their potential to reduce WIP, reduce setup time, and thereby reduce waste. The results of these treatments applied in the HMLV environment instead illustrate that these tradeoffs are more complicated than conventionally considered. For the Single Machine Manufacturing method, the component was manufactured with significantly reduced process intervention (an operator wasn't moving components), but in this HMLV application, the results of this experiment show that there is a reduction in product quality that overwhelms the benefits from reduced operator intervention. In this HMLV application, the types of parts that must be manufactured with this Single Machine are so numerous, that the multi-step manufacturing process is difficult to control. The complexity of machine setup, of inter-machining-step quality control, and of labor meant that the Single Machine manufacturing method produced lower quality parts that had to be reworked to meet specifications. The Single Machine processing method also reduced the cost of WIP, but decreased process effectiveness due to quality problems that were the result of the increased complexity of machine set up.

On the other hand, for the Cellular Manufacturing method, the experimental evidence indicates that internalizing non-valued added activities (i.e., “waste”) into value-added resulted in decreased production time and fewer quality errors. In this HMLV environment, manufacturing quality was improved because of the frequent human interventions and in-process quality checks. The Cellular Manufacturing method also significantly reduced the cost of WIP because of its increased throughput and reduced wait time.

These findings illustrate that although the philosophies and concepts of LSS are fundamental to improving productivity, the unique demands of the HMLV environment mean that many of the conventional LSS metrics and concepts that have been successfully applied to LMHV manufacturing must be re-validated in application to HMLV manufacturing.

In HMLV manufacturing environments, although there is some evidence to suggest that the combined application of Lean and 6σ can work well together, there is generally a high degree of variability in production processes that reduces the effectiveness of this combined approach due to decreased flexibility. Customized product, low batch sizes, and low repeatability make it more difficult to identify sources of variation and waste [78]. It is also difficult to standardize processes in this type of environment to an extent. It appears that Lean principles apply when used as simple waste reduction principles but are limited by the process variation. In addition to the production characteristics, resources are also constrained due to the high variability of both products and processes, making it more difficult to implement cost reduction efforts in a broad manner in HMLV manufacturing environments. This is a typical concern in HMLV environments, and it contributes to the need for highly skilled labor to make up the difference between documentation and processes that cannot be accounted for in engineering because of the high number and leads to the stronger labor involvement that reduces the ability to control process variation.

Lean and Quick Response Manufacturing

The experiments also revealed a strong negative correlation between Lean and QRM. This was inconsistent with existing literature that suggested that QRM was strengthened by continuous improvement programs such as Lean [71]. Lean Manufacturing is often considered a relentless pursuit of waste reduction [43]. This normally comes in the form of standardized products and processes, but the implementation is not normally limited to any specific type of manufacturing system [43].

However, in the experiments where these two paradigms were implemented together (Ex. 2, 4, and 5), they were implemented in parallel rather than in series. It was found that QRM principles, which focus on manufacturing critical path time [43], can create unwanted side effects [79]. For instance, if focused only on the critical path time for each component, the HMLV manufacturing environment has so many different components that changeovers happen more and more often while reducing total production time for a single work center. Ideally, Lean principles would have been applied prior to implementation of QRM so that those changeover times could be short enough to be negligible in the overall process time. Conversely, implementing Lean principles after QRM would also provide the benefit of reducing waste for the bottleneck areas that were exposed through QRM.

Lean and Just in Time

Another strong negative correlation between paradigms that was contradictory to the existing literature was between Lean and JIT. Both Lean and JIT aim to improve efficiency and reduce waste in manufacturing processes [22]. They share similar principles such as continuous improvement, employee empowerment, and are focused on customer value [35]. JIT is also frequently used to create a pull system within the context of Lean [61].

The experiments that used Lean and JIT in parallel (Ex. 4 and 5) provided solutions that negatively impacted certain metrics in order to improve others. For instance, in experiment 4, to improve throughput, a direct labor resource was used to perform setup and teardown operations for other test technicians. This labor resource did not perform any actual test operations that could be considered value-added. Doing this improved the overall throughput for test operations but did not remove waste in the overall system. Instead, the waste was made internal to value-added activities. This improved metrics for JIT but not for Lean.

In experiment 5, the goal to improve quality for the work center was done at the expense of increasing the overall lead time for each batch of components. This experiment was designed to reduce the waste produced through defects but increased the throughput time to do so. For both experiments where Lean and JIT were used in parallel, they were implemented using a trade-off scenario where the goal was overall cost reduction.

Upon examination of the various correlations, it was observed that Lean Manufacturing principles tended to exhibit more negative effects despite their foundational importance to the other industrial paradigms. An intriguing inference that can be drawn from the conducted experiments is that the implementation of Lean principles prior to the application of other industrial paradigms can be highly effective, as opposed to a parallel implementation. It is essential to note that every manufacturing environment possesses the potential to mitigate waste from its system by applying Lean principles. However, Lean principles, in isolation, are insufficient to fully achieve optimized costs, flexibility, and customer satisfaction in HMLV environments because they are limited with the goal of standardization in this environment.

Conclusions

This research explored the application of several industrial paradigms in the context of HMLV manufacturing environments. The research aimed to identify the benefits and limitations of each paradigm and understand their correlations with the key requirements, as identified in a needs analysis, of cost, throughput, and flexibility. Correlations between paradigm philosophies and their impact on the metrics were established through five experiments. These correlations provided insights into the combined application of paradigms for the subject manufacturer as well as other HMLV manufacturers.

The findings revealed that different paradigms provided varying benefits to the metrics used to measure the requirements. Lean and JIT, which heavily focused on standardization, showed limitations in performance. On the other hand, QRM and TPM demonstrated the most significant benefits across all metrics. However, when normalized for the frequency of paradigm usage, TQM emerged as providing the highest overall benefit.

In HMLV environments, characterized by high variation and frequent changeovers, quality issues can be prevalent. Improvements in quality had a positive impact on other metrics such as cost, throughput, and reduction of WIP. Balancing operational flexibility with these metrics posed a challenge in the HMLV environment. Quality, particularly in conjunction with flexibility, positively influenced other metrics and aligned with the strategic emphasis on quality identified through the Five Forces Analysis of the specific manufacturer.

Strong positive correlations were identified between paradigms such as JIT, TOC, OEE, Lean, and QRM with metrics like Total Cost and Throughput in Parts per Hour (PPH). QRM stood out due to its additional focus on flexibility, which contributed to its overall benefit.

However, caution is necessary when implementing these paradigms in HMLV environments. Paradigms like JIT and TOC, while positively correlated with cost and throughput, showed negative correlations with accuracy and performance. This can be attributed to JIT's emphasis on WIP reduction, which may not be suitable for handling the volatility in demand patterns observed in HMLV environments. The requirement for flexibility also introduced negative correlations in unexpected areas, such as performance with TOC and Lean, and process variation with TPM.

Of particular interest was the negative correlation between Lean and other paradigms, which contradicted existing literature. Lean philosophies, foundational to other paradigms, struggled to integrate effectively in HMLV environments due to their limited ability to handle disruptions caused by customization and volatile demand patterns. HMLV environments also present a higher level of complexity, where there are many converging value streams, making it necessary to adopt a holistic perspective.

Viewing HMLV environments as complex systems with multiple interactions, it became evident that a holistic approach was essential for optimizing cost, throughput, and flexibility.

Paradigm philosophies had evolved and built upon each other primarily in Low Mix High Volume (LMHV) environments, leading to a reduction in flexibility and increased standardization. Implementing these paradigms in HMLV environments with a narrow focus on a single value stream risked compromising the competitive advantage of flexibility.

Considering the results and correlations from the experiments, there is potential for exploring additional combined paradigm application in HMLV environments. However, careful consideration is required due to trade-offs observed in these environments. Implementing all paradigms may not be necessary, and the specific requirements of each HMLV environment should be taken into account.

This research emphasized the need for a holistic view when implementing paradigm philosophies in HMLV environments. Trade-offs may not be as apparent as in LMHV environments, and a narrow focus on individual operations or processes could negatively impact cost, throughput, and flexibility. Treating the manufacturing environment as a complex system with numerous interfaces and interdependencies is crucial for achieving optimal results.

The research surveyed existing literature to define the paradigm philosophies and conducted five experiments to understand their application in HMLV environments. The findings shed light on the complexity of these environments and the importance of a system-level viewpoint. The research also identified future opportunities for larger-scale experimentation and expansion to other HMLV environments to validate and refine the findings. Furthermore, the order and extent of implementing each paradigm could be further explored to optimize their effectiveness.

In conclusion, this research has contributed to a deeper understanding of the requirements and challenges specific to HMLV manufacturing. By adopting a holistic viewpoint and considering the unique characteristics of these environments, improvements can be made in cost, throughput, and flexibility. The findings of this dissertation provide valuable insights for practitioners and researchers aiming to optimize HMLV manufacturing systems.

References

[1] Aljubiri, Abdullah. 2019. "AN IMPLEMENTATION STRATEGY for LEAN MANUFACTURING in HIGH MIX and LOW VOLUME (HMLV) ENVIRONMENT." Etd.ohiolink.edu. 2019. https://etd.ohiolink.edu/apexprod/rws_olink/r/1501/10?clear=10&p10_accession_num=akron1564787755980795.

[2] Amaresh, Amaresh, and Kuriachen Oooramvely. 2020. "Standardization in a High Mix Low Volume Company: A Case Study." Jönköping University. May 2020. https://www.diva-portal.org/smash/get/diva2:1442082/FULLTEXT01.pdf.

[3] Araya, Juan. 2012. "Value Stream Mapping Adapted to High- Mix, Low-Volume Manufacturing Environments." https://www.diva-portal.org/smash/get/diva2:557027/FULLTEXT01.pdf.

[4] Azeem, S. MD Abdul. 2016. "Implementation of Value Stream Mapping in a Job Shop for High – Mix, Low - Volume Environment." *47*, September. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2411801.

[5] Bohnen, Fabian, Thomas Maschek, and Jochen Deuse. 2011. "Leveling of Low Volume and High Mix Production Based on a Group Technology Approach." *CIRP Journal of Manufacturing Science and Technology* 4 (3): 247–51. https://doi.org/10.1016/j.cirpj.2011.06.003.

[6] Bosman, Lisa, Nathan Hartman, and John Sutherland. 2019. Review of *How Manufacturing Firm Characteristics Can Influence Decision Making for Investing in Industry 4.0 Technologies*. Emerald Insight. October 28, 2019.

https://www.emerald.com/insight/content/doi/10.1108/JMTM-09-2018-0283/full/html?skipTracking=true&utm_source=TrendMD&utm_medium=cpc&utm_campaign=Journal_of_Manufacturing_Technology_Management_TrendMD_0&WT.mc_id=Emerald_TrendMD_0.

[7] Brem, Alexander, Eric Viardot, and Petra A. Nylund. 2020. "Implications of the Coronavirus (COVID-19) Outbreak for Innovation: Which Technologies Will Improve Our Lives?" *Technological Forecasting and Social Change* 163 (November): 120451. https://doi.org/10.1016/j.techfore.2020.120451.

[8] Chen, Li, and Bin Hu. 2014. "Offshoring versus Reshoring: A Tug-of-War between Operational Flexibilities." 2014. http://www-2.rotman.utoronto.ca/MSOM-2015/Documents/MSOM2015_0239.pdf.

[9] Chua, Tay-Jin, Tian-Xiang Cai, and Feng-Yu Wang. 2012. "Practical Order Release Planning Linking Enterprise and Shop Floor Tracking Systems for High-Mix Low-Volume (HMLV) Manufacturing." IEEE Xplore. December 1, 2012. https://doi.org/10.1109/IEEM.2012.6838135.

[10] Cesaní, Viviana I., and Harold J. Steudel. 2005. "A Study of Labor Assignment Flexibility in Cellular Manufacturing Systems." *Computers & Industrial Engineering* 48 (3): 571–91. https://doi.org/10.1016/j.cie.2003.04.001.

[11] Colombo, Armando W., Stamatis Karnouskos, Okyay Kaynak, Yang Shi, and Shen Yin. 2017. "Industrial Cyberphysical Systems: A Backbone of the Fourth Industrial Revolution." *IEEE Industrial Electronics Magazine* 11 (1): 6–16. https://doi.org/10.1109/mie.2017.2648857.

[12] Dalenogare, Lucas Santos, Guilherme Brittes Benitez, Néstor Fabián Ayala, and Alejandro Germán Frank. 2018. "The Expected Contribution of Industry 4.0 Technologies for Industrial Performance." *International Journal of Production Economics* 204 (October): 383–94. https://doi.org/10.1016/j.ijpe.2018.08.019.

[13] Dalrymple, John F. 2000. Review of *Product Customisation and Manufacturing Strategy*. *International Journal of Operations & Production Management* 20 (4): 441–67. https://doi.org/https://doi.org/10.1108/01443570010314782.

[14] Dequeant, Kean, Philippe Vialletelle, Pierre Lemaire, and Marie-Laure Espinouse. 2016. "A Literature Review on Variability in Semiconductor Manufacturing: The next Forward Leap to Industry 4.0." IEEE Xplore. December 1, 2016. https://doi.org/10.1109/WSC.2016.7822298.

[15] Duda, Jerzy, Andrzej Macioł, Stanisław Jędrusik, Bogdan Rębiasz, Adam Stawowy, and Monika Sopińska-Lenart. 2021. "Quick Response Manufacturing for High Mix, Low Volume, High Complexity Manufacturers." *Management and Production Engineering Review* Vol. 12, No. 1. https://doi.org/10.24425/mper.2021.136873.

[16] *Excellence Through Quality | ASQ*. (2021). Asq.Org. https://asq.org/

[17] Gaskell, T.A. 2007. "COST-EFFECTIVE AGILITY in the MANUFACTURE of LOW VOLUME HIGH MIX PRODUCTS." IEEE Xplore. July 1, 2007. https://ieeexplore.ieee.org/document/4286497.

[18] Frazee, Todd, and Charles Standridge. 2016. "CONWIP versus POLCA: A Comparative Analysis in a High-Mix, Low-Volume (HMLV) Manufacturing Environment." *Journal of Industrial Engineering and Management* 9 (2): 432. https://doi.org/10.3926/jiem.1248.

[19] Fredriksson, Peter, and Lars-Erik Gadde. 2005. "Flexibility and Rigidity in Customization and Build-To-Order Production." *Industrial Marketing Management* 34 (7): 695–705. https://doi.org/10.1016/j.indmarman.2005.05.010.

[20] Gantner, Karl (Karl Andrew). 2016. "Production Leveling and Cycle Time Reduction in Satellite Manufacturing." Dspace.mit.edu. 2016. https://dspace.mit.edu/handle/1721.1/104217.

[21] Gil-Vilda, Francisco, José A. Yagüe-Fabra, and Albert Sunyer. 2021. "From Lean Production to Lean 4.0: A Systematic Literature Review with a Historical Perspective." *Applied Sciences* 11 (21): 10318. https://doi.org/10.3390/app112110318.

[22] Girod, Olivia. 2014. "A Hybrid-Dynamic Transition Phase for High Mix Low Volume Small-And-Medium Manufacturers." Honors Project, Oregon State University.

[23] Girod, Olivia, Hao Zhang, Javier Calvo-Amodio Ph.D., and Karl R. Haapala Ph.D. 2014. "A Proposed Hybrid-Dynamic Transition Phase for High Mix Low Volume Manufacturers." In *Industrial and Systems Engineering Research Conference*. https://www.proquest.com/openview/b725314a3bc097a12c0d52dfd5508a02/1?pq-origsite=gscholar&cbl=51908.

[24] Glagolev, S, S Bukhonova, and E Chikina. 2020. "Research of Theoretical and Methodological Approaches to the System of Lean Manufacturing." State Technological University. https://www.atlantis-press.com/article/125936358.pdf.

[25] Gödri, István, Csaba Kardos, András Pfeiffer, and József Váncza. 2019. "Data Analytics-Based Decision Support Workflow for High-Mix Low-Volume Production Systems." *CIRP Annals* 68 (1): 471–74. https://doi.org/10.1016/j.cirp.2019.04.001.

[26] Goldratt, E M. 1990. *Theory of Constraints : What Is This Thing Called and How Should It Be Implemented?* Great Barrington, Ma: North River Press, Cop.

[27] Gómez Paredes, Fernando José, Moacir Godinho Filho, Matthias Thürer, Nuno O. Fernandes, and Charbel José Chiappeta Jabbour. 2020. "Factors for Choosing Production Control Systems in Make-To-Order Shops: A Systematic Literature Review." *Journal of Intelligent Manufacturing* 33 (October): 639–74. https://doi.org/10.1007/s10845-020-01673-z.

[28] Grube Hansen, D[avid]; Malik, A[li] A[hmad] & Bilberg, A[rne] (2017). Generic Challenges and Automation Solutions in Manufacturing SMEs, Proceedings of the 28th DAAAM International Symposium, pp.1161-1169, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-11-2, ISSN 1726-9679, Vienna, Austria DOI: 10.2507/28th.daaam.proceedings.161

[29] Guan, Zailin, Chuangjian Wang, Jinguo Huang, Lizhi Wan, and Xinyu Shao. 2010. "Optimization of Manufacturing Systems Using Genetic Search and Muti-Resolution Simulation." IEEE Xplore. June 1, 2010. https://doi.org/10.1109/ICCA.2010.5524439.

[30] Guan, Zailin, Yunfang Peng, Li Ma, Chaoyong Zhang, and Peigen Li. 2008. "Operation and Control of Flow Manufacturing Based on Constraints Management for High-Mix/Low-Volume Production." *Frontiers of Mechanical Engineering in China* 3 (4): 454–61. https://doi.org/10.1007/s11465-008-0083-5.

[31] Gundogar, Emin, Murat Sari, and Abdullah H. Kokcam. 2016. "Dynamic Bottleneck Elimination in Mattress Manufacturing Line Using Theory of Constraints." *SpringerPlus* 5 (1). https://doi.org/10.1186/s40064-016-2947-1.

[32] Henegedara, Asanka. 2019. "How to See 99% of Non-Value Adding Activities of Your Processes." November 22, 2019. https://www.linkedin.com/pulse/how-see-99-non-value-adding-activities-your-processes-henegedara/.

[33] Heyde, C. C. "Central Limit Theorem." *Encyclopedia of Actuarial Science*, September 24, 2004. https://doi.org/10.1002/9780470012505.tac019.

[34] Hofmann, P., and D. Powell. 2012. "The Combination of Lean Thinking and Systems Thinking in the Design of Manufacturing Systems." *2012 IEEE International Conference on Industrial Engineering and Engineering Management*, December. https://doi.org/10.1109/ieem.2012.6837701.

[35] Hussain, Anees, J. Eduardo Munive-Hernandez, and I. Felician Campean. 2020. "Lean Approach in a High Mix, Low Volume Manufacturing Environment-Case Study." Bradscholars.brad.ac.uk. March 1, 2020. https://bradscholars.brad.ac.uk/handle/10454/18203.

[36] Irani, Shahrukh. 2011. "Choosing What Works." *Industrial Engineer* 43 (8): 42–47.

[37] Irani, Shahrukh. 2017. Review of *Lean and Flexible*. Lean + Flexible. 2017. www.leanandflexible.com.

[38] Irani, Shahrukh A. 2020. *Job Shop Lean: An Industrial Engineering Approach to Implementing Lean in High-Mix Low-Volume Production Systems*. *Google Books*. CRC Press. https://books.google.com/books?hl=en&lr=&id=binhDwAAQBAJ&oi=fnd&pg=PT15&dq=8+wastes+in+hmlv+manufacturing&ots=dRqbdKN-et&sig=bWHlBPaJTRoshUWNj6agfRfdYgA.

[39] Irani, S. A., H. Zhang, J. Zhou, H. Huang, T.K. Udai, and S. Subramanian. 2000. "Production Flow Analysis and Simplification Toolkit (PFAST)." *International Journal of Production Research* 38 (8): 1855–74. https://doi.org/10.1080/002075400188636.

[40] Jaegler, Yann, Anicia Jaegler, Fatima Zahra Mhada, Damien Trentesaux, and Patrick Burlat. 2021. "A New Methodological Support for Control and Optimization of Manufacturing Systems in the Context of Product Customization." *Journal of Industrial and Production Engineering* 38 (5): 341–55. https://doi.org/10.1080/21681015.2021.1891147.

[41] Jauregui Becker, Juan M., Jesper Borst, and Abele van der Veen. 2015. "Improving the Overall Equipment Effectiveness in High-Mix-Low-Volume Manufacturing Environments." *CIRP Annals* 64 (1): 419–22. https://doi.org/10.1016/j.cirp.2015.04.126.

[42] Javadian Kootanaee, Akbar, K. Nagendra Babu, and Hamid Foladi Talari. 2013. "Just-In-Time Manufacturing System: From Introduction to Implement." *SSRN Electronic Journal* 1 (2). https://doi.org/10.2139/ssrn.2253243.

[43] Joing, Matthew. 2004. "Applicability of Lean Manufacturing and Quick Response Manufacturing in a High-Mix Low-Volume Environment." Thesis, Massachusettes Institute of Technology. https://dspace.mit.edu/handle/1721.1/34767.

[44] Karthi, S., S.R. Devadasan, and R. Murugesh. 2011. "Integration of Lean Six-Sigma with ISO 9001:2008 Standard." *International Journal of Lean Six Sigma* 2 (4): 309–31. https://doi.org/10.1108/20401461111189416.

[45] Kocsi, Balázs, Michael Maiko Matonya, László Péter Pusztai, and István Budai. 2020. Review of *Real-Time Decision-Support System for High-Mix Low-Volume Production Scheduling in Industry 4.0*. *Processes*, August 1, 2020.

https://www.researchgate.net/publication/343410901_Real-Time_Decision-Support_System_for_High-Mix_Low-Volume_Production_Scheduling_in_Industry_40.

[46] Kornicki, Lucjan, and Thomas Koch. 2004. "TECHNICAL ASPECTS of MASS CUSTOMIZATION in the LEAN PRODUCTION SYSTEM." Wroclaw University of Technology. https://mcp-ce.org/wp-content/uploads/proceedings/2004/9-Kornicki.pdf.

[47] Lane, Greg. 2007. *Made-To-Order Lean : Excelling in a High-Mix, Low-Volume Environment*. New York: Productivity Press.

[48] Lanza, Gisela, Johannes Stoll, Nicole Stricker, Steven Peters, and Christof Lorenz. 2013. "Measuring Global Production Effectiveness." *Procedia CIRP* 7: 31–36. https://doi.org/10.1016/j.procir.2013.05.006.

[49] Li, Bo. 2009. "Making a High-Mix Make-To-Order Production System Lean." Thesis, Massachusetts Institute of Technology.

[50] Manyika, James, Katy George, Eric Chewning, Jonathan Woetzel, and Hans-Werner Kass. 2021. "US Manufacturing: Building a More Competitive Sector | McKinsey." Www.mckinsey.com. 2021. https://www.mckinsey.com/featured-insights/americas/building-a-more-competitive-us-manufacturing-sector.

[51] McKenney, Kevin (Kevin Bryan). 2005. "Development and Application of Management Tools within a High-Mix, Low-Volume Lean Aerospace Manufacturing Environment." *Dspace.mit.edu*. Thesis, Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/34825.

[52] Micheli, Pietro, Mark Johnson, and Janet Godsell. 2021. "Editorial How the Covid-19 Pandemic Has Affected, and Will Affect, Operations and Supply Chain Management

Research and Practice." *International Journal of Operations & Production Management* 41 (6): 773–80. https://doi.org/https://doi.org/10.1108/IJOPM-06-2021-902.

[53] Mohammadpour, Violet, and Sebastian Häll. 2021. "Supporting the Development of a HMLV Production Cell." Thesis, Mälardalen University Sweden. https://www.diva-portal.org/smash/get/diva2:1561529/FULLTEXT01.pdf.

[54] National Research Council, Division on Engineering and Physical Sciences, Board on Manufacturing and Engineering Design, and Committee on Comparative Cost Factors and Structures in Global Manufacturing. 1992. *Dispelling the Manufacturing Myth: American Factories Can Compete in the Global Marketplace*. *Google Books*. National Academies Press.

[55] Neoh, Siew-Chin, Norhashimah Morad, Chee-Peng Lim, and Zalina Abdul Aziz. 2010. "A Layered-Encoding Cascade Optimization Approach to Product-Mix Planning in High-Mix–Low-Volume Manufacturing." *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 40 (1): 133–46. https://doi.org/10.1109/tsmca.2009.2029557.

[56] Obara, Samuel, and Darril Wilburn. 2012. *Toyota by Toyota : Reflections from the inside Leaders on the Techniques That Revolutionized the Industry*. Boca Raton, Fl: Crc Press.

[57] Oehmen, Josef. 2012. *The Guide to Lean Enablers for Managing Engineering Programs*. 1.0 ed. Joint MIT-PMI-INCOSE Community of Practice on Lean in Program Management. https://dspace.mit.edu/handle/1721.1/70495.

[58] Oppenheim, Bohdan W. 2011. *Lean for Systems Engineering with Lean Enablers for Systems Engineering*. Hoboken, N.J.: Wiley.

[59] Oxford English Dictionary. 2022. "Oxford English Dictionary." OED.com. Oxford University Press. 2022. https://www.oed.com/.

[60] Oxford University. 2019. "Happy Workers Are 13% More Productive | University of Oxford." Www.ox.ac.uk. October 24, 2019. https://www.ox.ac.uk/news/2019-10-24-happy-workers-are-13-more-productive.

[61] Pandolfo, Christopher R. (Christopher Robert). 2004. "Optimization of In-Line Semiconductor Measurement Rates : Balancing Cost and Risk in a High Mix, Low Volume Environment." Dspace.mit.edu. 2004. https://dspace.mit.edu/handle/1721.1/34770.

[62] Pugalenthi, Pandian, Leo Yang, and Xinyu Liu. 2021. "Lean Transformation for High Mix Low Volume Production: A Case Study." IIE Annual Conference. Institute of Industrial and Systems Engineers. 2021. https://www.proquest.com/docview/733013083?pq-origsite=gscholar&fromopenview=true.

[63] Ravensbergen, Robert. 2021. "Maximizing Quality, Minimizing Rework with Autonomous Robots." Quality Magazine. April 2021. https://www.proquest.com/openview/5db66e57b595736ddf278b949bd5a958/1?pq-origsite=gscholar&cbl=35812.

[64] Rheaume, Jonathan. 1995. "High-Mix, Low-Volume Lean Manufacturing Implementation and Lot Size Optimization at an Aerospace OEM." Thesis. https://dspace.mit.edu/bitstream/handle/1721.1/82699/53343030-MIT.pdf.

[65] Seth, Dinesh, Nitin Seth, and Pratik Dhariwal. 2017. "Application of Value Stream Mapping (VSM) for Lean and Cycle Time Reduction in Complex Production Environments: A

Case Study." *Production Planning & Control* 28 (5): 398–419. https://doi.org/10.1080/09537287.2017.1300352.

[66] Song, Jing-Sheng, and Paul Zipkin. 1993. "Inventory Control in a Fluctuating Demand Environment." *Operations Research* 41 (2): 351–70. https://doi.org/10.1287/opre.41.2.351.

[67] Sprovieri, John. 2004. "Managing High-Mix, Low-Volume Assembly." *Assembly*, March 5, 2004. https://www.assemblymag.com/articles/83764-managing-high-mix-low-volume-assembly.

[68] Standridge, Charles. 2019. *Introduction to Production: Philosophies, Flow, and Analysis*. *Open Textbooks*. Grand Valley State University. https://scholarworks.gvsu.edu/books/22/.

[69] Strøm, Ruben Eide. 2018. "Production Planning and Control in Make-To-Order Manufacturing - Selection Criteria." *Ntnuopen.ntnu.no*. Thesis, Norwegian University of Science and Technology. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2562562.

[70] Stump, Brandon, and Fazleena Badurdeen. 2009. "Integrating Lean and Other Strategies for Mass Customization Manufacturing: A Case Study." *Journal of Intelligent Manufacturing* 23 (1): 109–24. https://doi.org/10.1007/s10845-009-0289-3.

[71] Suri, Rajan. 1998. *Quick Response Manufacturing: A Companywide Approach to Reducing Lead Times*. Portland, Or. Productivity Press.

[72] Svancara, Juraj, Zdenka Kralova, and Michal Blaho. 2012. "Optimization of HMLV Manufacturing Systems Using Genetic Algorithm and Simulation." *International Review on Modeling and Simulations* 5 (1). https://www.researchgate.net/profile/Zdenka-

Kralova/publication/289291274_Optimization_of_HMLV_manufacturing_systems_using_genetic_algorithm_and_simulation/links/6135e0740360302a0081a08b/Optimization-of-HMLV-manufacturing-systems-using-genetic-algorithm-and-simulation.pdf.

[73] Synnes, Elisabeth Lervåg, and Torgeir Welo. 2016. "Bridging the Gap between High and Low-Volume Production through Enhancement of Integrative Capabilities." *Procedia Manufacturing* 5: 26–40. https://doi.org/10.1016/j.promfg.2016.08.006.

[74] Thompson, Kristy. 2020. "Manufacturing Industry Statistics." NIST. January 24, 2020. https://www.nist.gov/el/applied-economics-office/manufacturing/manufacturing-industry-statistics.

[75] T. L., Lim, Kow M. Y., Nooh A. B, and Yip M. W. 2015. "Case Studies in Implementing Dynamic Production Planning and Scheduling System in Make-To-Order High-Mix-Low-Volume Small and Medium-Scaled Industries for Production Efficiency." *International Journal of Innovative Computing* 5 (1). http://161.139.68.238/index.php/ijic/article/view/106.

[76] Tomašević, Ivan, Dragana Stojanović, Dragoslav Slović, Barbara Simeunović, and Ivona Jovanović. 2020. "Lean in High-Mix/Low-Volume Industry: A Systematic Literature Review." *Production Planning & Control*, June, 1–16. https://doi.org/10.1080/09537287.2020.1782094.

[77] "Understanding OEE in Lean Manufacturing | Lean Production." n.d. Www.leanproduction.com. https://www.leanproduction.com/oee/.

[78] Upton, David M. 1995. “Flexibility as Process Mobility: The Management of Plant Capabilities for Quick Response Manufacturing.” *Journal of Operations Management* 12 (3-4): 205–24. https://doi.org/10.1016/0272-6963(95)00004-C.

[79] Velaga, Prasad. 2017. “Control of a High-Mix, Low-Volume Production Line Involving Multi-Skilled Workers.” Www.linkedin.com. October 23, 2017. https://www.linkedin.com/pulse/control-high-mix-low-volume-production-line-involving-prasad-velaga/.

[80] Xu, Min, Jeanne M. David, and Suk Hi Kim. 2018. “The Fourth Industrial Revolution: Opportunities and Challenges.” *International Journal of Financial Research* 9 (2): 90–95. https://doi.org/10.5430/ijfr.v9n2p90.

[81] Yadav, Gunjan, and Tushar J. Desai. “Lean Six Sigma: A Categorized Review of the Literature.” *International Journal of Lean Six Sigma* 7, no. 1 (March 1, 2016): 2–24. https://doi.org/10.1108/ijlss-05-2015-0015.

Appendix A: Needs Analysis

Operations analysis

Analyze projected needs

The following needs have been identified by the high-mix low-volume manufacturer, Company XYZ:

- Need to be competitive in the world market for firefighting equipment.
- Need to keep a customer focus, which includes a demand for more customized product offerings.
    - Must be able to accommodate extremely low production volumes when necessary
- Manufacturing costs must be reduced to keep our products affordable and help us to gain market share.
- Must have a product lead time that is comparable to competitor lead times. Ideally, this would be 8 weeks or less for any product. Not all competitors are HMLV.
- Need to continue to support legacy product wherever possible. It is ok if this is expensive for product that should be well past its useful life (60+ years old).

Define operational approach

The projected needs are translated into the objectives in Figure 33.

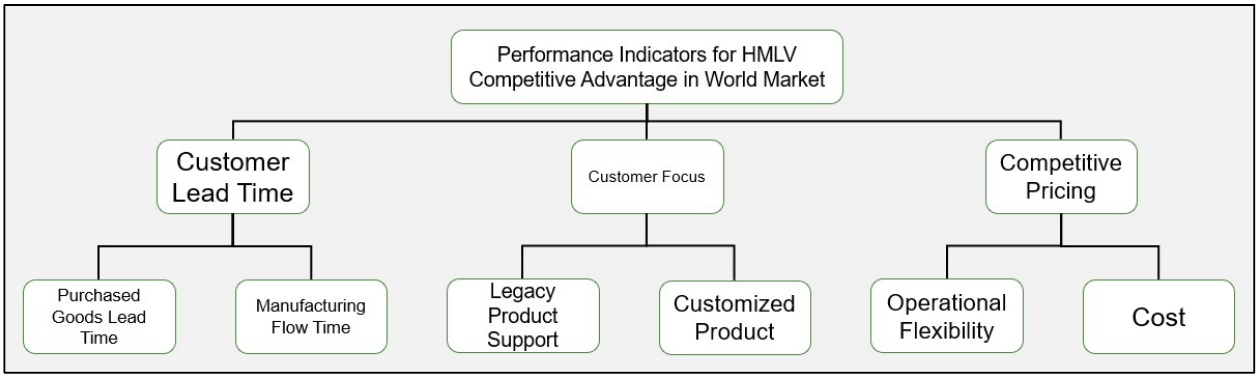


Figure 33: Needs Analysis for HMLV Manufacturer

Using a Five Forces market analysis (Figure 33), in conjunction with the current state of the art literature review and the needs defined (Figure 32), it can be determined that lead time (flow time in manufacturing), cost, and operational flexibility are the most important contributors to competitive advantage.

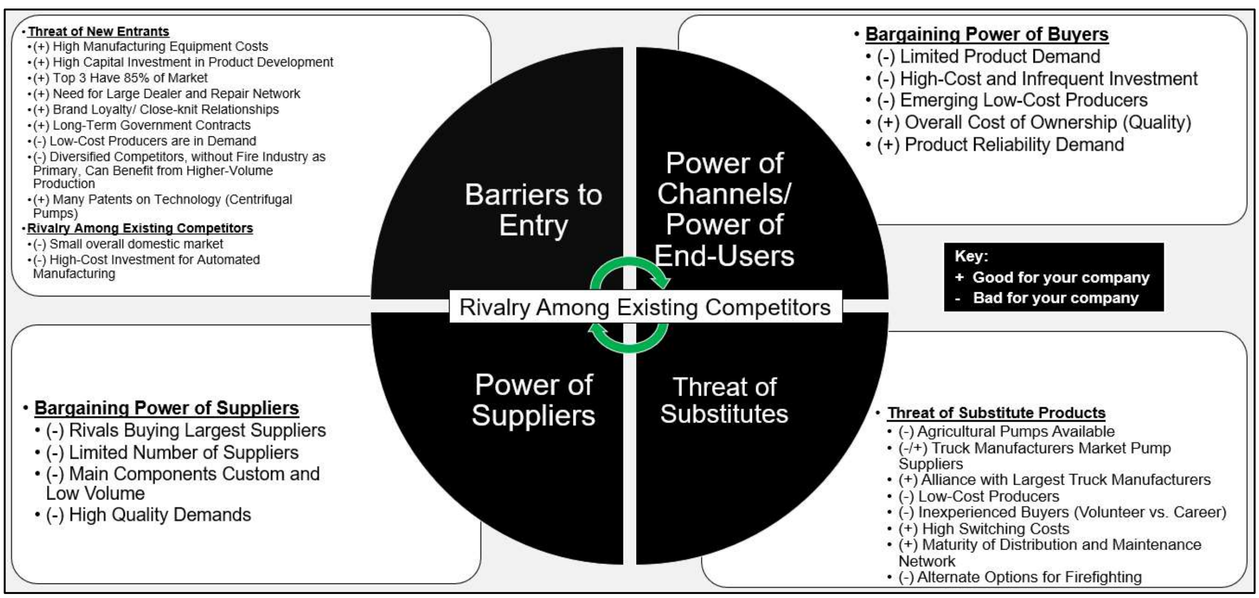


Figure 34: Five Forces Analysis for HMLV Manufacturer – Rivalry Among Existing Competitors

Functional analysis

Using the determined objectives, Table 46 defines the derived functions.

Table 46: Candidate applied projects for case studies at the subject manufacturer

ID	F ID	Candidate Process	Description
S1	F1	Purchased goods warehousing on site	Stock long lead purchased goods (anything over the 8-week customer lead time)
S2	F1	Purchased goods warehousing off site/ supplier Kanban	Have suppliers stock set quantities of purchased goods to be available for immediate shipment
S3	F1	Predictive ordering based on previous demand	Using existing data, predict demand levels for purchased goods and order based on historical
S4	F1	Restrict supplier geographic area to reduce travel time for goods	All suppliers to be within a set number of hours drive time to ensure same day delivery or pickup
S5	F1	Increase supplier base to improve lead times	Multiple suppliers for single items to ensure lower lead times and competitive pricing
S6	F1	Use economies of scale and a secondary supplier	Outsource purchasing – increase order quantities and decrease lead times with higher volume orders (combined with other OEMs)
S7	F1	Reduce purchased goods ordered (SKUs)	Modular design to use same cmponents when possible
S8	F2	Manufactured finished goods warehousing on site	Warehouse finished goods based on expected demand
S9	F2	Raw material warehousing	Warehouse raw materials based on expected demand (to remove material lead time from overall produce lead time)
S10	F2	Reduce manufactured goods needed (SKUs)	Consolidate product offerings to reduce number of components needed
S11	F2	Automate production facility – material handling	Material movement to be automated to remove labor input (labor for direct instead of indirect)
S12	F2	Load leveling to reduce WIP	Level workload across work centers to reduce WIP between operations
S13	F2	Changeover reduction to reduce economic order quantities	Reduce component, sub assembly, assemble change over times

S14	F2	Employee cross training	All work centers to have more than one employee trained to perform work required
S15	F2	Robust preventative maintenance program and maintenance warehouse	Reduce potential equipment down time with spare maintenance parts inventory and preventative maintenance
S16	F2	Cellular manufacturing – group by operation type	Group components in work cells based on the operations required to manufacture
S17	F2	Outsource components	Outsource "higher volume" and manufacture complex in house
S18	F2	Hybrid dynamic manufacturing flow	Separate ultra-low volume from main production flow
S19	F2	Increase labor hours available with added work shifts	Current shifts do not include regular weekend hours
S20	F3	Define support time frame	Reduce from 60 years
S21	F3	Additive manufacturing for legacy parts	Print castings/ parts
S22	F4	Determine options most used and remove rest	Reduce overall product offerings
S23	F4	Make product modular	Reduce options, customize with "standard parts"
S24	F4	Increase operational flexibility	Improve flexibility in process changeovers, workforce, and product
S25	F4	Increase prices for custom options outside normal options	Determine what is "standard" and increase customer price for rest
S26	F5	Standardize processes	Focus on process rather than product standards
S27	F5	Reduce change over times	Time to switch between products
S28	F5	Employee cross training	Allow flexibility in moving employees where needed
S29	F5	Modular product	Build with subassemblies and use options for more than one product
S30	F6	Consolidate raw material purchasing	Increase volume per material to reduce cost
S31	F6	Material handling	Reduce labor input for material handling
S32	F6	Reduce labor	Reduce labor input for processing raw materials

S33	F6	Green power generation	Generate power to reduce overall operating expenses
S34	F6	Outsource all components	Outsourcing all reduces equipment overhead, labor input, all processing time
S35	F6	Automate scheduling to reduce WIP	Load leveling operations to reduce material between operations

Appendix B: Potential Applications vs. Requirements and Paradigms

Table 47: Potential application projects vs requirements and paradigms

		Requirements							Paradigms								
Candidate Process	**Description**	**F1: Minimize purchased goods lead time**	**F2: Minimize manufacturing flow time**	**F3: Maintain legacy product support**	**F4: Maintain customized product**	**F5: Maximize operational flexibility**	**F6: Reduce cost**		**Just in Time (JIT)**	**Total Quality Management (TQM)**	**Theory of Constraints (TOC)**	**Overall Equipment Effectiveness (OEE)**	**Total Productive Maintenance (TPM)**	**Lean Manufacturing (Lean)**	**Six Sigma**	**Quick Response Manufacturing (QRM)**	**Description of Decision Making**
Purchased goods warehousing on site	Stock long lead purchased goods (anything over the 8-week customer lead time)	+	N/A	+	+	-	-		-	-	+	N/A	N/A	-	N/A	N/A	Warehousing purchased goods removes the lead time factor but increases carrying costs for inventory
Purchased goods warehousing off site/ supplier Kanban	Have suppliers stock set quantities of purchased goods to be available for immediate shipment	+	N/A	+	+	-	-		-	-	+	N/A	N/A	+	N/A	+	Offsite warehousing removed lead time factor but reduces flexibility and could increase costs if inventory is in stock and a change is made to components

Predictive ordering based on previous demand	Using existing data, predict demand levels for purchased goods and order based on historical	+	+	N/A	-	-	-		+	-	-	+	+	-	-	-	In highly configured products, with market volatility, predicting future demand is difficult and could lead to excessive inventory of items not needed
Restrict supplier geographic area to reduce travel time for goods	All suppliers to be within a set number of hours drive time to ensure same day delivery or pickup	+	N/A	+	+	N/A	+		+	+	+	N/A	N/A	+	N/A	+	Overall, this is helpful in quick product turnaround but may restrict options to the point where competitive pricing is at risk
Increase supplier base to improve lead times	Multiple suppliers for single items to ensure lower lead times and competitive pricing	+	N/A	-	+	+	+		+	+	+	N/A	N/A	+	N/A	+	Increasing the supplier base will reduce cost competitiveness due to reduced order quantities at a single supplier
Use economies of scale and a secondary supplier	Outsource purchasing – increase order quantities and decrease lead times with higher volume orders (combined with other OEMs)	+	+	-	+	-	+		+	-	+	N/A	N/A	+	-	-	Higher volume ordering for low volume production reduces flexibility and increases inventory carrying

Reduce purchased goods ordered (SKUs)	Modular design to use same components when possible	+	N/A	+	-	+	+		+	+	+	+	N/A	+	+	+	Reducing options increases order quantities with fewer components to order (consolidated), this also reduces flexibility and customized product (See also S10 and S22)
Manufactured finished goods warehousing on site	Warehouse finished goods based on expected demand	N/A	+	+	+	-	-		-	-	+	+	N/A	-	-	-	Warehousing goods means components are available when needed but also increases carrying costs and decreases flexibility
Raw material warehousing	Warehouse raw materials based on expected demand (to remove material lead time from overall produce lead time)	+	+	+	-	+	-		-	-	+	+	N/A	-	-	-	Warehousing raw materials without consolidating offerings increases material carrying costs and ability to support legacy product
Reduce manufactured goods needed (SKUs)	Consolidate product offerings to reduce number of components needed	N/A	+	N/A	-	+	+		+	+	+	+	+	+	+	+	Reducing options increases order quantities with fewer components to order (consolidated),

																	this also reduces flexibility and customized product (See also S7, S23, S25, and S22)
Automate production facility – material handling	Material movement to be automated to remove labor input (labor for direct instead of indirect)	N/A	+	N/A	-	-	+		+	+	+	+	+	+	N/A	+	Automation is typically only cost effective in higher volume operations and requires even higher costs to create flexibility
Load leveling to reduce WIP	Level work load across work centers to reduce WIP between operations	+	+	N/A	-	+	+		+	+	+	+	+	+	+	+	Load leveling helps operational efficiencies but can also increase the work that it takes to make changes to the production schedule
Changeover reduction to reduce economic order quantities	Reduce component, sub assembly, assemble change over times	N/A	+	+	+	+	+		+	+	+	+	+	+	+	+	Reducing changeovers is always beneficial because changeovers are indirect time
Employee cross training	All work centers to have more than one employee trained to perform work required	N/A	+	+	+	+	N/A		+	+	+	+	+	+	+	+	Flexibility in employee capabilities is always beneficial but also reduces their ability to

																	streamline their operations (See also S28)
Robust preventative maintenance program and maintenance warehouse	Reduce potential equipment down time with spare maintenance parts inventory and preventative maintenance	N/A	+	N/A	+	+	+		+	+	+	+	+	+	+	+	Preventative maintenance is always ideal because unexpected downtime is harder to schedule
Cellular manufacturing – group by operation type	Group components in work cells based on the operations required to manufacture	N/A	+	+	+	+	+		+	+	+	+	+	+	+	+	Process grouping rather than product grouping allows more flexibility
Outsource components	Outsource “higher volume” and manufacture complex in house	-	+	+	+	+	+		+	+	-	-	-	-	N/A	+	Outsourcing "higher volume" components will increase the cost of the lower volume since manufacturing overhead would not be offset with less expensive to make components
Hybrid dynamic manufacturing flow	Separate ultra-low volume from main production flow	N/A	+	+	+	+	+		N/A	-	+	-	-	-	-	-	Hybrid dynamic flow is ideal for HMLV manufacturing. It allows for efficiency gains in the

																	main product flow
Increase labor hours available with added work shifts	Current shifts do not include regular weekend hours	N/A	+	+	+	+	-		+	N/A	+	+	+	N/A	N/A	+	Increasing labor hours may not be fully offset with increased production. Adding employees also increases overhead and OT pay adds direct labor costs.
Define support time frame	Reduce from 60 years	+	+	+	+	+	+		+	-	N/A	+	N/A	+	+	+	Supporting legacy product is expensive but it is also a selling point for customers
Additive manufacturing for legacy parts	Print castings/ parts	+	+	+	+	+	+		+	+	+	+	+	+	+	+	Additive manufacturing has a high cost to entry and may be difficult to cost justify based on volumes
Determine options most used and remove rest	Reduce overall product offerings	+	+	-	+	+	+		+	+	+	+	+	+	+	+	Reducing options increases order quantities with fewer components to order (consolidated), this also reduces flexibility and

																customized product (See also S10, S23, S25, and S7)
Make product modular	Reduce options, customize with “standard parts”	+	+	-	+	+	+		+	+	+	+	+	+	+	+	Reducing options increases order quantities with fewer components to order (consolidated), this also reduces flexibility and customized product (See also S10, S22, S25, and S7)
Increase operational flexibility	Improve flexibility in process changeovers, workforce, and product	N/A	+	+	+	+	+		-	+	-	-	+	+	-	+	Define measures of flexibility and optimize
Increase prices for custom options outside normal options	Determine what is "standard" and increase customer price for rest	+	+	N/A	+	N/A	+		+	-	-	N/A	N/A	N/A	N/A	N/A	Reducing options increases order quantities with fewer components to order (consolidated), this also reduces flexibility and customized product (See also S10, S22, S23, and S7)

Standardize processes	Focus on process rather than product standards	N/A	+	+	+	+	+		+	-	-	+	+	+	+	+	Process standardization instead of product maintains production customization options
Reduce change over times	Time to switch between products	N/A	+	+	+	+	+		+	-	+	+	+	+	+	+	Reducing change overs is always beneficial because changeovers are indirect time
Employee cross training	Allow flexibility in moving employees where needed	N/A	+	+	+	+	N/A		+	+	+	+	+	+	+	+	Flexibility in employee capabilities is always beneficial but also reduces their ability to streamline their operations (See also S14)
Modular product	Build with subassemblies and use options for more than one product	+	+	+	-	+	+		+	+	+	+	+	+	+	+	This makes sense in all categories but customization since options would be reduced. A different option would be "base models" with configured options.

Consolidate raw material purchasing	Increase volume per material to reduce cost	+	N/A	+	-	-	+		-	+	-	N/A	N/A	-	N/A	-	Material costs differ greatly and going to the "highest standard" for each would be cost prohibitive for reducing number of different types of materials.
Material handling	Reduce labor input for material handling	N/A	+	N/A	N/A	+	+		+	+	+	+	+	+	N/A	+	Reducing direct labor used for indirect tasks can be done through automated material handling but should also consider more indirect labor if more cost effective.
Reduce labor	Reduce labor input for processing raw materials	N/A	+	-	-	-	+		+	+	+	+	+	+	N/A	+	Overprocessing of raw materials to accommodate legacy product features should be reduced with reduction in support time frame for product.
Green power generation	Generate power to reduce overall operating expenses	N/A	+	N/A	N/A	N/A	+		N/A	N/A	+	N/A	N/A	N/A	N/A	N/A	This represents a constraint in the manufacturing flow where the product test facilities are limited by

																power demand - changing this reduces the constraint
Outsource all components	Outsourcing all reduces equipment overhead, labor input, all processing time	-	+	-	-	-	+	-	-	-	-	-	N/A	-	-	In general, most components could be manufactured elsewhere with lower overhead but this also means reducing process control and creating external dependencies.
Automate scheduling to reduce WIP	Load leveling operations to reduce material between operations	N/A	+	+	+	+	+	+	-	+	+	+	+	-	+	This makes sense overall. There is little downside and implementation costs would be offset by reduced indirect labor input.

Appendix C: List of Variables

Table 48: List of all variables used in paper

Variable	Description	Experiment(s)
H_{LV}	Hours of operations Low Volume	1
H_{MP}	Hours of operations Main Production	1
IW_{LV}	value of inventory between operations Low Volume	1
IW_{MP}	value of inventory between operations Main Production	1
M_{LV}	Number of machines in Low Volume Cell	1
M_{MP}	Number of machines Main Production	1
OH_{EX}	Overhead multiplier for the experimental period (3 months)	1, 2, 3, 4, 5
OH_{LV}	Overhead in low volume	1
OH_{MP}	Overhead in main production	1
O_{LV}	Number of operators in the LV Cell	1
O_{MP}	Number of operators in the main production line	1
OW_{LV}	Operator wage in ultra-low volume cell	1
OW_{MP}	Operator wage in main production	1
PPH_{LV}	Parts per hour manufactured in ultra-low volume cell	1
PPH_{MP}	Parts per hour manufactured in main production	1
PV_{LV}	Part value for parts produced in the LV cell	1
PV_{MP}	Part value for parts produced in the main production line	1
μ	Average Value from Population	2, 5
C_E	Cost of engineering	2
C_F	Cost of fixtures and components	2
C_M	Cost of material	2
C_P	Cost of programming	2
C_S	Cost of Space	2, 3
C_T	Cost of training time (how to do the new setup process)	2
IW	Inventory Value in WIP	2, 3, 4
M_S	Machine Setup Time	2, 3, 4, 5
N	Number of Values in Population	2, 5
OH_{WC}	Overhead for the parts produced in the LV cell (3 months)	2, 3, 4, 5
OW_{WC}	Operator wage in the LV cell	2, 3, 4, 5
PPH	Parts Per Hour	2
PV	Part Value	2, 5

$\mathbf{Q_B}$	Number of parts in batch	2, 3, 5
$\mathbf{Q_S}$	Quantity of Non-Conforming Product	2, 3, 4, 5
$\mathbf{T_A}$	Time for Machine Adjustments	2, 5
$\mathbf{T_{IN}}$	Labor time for inventory	2
$\mathbf{T_J}$	Time operator is on the specific job	2, 3, 4, 5
$\mathbf{T_M}$	Labor time for material handling	2
$\mathbf{T_O}$	Labor time for operator	2, 3, 4, 5
$\mathbf{T_{OM}}$	time operator is assigned to machine	2
$\mathbf{T_P}$	Planned production time	2, 3, 4, 5
$\mathbf{T_S}$	Machine time spent on scrap parts	2, 5
$\mathbf{T_{SC}}$	Labor time for scheduling	2
$\mathbf{X_i}$	each value from the population	2, 5
D	Defects	3
$\mathbf{T_C}$	Cycle Time (per part)	3, 4, 5
X-bar	Mean or average change in process over time	3
$\boldsymbol{\sigma}$	Standard Deviation	3, 5
FPY	First Pass Yield over experiment period	4
$\mathbf{H_T}$	Total process hours	4
$\mathbf{H_U}$	Hours of time producing product	4
LT	Lead Time Average over time period (days)	4, 5
$\mathbf{Q_P}$	Production quantity over time period	4
$\mathbf{T_I}$	Ideal Cycle Time (Avg from St Rtg)	4, 5
H	Hours	5
$\mathbf{IW_{WC}}$	Inventory in WIP Value	5
M	Number of Machines	5
$\mathbf{PPH_{WC}}$	Parts Per Hour Produced for Work Center	5

Appendix D: List of Metric Equations

Table 49: List of all metric calculations used in paper

Ex	Paradigm	Metric	Variable	Equation
2, 5	TQM	Accuracy (A)	A	$(Q_B - Q_S)/Q_B$
1	TOC	Inventory	C_I	$IW * OH_{WC} * OH_{EX}$
1	TOC	Total Cost (C_P) Baseline	C_P	$(OW_{MP} * H_{MP} * OH_{MP})+(H_{MP} * OH_{MP} * OH_{MP})+(IW_{MP} * OH_{MP} * OH_{WIP})$
1	TOC	Total Cost (C_P) Experiment	C_P	$(OW_{MP} * H_{MP} * OH_{MP})+(H_{MP} * OH_{MP} * OH_{MP})+(IW_{MP} * OH_{MP} * OH_{WIP})+(OW_{LV} * H_{LV} * OH_{LV})+(H_{LV} * OH_{LV} * OH_{LV})+(IW_{LV} * OH_{LV} * OH_{WIP})$
2	TQM	Cost (C_P)	C_P	$C_E(T_E) + C_{PR}(T_P) + OW_F(T_F) + C_M + (IW)(OH_{EX}) + OW_{WC}(T_O) + C_T + C_S + C_F$
3	All	Total Cost	C_P	$(T_C + (M_S / Q_B)) * (OW_{WC} + OH_{WC})$
4	All	Total Cost (C_P)	C_P	$T_C * (OH_{WC} + OW_{WC})$
5	All	Total Cost	C_P	$(PPH_{WC} * PV * M)H - (OW_{WC} + OH_{WC})H - (IW_{WC} * OH_{EX})$
3	6σ	Process Variability	Cpk	$\overline{x} / \sigma$
2	Lean	Initial Setup Cost (C_{SR})	C_{SR}	$C_E + C_P + C_T + C_M + C_F$
3, 4, 5	OEE	Effectiveness	E	$(((Q_B - Q_S) * T_P) / T_O) / 100$
1	TOC	Throughput	F	Measured Value of Job Completions
3, 4, 5	OEE	Performance	H_C	T_C / Q_B
2	Lean	Labor Hours (H_L)	H_L	$T_E + T_P + T_F + T_O + T_M + T_{IN}$
4	Lean	Process Time per Unit (H_P)	H_P	$T_C + T_S$
5	Lean	Process Time Per Unit	H_P	Measured Value: Quantity Produced/ Time to Produce
2, 5	TQM	Reliability (H_R)	H_R	$1 - (T_A + T_S) / T_J$
2	TPM / QRM	Uptime (H_U)	H_U	$(T_{OM} - (T_J - M_S))/T_{OM}$
3, 4	TPM	Uptime	H_U	$(T_C * Q_B) / T_J$
5	TPM	Uptime	H_U	T_C / T_O
3	6σ	Lead Time	LT	Measured Value: Average Hours Per Batch

4	6σ	Lead Time (LT)	LT	Average Hours Per Unit
5	6σ	Lead Time	LT	Measured Value: Completion - Start
3	JIT	On Time Delivery	OTD	Measured Value: Quantity Batches Completed on Time/ Total Batches
2, 3, 4, 5	QRM	Parts Per Hour (PPH)	PPH	Q_B / T_J
1	TOC	Total Value Baseline	V_B	$(PPH_{MP} * PV_{MP} * M_{MP})H_{MP} – (OW_{MP} + OH_{MP})H_{MP} – IW_{MP}$
1	TOC	Total Value with LV	V_{EX}	$((PPH_{MP} * PV_{MP} * M_{MP}) + (PPH_{LV} * PV_{LV} * M_{LV})\ H_{LV} – (OW_{MP} + OH_{MP}\ OW_{LV} + OH_{LV})H_{LV} – IW_{MP} – IW_{LV}$
3, 4	JIT	WIP (WIP)	WIP	IW * OH
5	JIT	Work In Process	WIP	$IW * OH_{WC} * OH_{EX}$
5	6σ	Process Variation	σ	$\sigma(\Sigma(x_i - \mu)^2/N)$

Appendix E: Design of Experiments Illustrations

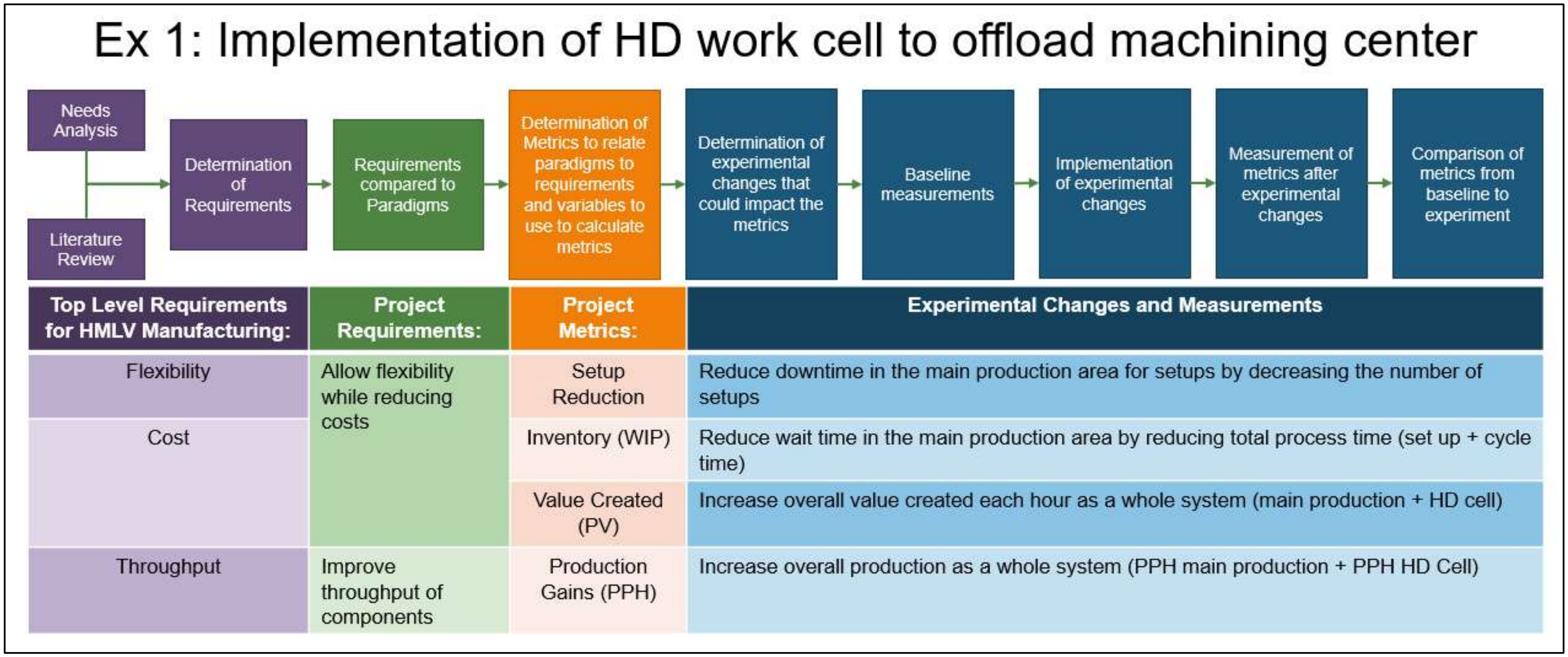
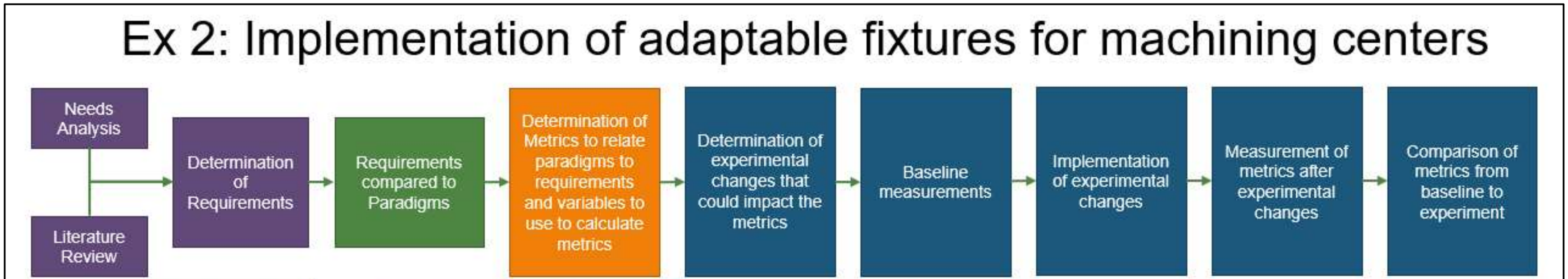


Figure 35: Experimental Design of Experiment 1: Hybrid Dynamic Manufacturing as a Theory of Constraints Application Method



Top Level Requirements for HMLV Manufacturing:	Project Requirements:	Project Metrics:	Experimental Changes and Measurements
Flexibility	Quick changeovers	Setup Reduction (C_{SR})	Implement flexible fixturing techniques to use the same fixture for more than one component.
Cost	Process quality	Accuracy (A)	Improve or maintain scrap rate/ rework rate for components
		Process Variation (σ)	Stabilize time to change over between components to allow efficiency in scheduling
		Uptime (H_U), Labor Hours (H_L)	Maximize machine time spent on value added activities to aid in throughput improvement
Throughput	Improved throughput to remove bottleneck	Parts per hour (PPH)	Maximize parts produced per hour to improve value produced over time
		Reliability (H_R)	Maximize process consistency to reduce unknown consequences

Figure 36: Experimental design of Experiment 2: Increase Operational Flexibility Using Adaptable Machining Fixture Methods

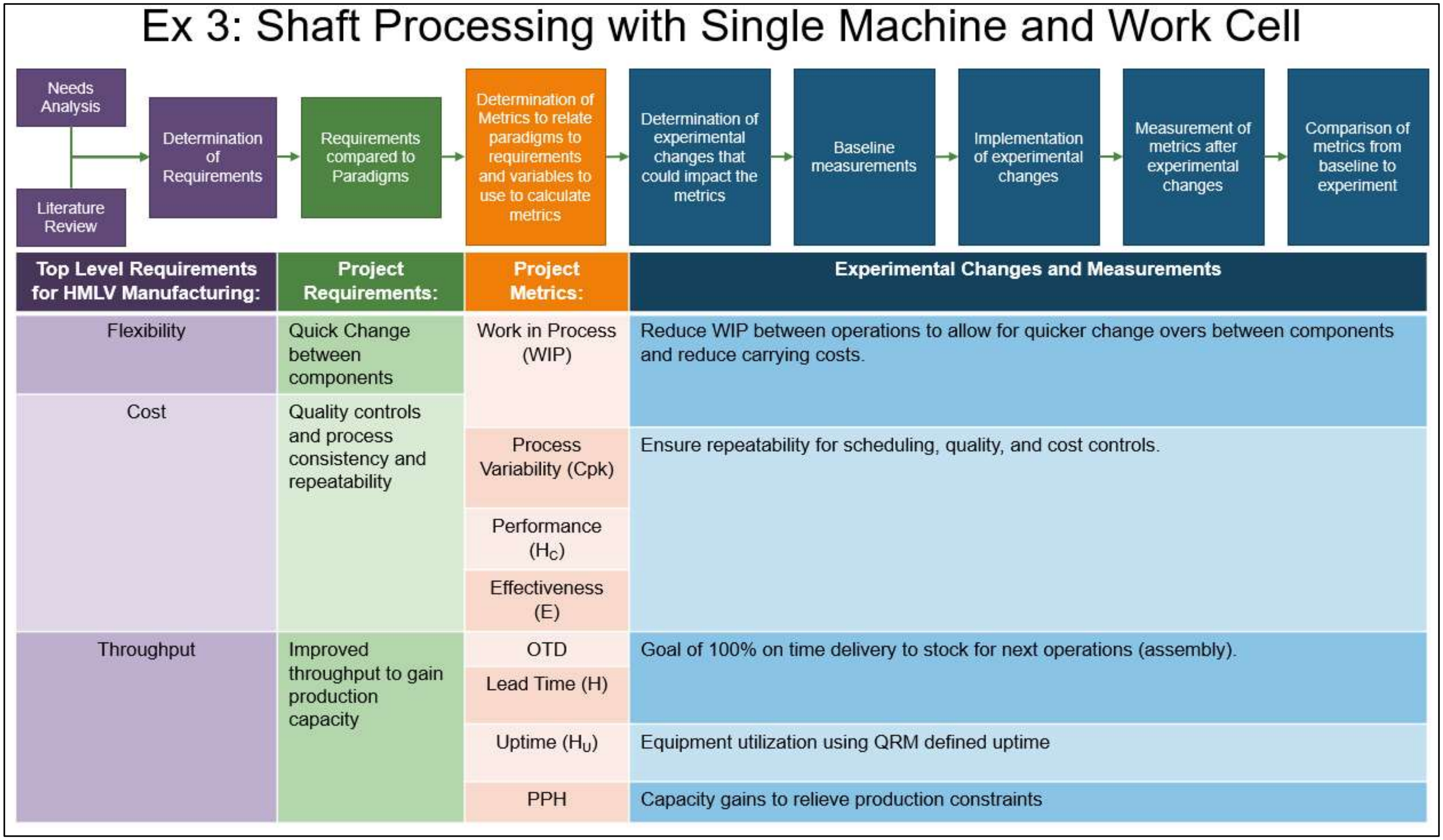


Figure 37: Experimental design of Experiment 3: Standardization with Machine Process Flow

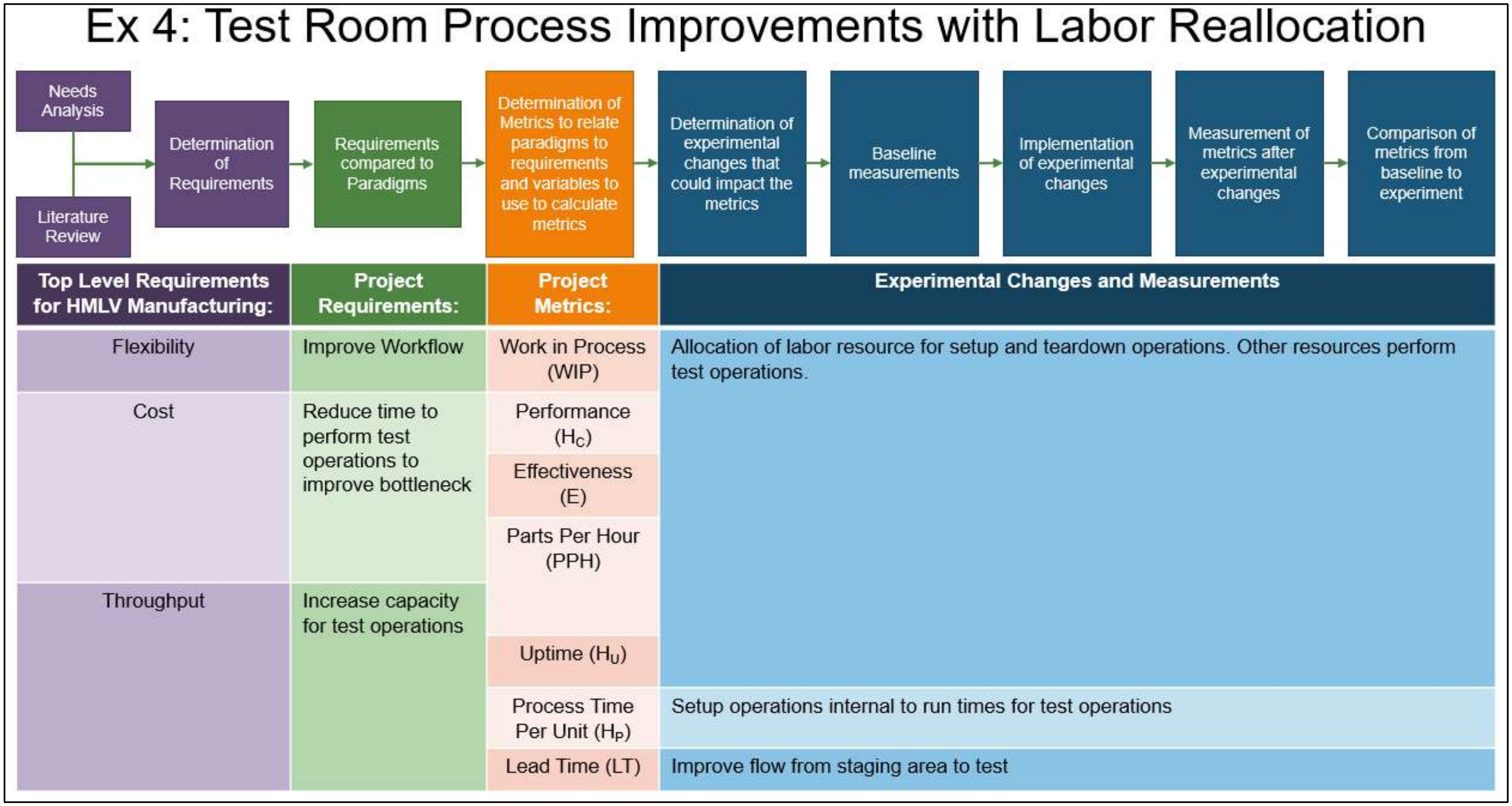


Figure 38: Experimental Design of Experiment 4: Reducing Change Over Times Using Adjusted Process Flow and Internalized Operations

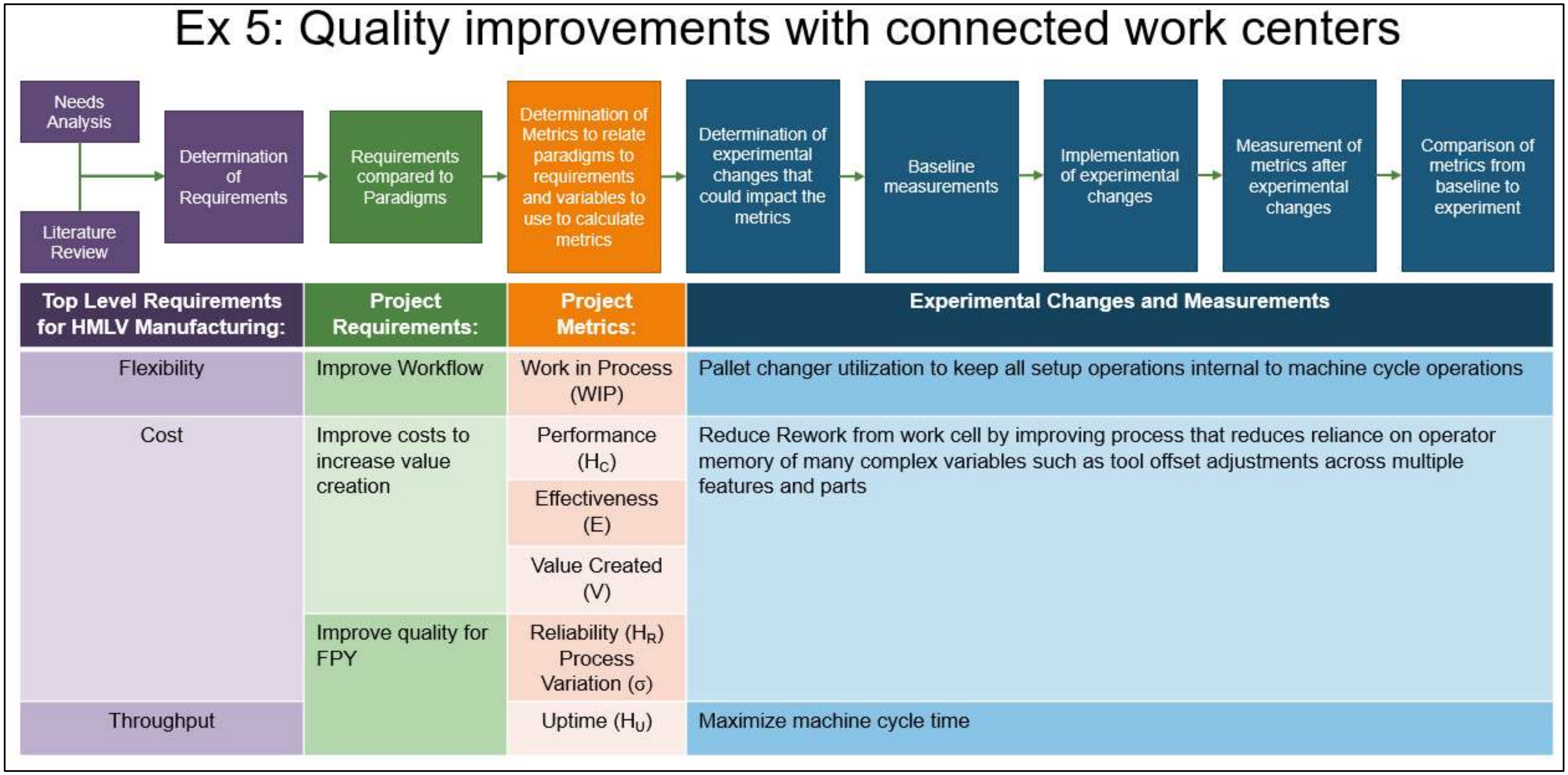


Figure 39: Experimental Design of Experiment 5: Load Leveling Operations to Optimize Flexibility, Balance Throughput, and Improve Quality

List of Abbreviations

Abbreviation or Acronym	Definition
6σ	Six Sigma
CNC	Computer Numerically Controlled Machines
ERP	Enterprise Resource Planning
FIFO	First-In First-Out
FPY	First Pass Yield
HD	Hybrid-Dynamic Manufacturing
HMLV	High-Mix Low-Volume
JIT	Just In Time
Lean	Lean Manufacturing
LMHV	Low-Mix High-Volume
LSS	Lean Six Sigma
LV	Low Volume
MCT	Manufacturing Critical-Path Time
NCR	Non-Conformity Report
OEE	Overall Equipment Effectiveness
QRM	Quick Response Manufacturing
SE	Systems Engineering
SMED	Single Minute Exchange of Dies
TOC	Theory of Constraints
TQM	Total Quality Management
VSM	Value Stream Map
WIP	Work In Process