AN ABSTRACT OF THE THESIS OF

Olivia J. Girod for the degree of Honors Baccalaureate of Science in Industrial Engineering presented on March 14th, 2014. Title: A Hybrid-Dynamic Transition Phase for High Mix Low Volume Small-and-Medium Manufacturers.

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SMEs with high-mix and low-volume (HMLV) operations face special challenges when implementing lean manufacturing practices due to scarcity of resources and ever changing market conditions. This is especially critical for manufacturers that need to deliver orders to a high variety of customers with varying time response requirements. The objective of this study is to present a holistic approach to design hybrid-dynamic manufacturing systems (HDMS) for HMLV SMEs. The HDMS is introduced as a case-study, for an Oregon-based laboratory equipment HMLV manufacturer. The HDMS was utilized to incorporate hybrid lead times using an express line for high production volume products that would run in parallel with the regular production stream. The performance of the designed express line is modeled and validated with historical system performance. The simulation results indicate that the lead time of identified product models can be reduced without affecting the rest of the production flow. The case study shows that for HMLV SME manufacturers, a HDMS can provide a solution to implement hybrid lead times into their production lines.

Keywords: Lean manufacturing, Hybrid-dynamic manufacturing system (HDMS), Small-to-medium enterprise (SME), High-Mix-Low-Volume (HMLV)

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A Hybrid-Dynamic Transition Phase for High Mix Low Volume Manufacturers

by

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Olivia J. Girod, Author

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CONTRIBUTION OF AUTHORS

Two capstone senior design projects served as the basis for my thesis research. The first senior design project focused on the case study company and the implementation of an express line using a kanban-technique. This senior design project team included two other members, Adam Strength and James Amrhein. I was a part of this senior design project and it aided in the background research and understanding of the case study company. The second senior design project was also for the case study company and focused on updating their current scheduling system. This team was comprised of Chris Thompson, Matthew Munson and Dat Ho. The proposed scheduling heuristic included in this report which is specific to the case study company was created by this team. Thank you for your contributions.

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DEDICATION

This thesis is dedicated to my mother and father,

Julia and Dennis Girod.

A HYBRID-DYNAMIC TRANSITION PHASE FOR HIGH MIX LOW VOLUME SMALL-AND-MEDIUM MANUFACTURERS

1. INTRODUCTION

Small-and-medium enterprises (SMEs) are increasingly more prevalent in the United States as well as globally and are a vital component to the economy. In the State of the Union Address by President Barack Obama on January 28th, 2014, it was noted that 98% of exporters from the United States are small businesses [1]. According to surveys conducted by the Small Business Administration (SBA), approximately 99% of all manufacturing companies in the United States are SMEs [2]. A small to medium-sized enterprise (SME), for a manufacturing or non-exporting service firm, is one that employs fewer than 250 persons and has an annual revenue not exceeding $25 million [3]. As SMEs are often young companies or service a small portion of an industry comparative to a large corporation, SMEs face unique challenges. First, SMEs often have limited resources, both monetarily and personnel-wise. SMEs may not have the engineering staff and capabilities of a larger company. Additionally, SMEs often don't have personnel with experience in implementing lean principles. With this, SMEs may be unaware of the opportunities for improvement from their current state. If the profits are still positive, an SME may not seek to make changes. These individual challenges can be overlooked in research and case studies as each is unique to the industry. Creating a solution for one may not apply to all or benefit a large number of companies.

High mix low volume (HMLV) is a manufacturing environment where the products being made vary in application, lot size and production process [4]. In HMLV manufacturing, the company has a variety of product offerings which are each produced in relatively small amounts. SMEs with a HMLV of products face unique challenges in solving problems. With an HMLV of products, it is difficult to establish a flow within the company due to three main variance types: (1) Variance of products: it is difficult for companies to establish product flow as there is a large variety of products which require different raw materials, various processing times and process procedures; (2) Variance of routings: with a low volume of each of the wide variety of products, it is difficult to create consistency on the line as batching products or creating a back-log of inventory is not ideal. Each product may not pass through all process steps; and (3) Variance of cycle times at each process: with many products it is difficult to create a balanced line as each product has a varying cycle time at each process step [5].

1.1 Research Objective

The objective of this study to propose a hybrid dynamic manufacturing system (HDMS) which adapts to varying customer demand levels and accommodates certain high production volume products, in addition to providing scheduling for standard products. The HDMS, specifically for SMEs with an HMLV of products, addresses issues of long lead times to customers and balancing unpredictable customer demand. To do so, HMLV companies should focus on streamlining the flow of the high mix of products across many process steps. This paper presents a systemic approach to design an HDMS for HMLV SMEs. An HDMS incorporates multiple product flow approaches and is able to adapt to customer demand levels and company manufacturing requirements. The approach is illustrated with a case study conducted in an Oregon-based SME laboratory equipment HMLV manufacturer.

2. BACKGROUND

Selected prior research for SMEs with an HMLV of products is reviewed in the following section. There is a fair amount of recent research on methods to improve customer relations and reduce cycle times at SMEs. SMEs have resources available to implement large-scale lean management techniques into their manufacturing. These opportunities which will be investigated relate specifically to individual ways to value stream map (VSM) the facility, facilities layout, product mix planning and lot size optimization. The literature reviewed herein is intended to provide insight into the problems faced by SMEs specifically with HMLV products, and the prior methods for solving these issues with lean techniques.

2.1 Value Stream Mapping

Value stream mapping (VSM) is a lean management technique used to analyze the flow of materials and information to create a product or service [5]. A VSM identifies value-added time, non-value-added time, the number of operators and the number of machines for a given process. Creating a VSM is a good way to see areas of opportunity to reduce non-value-added time or redistribute personnel across processes to reduce cycle times. One VSM approach for HMLV manufacturers differs from the traditional approach in that it incorporates the Toyota Way Lean principles, value network mapping and Made to Order Lean visual management production control [5]. Traditionally, a VSM is created for a single product but in this approach it incorporates the whole process. This approach creates a box for each process where the box size is proportionate to the percentage of demand that passes through the station [5]. As this approach is holistic and incorporates all products, it requires specialized software to create the VSM, a resource to which many SMEs do not have access.

While this approach creates a basis for Value Stream Mapping of an HMLV facility, it does not address the issues faced when dealing with HMLV products.

2.2 Facility Layout Planning

An SME with an HMLV of products can benefit greatly from considering the facility layout or redesigning their current flow. Two such methods of facilities layout are introduced by [6], which are a modular layout and a hybrid flow shop layout. The first of these options, a modular layout, in an ideal situation, would have individual modules that each product separate products or groups of products. This would allow for material batching, reduce material travel distance and create more predictable cycle times within a given module. As each product would have its own module, this design could reduce customer lead time on an individual product basis. The second layout type discussed in [6] is a hybrid flow shop layout which aims to create a single direction flow and reduce backtracking. In this layout, machines are grouped by those which can perform consecutive operations occurring in the operation sequences of a large number of parts [6]. This design layout is not as ideal for an HMLV of products as each product has varying routings and it would be difficult to establish an operational sequence. These layout alternatives for SMEs with HMLV of products aim to simplify the material flow into more predictable and manageable subsections. This solution provides long-term benefits but may not feasible with the small budgets at many SMEs.

2.3 Product Mix Planning

Product mix planning is essential at an SME where customer demand levels vary to reduce changeover costs and time in addition to increasing equipment efficiency. As SMEs with

HMLV product offerings must hold a lot of raw materials to produce the diverse products, they often see high inventory costs. Additionally, to offer a wide mix of products, changeover time and costs are typically high. To combat these issues, an optimization technique for inventory lot sizing for sets of machines with high replenishment costs was created in [7]. This method suggests calculating lot sizes for part families which share set-ups and using these values to create the production schedule. This method will reduce product changeover costs and increase machine efficiencies by reducing downtime due to machine changeover but this method is inflexible in the long-term. The calculations will need to be redone for each new product family that is introduced and for varying demand. Thus, it does not address the research objective of accommodating varying customer demand levels.

Currently, the research and case studies which exist for SMEs with an HMLV of products, as introduced above, do not address the unique situations which they face with limited resources, highly unpredictable demand, large varieties of inventories and difficulties with creating material flow. The HDMS design being proposed will be implementable at SMEs with an HMLV of products with low personnel and monetary resources.

3. METHODOLOGY

To address the issues of greater cycle times than customer desired delivery dates and excessive finished goods inventories at SMEs with an HMLV of products, a systemic approach is developed. This methodology is designed for HMLV SMEs where changes are needed to product scheduling and product lead times, yet little to no funds exist to realize these changes. Additionally, management must be willing and committed to adopting a lean culture. Management or personnel should have a basic understanding of lean concepts (e.g., understand a kanban system, just-in-time (JIT) production, and muda), or be willing to commit the time or resources to gain this knowledge.

3.1 Rationale

As demand is highly unpredictable in SMEs with an HMLV of products, implementing a one-time change will not be beneficial once product demand and product mix change. Thus, an HDMS is ideal as it can accommodate these changes because while it requires new methods, these can change with varying product and market demand. Additionally, a focus on lean manufacturing is essential at an SME with an HMLV of products. With the issue of limited resources, both monetary and personnel, which SMEs often face, it is more feasible for SMEs to focus on continuous improvement and waste reduction instead of an immediate large change.

3.2 Methodological Approach

The general methodology which can be used at an SME with an HMLV of products to implement an HDMS is shown in Figure 1.

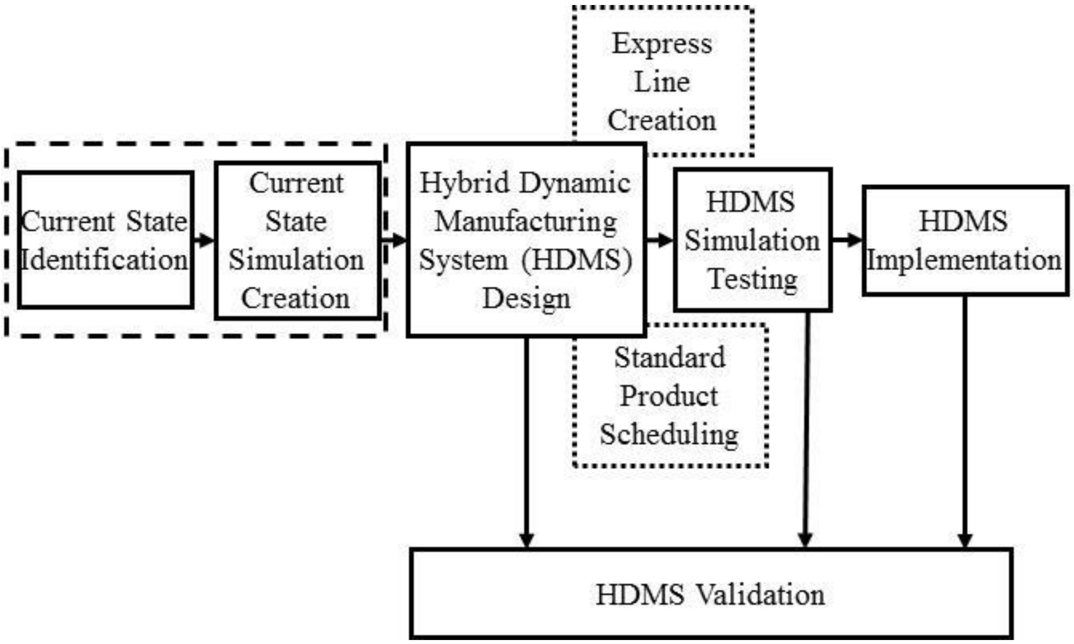


Figure 1: Methodology to implement an HDMS at an SME with an HMLV of products

As shown in Figure 1, the HDMS design incorporates both creating the express line and scheduling for the standard products. Current state identification and current state simulation creation are activities which both relate to how the company currently operates and creating a benchmark for the new HDMS design. The grouping of these two activities is denoted with the dashed box, shown in Figure 1. These are grouped together as the identification of the current state contributes directly to creating the simulation for the current state. Additionally, it should be addressed that in Figure 1 validation occurs during the HDMS design, testing and implementation phases. As the design is dynamic, it will constantly be validated to ensure it meets the needs of the company and customers and can be revised for product and customer expectation changes. The approach presented in Figure 1 will be described in further detail in the subsequent sections.

3.3 Current State Identification

To begin, an SME should understand their current state, shown in the first box in Figure 1, by creating a value stream map (VSM), performing a root cause analysis (RCA), creating a fishbone diagram, asking the five whys or other methods for identifying production bottlenecks and problems. The current state primarily includes objective data such as product cycle times, machine information and inventory levels. Once an understanding of the current state of the manufacturing processes is gained, an understanding of the current personnel behaviors must be gathered. SMEs at the initial state of implementing lean often lack standardized documentation such as standard operating procedures (SOPs). To understand how employees currently operate, direct observation of the manufacturing floor and interviews with personnel can be conducted. Example questions that should be answered from these two methods include:

- How does an operator select which product to process next?
- Approximately how many products are waiting to be processed at each step at any given time?
- What steps go into a machine changeover for a certain model?
- What training is provided to an operator to learn how to produce a given product?
- How are manufacturing processes specified for a given product?

From the current state of manufacturing and personnel behavior understanding, steps can then be identified as value-added, support activities or non-value-added (waste). Value-added activities add market form or function to the product [8] and are things which the customer is willing to pay for. Support activities are those which do not add market form or function to the product but are necessary for the finished product. These should be reduced in cycle time, if possible. Non-value-added behaviors are any which do not add market form or function to the product or items which the customer is not willing to pay for [8]. Those which are non-value-added should be sought to be eliminated.

Once the personnel identify the current state behaviors and identify non-value-added and support activities, they can begin to move towards the creation of a solution.

3.4 Current State Simulation Creation

The first step in Figure 1 assists with identifying problem areas and moving an SME towards a leaner state but more analysis is needed for a dynamic simulation. A software simulation can be updated for new products, fluctuating demand, and varying process times, thus, it is ideal for the HDMS creation process. Simulation helps to understand where issues exist and how a change will affect the manufacturing line. A simulation of the current state with processing times and machine capabilities gathered from the VSM and from direct observation can be created. Commercially available software tools for manufacturing simulation include Arena and Witness.

3.5 HDMS Design

An HDMS can account for an HMLV of products with varying processing times and manufacturing steps. Additionally, it is able to adapt to change over time. The HDMS is divided into two subsections: the express line for comparatively higher weekly demand and shorter cycle time products and the standard line for all other products. This design creates a flexible manufacturing production of both high-volume products and non-high-volume products.

3.5.1 Express Line Design

The current and future state simulations lend themselves to the implementation of a system with an express line of products. To create the system, first, the products for the express line should be identified. These products should have comparatively high weekly demand and comparatively low cycle times. Once the products have been identified, processing information (e.g., process time, specifications, operating procedures) and machine information (e.g., capacity) need to be gathered for scheduling of the express line products.

3.5.2 Standard Product Scheduling

The second component of the HDMS is the scheduling for the standard products. The technique will need to adapt to the current scheduling software (if one exists) and the available resources. Each SME is unique and an example of one scheduling technique will be presented in the case study, however, these general guidelines should be adhered to for optimal results. First, the scheduling system should be resilient and better adapt to fluctuating customer demand. The system should be able to accommodate an array of material volume levels and promised customer delivery dates. Although all these scenarios will likely to not occur, the capability to schedule for any such occurrence is important.

Second, this scheduling system should use a decision support heuristic which walks the scheduler through the process. The heuristic will require trial and error and revisions to better fit the company's needs. Scheduling products by a heuristic is ideal because it can be completed by multiple personnel. The knowledge of scheduling the products will not belong to a single person and will provide more flexibility for the company. Additionally, a heuristic creates the potential for automating the scheduling system in the long-term with a program such as Excel with VBA.

The third important component of the schedule is it should be created for as close to one-piece flow as possible. With an HMLV of products, it is often not possible to group identical products therefore similar products get grouped together which then creates issues of products waiting to move onto the next process step. One-piece flow creates more flexibility in product scheduling. Finally, components which are not part of the main assembly or can be assembled aside from the main product flow should be processed in parallel to the main assembly. Thus, when the main assembly reaches the final assembly step, the subcomponents will already be completed. This process is known as concurrent manufacturing.

3.6 HDMS Simulation Testing

Prior to implementing the express line and standard product scheduling, both should be tested to create a smoother implementation process. A simulation should be created for the HDMS system. As the same data from the first simulation (current state simulation before HDMS) can be used for machine processing times and machine changeover times, this will demonstrate the benefits and areas for the improvement in the HDMS. The improvements demonstrated in the simulations can serve as the basis for requesting funds and/or gaining manufacturing personnel and management support for the HDMS implementation. Through a process of trial and error, a decision support heuristic for the daily scheduling system and the express line design should be ready to be implemented at the SME.

3.7 HDMS Implementation

Once the design and simulation testing are completed, the physical implementation of the HDMS should occur. This phase may take up to several months depending on whether it occurs in phases or all at once. Implementation in phases would make for a smoother transition with less disruption to production; however, the full results would not be seen until implementation is complete. One option for implementation in phases is to begin with changing the production scheduling system. Then, once the scheduling change has been executed, the express line can be implemented.

3.8 HDMS Validation

As mentioned previously, the purpose of an HDMS is to be able to adapt to varying customer demand and an HMLV of products. This adaptability means that when new products are added to the manufacturing line or a product has steady, increased demand, the HDMS should change to meet these needs. Thus, the validation phase will be ongoing for the life of the HDMS. For example, if a product is seeing high weekly demand on the standard line on a consistent basis and has a comparatively low cycle time to the other products, the company should look at adding the product, or exchanging it for another product, on the express line. To validate the possible changes, it can first be modeled using software simulation to predict the effect of the change on the non-value-added time, value-added time, and time for support activities during production.

4. CASE STUDY

The proposed systemic approach to design the hybrid dynamic manufacturing system (HDMS) is illustrated below with an Oregon-based laboratory equipment HMLV manufacturer.

The case study company designs and manufactures constant temperature equipment with over 100 different models. There is a lack of standardization across the products. Two models may be similar in shape or size, but the components which make up the assembly are not the same. This increases the raw materials needed on hand. There is a wide variety of customers, and each has different product expectations and varying time response requirements. Currently, the average lead time for products is approximately three weeks. To shorten lead time, the company holds a finished goods inventory, which also helps with customer relationships. If a product undergoes a design change, however, the items in the finished goods inventory must be modified to meet customer specifications. This additional processing leads to increased manufacturing costs and increased lead time.

4.1 Current State Description

The facility has one manufacturing line and four assembly lines, which are operated by approximately 60 people in the manufacturing department. Typically, it operates four days per week with the main day shift working four, ten-hour shifts. In addition to the day shift, there is also a swing shift which is typically scheduled based upon need. Though there are the manufacturing lines, the company operates in the style of a job shop, creating custom units and adjusting to customer requests and demand levels. The manufacturing floor is divided into two sections: the metal shop and the assembly shop. To provide a better understanding of facility operations, a high-level material flow diagram is shown in Figure 2, and Figure 3 shows the plant layout for the manufacturing facility.

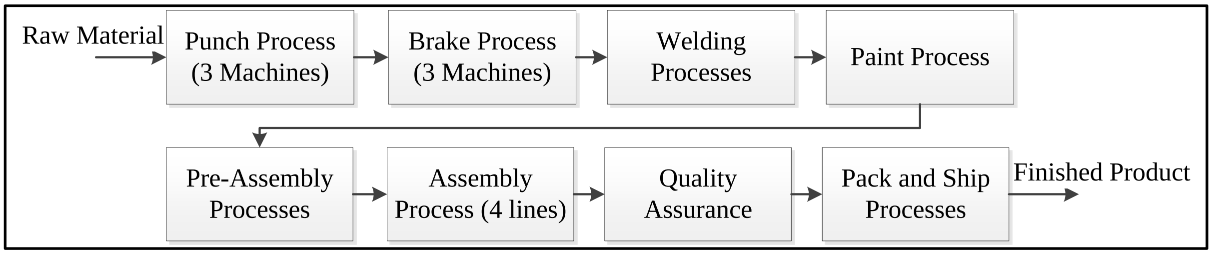


Figure 2: High-level process flow for the facility under consideration

The first four processes, punch, brake, welding and paint, are housed on the metal shop side of the facility. The final three processes, assembly, quality assurance, and pack and ship, are on the assembly side of the facility. A more detailed version of the process flow is shown on the value stream map (VSM) contained in the Appendix. It should be noted that parts for a particular product model have different product routings; therefore, all parts do not pass through every process step. The discussion below provides more detail into the background of the production areas, material flow, and staffing.

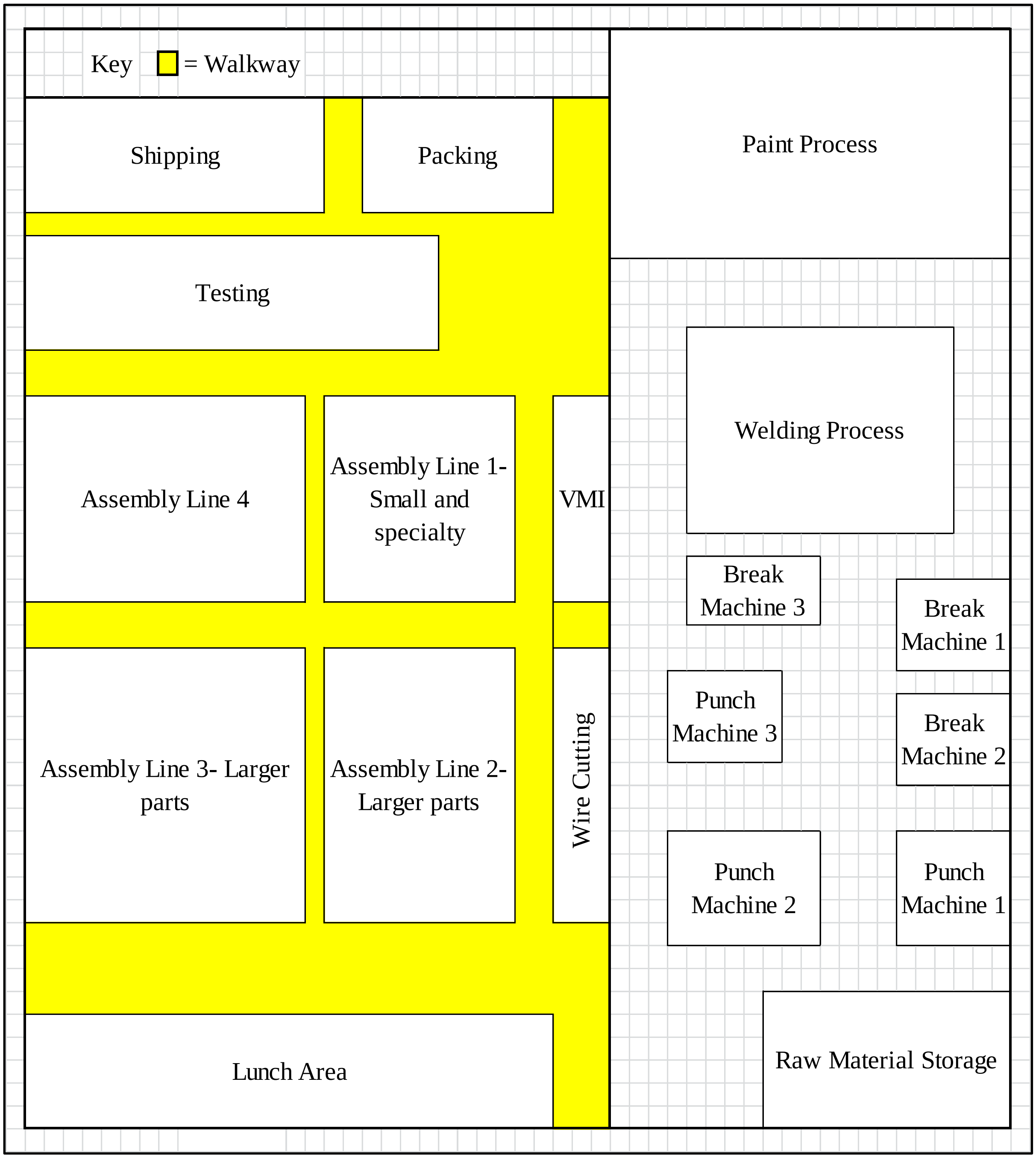


Figure 3: Layout of the facility under consideration

4.1.1 Metal Shop Processes

The metal shop utilizes four main processes: punch, brake, weld, and paint. The operations begin with metal sheets as the raw material. This material is ordered in large batches to reduce costs; excess is stored in the raw material storage area indicated in the bottom right corner of Figure 3. There are approximately 80 different metal variations used at the facility, which range in size, gauge, metal type, and several other specifications. These metal sheets first are processed at one of three punch machines, as shown in Figure 2. Referring to Figure 3, the punch machines are shown near the lower right corner. This process step is the responsibility of five operators. As the pieces are punched from large metal sheets, there is a portion of the sheet leftover which has not been punched. To avoid having partially punched sheets, operators punch additional pieces from the sheet. The additional pieces which are punched are up to the discretion of the machine operator and are usually selected based upon frequency of need. The pieces which are punched and not currently needed are stored in racking until the demand arises. Metal pieces which have been punched then pass to one of three break machines run by five operators. The break process involves clamping the work piece between a matching punch and die to break the piece to a pre-determined radius. The actual processing times for pieces are minimal. A large portion of time at the break process is from set-up including changing out the dies and punches. It takes one week for metal sheets to be punched and bent.

Once the metal pieces have been bent at the brake machine, most must pass through the welding and paint processes for the metal shop side. First, they go to the welding department, located towards the upper right of Figure 3. Parts can be welded manually, by the robotic welder, or using a spot-welding machine. This process requires four full-time operators and two half-time operators, with two additional machines and two operators at the spot-welding workstation. Typically, welding jobs are started on the first working day of the week, and take about four days to complete. Thus, if a product arrives at the welding station on Tuesday, it will not be processed until the following Monday, increasing the non-value-added time for the product. Next, parts are ground by a single machine and operator, and then sent to the paint department located in the top right of Figure 3. Paint jobs are batched by color specification because changing paint colors requires machine changeover time. Thus, operators try to create as large or batches as possible for a given color prior to switching to the next color. Once products are dry, they are moved to the assembly shop.

4.1.2 Assembly Shop Processes

Once products have completed the process steps on the metal shop side, they pass to the assembly shop processes. On the assembly shop side, there are four process steps: pre-assembly, assembly, quality assurance, and packing and shipping. The shop includes four assembly lines. Line 1 is designated for smaller and specialty products. Lines 2 and 3 are for bigger products and Line 4 does not have any specific designation. In the past, the company used all five assembly lines. The fifth assembly line was located where the current lunch area is in the bottom left of Figure 3. With their current levels of demand, only four assembly lines are needed. Each of the four assembly lines has four operators working on day shift. Products are scheduled to maximize utilization at the assembly stations. When assembling products, operators aim to batch the same or similar products.

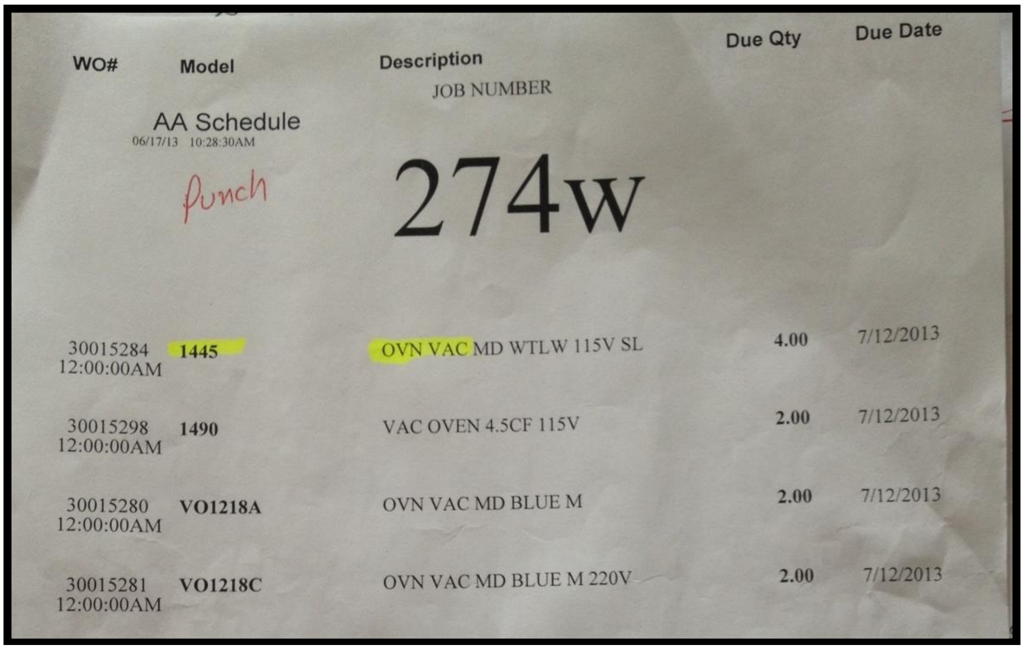
Once products have been assembled, the next process step is quality assurance (QA). Here, products are inspected to ensure they conform to quality standards. If there is a defect in the product, it must be reworked or replaced. There are two operators who work in QA. As shown in Figure 3, there is not a specific physical location dedicated to QA, it is typically performed in the assembly area once it is fully assembled. After QA, products are packaged to protect from damage during shipping. Finally, products which have been ordered by a customer are shipped. Those which are manufactured for the finished goods inventory are stored in the shipping area to be shipped when the demand arises.

4.1.3 Material Scheduling

The production manager (PM) serves as the central controller of material flow, by creating a production schedule at the beginning of each week. The PM releases the orders electronically, which then determines the flow of materials through the shop. The PM receives orders from customers throughout the week and schedules the products based upon the delivery date requested, the availability of the four assembly lines and similar products which are being scheduled.

Each customer submits an expected delivery date for the product. The PM aims to have the product arrive at the customer by this date by managing the scheduling system. Thus, the delivery date requested for each product weighs heavily on the scheduling decisions of the production manager. Lastly, as described previously, the company has four assembly lines which are dedicated to specific product types. The PM evaluates the material levels for each of the four lines to determine the available capacity for a given week. Products are batched with like items, therefore products may be scheduled which are not requested by a customer to create a complete batch.

Once products have been released electronically, they must be uniquely identified and tracked. Products are assigned to a job. Currently, there is no computerized inventory tracking system in place. Once products are assigned to a job, a router is printed. An example of a product router is shown in Figure 4.



AA Schedule
06/17/13 10:28:30AM
Punch

JOB NUMBER
274w

WO#	Model	Description	Due Qty	Due Date
30015284 12:00:00AM	1445	OVN VAC MD WTLW 115V SL	4.00	7/12/2013
30015298 12:00:00AM	1490	VAC OVEN 4.5CF 115V	2.00	7/12/2013
30015280 12:00:00AM	VO1218A	OVN VAC MD BLUE M	2.00	7/12/2013
30015281 12:00:00AM	VO1218C	OVN VAC MD BLUE M 220V	2.00	7/12/2013

Figure 4: Sample product router with work order, model, description, quantity, and due date information indicated

The router specifies which processes are required for this product, a description of the processes and the required quantity and due date for the respective processes. Additionally, each job has a unique identifier comprised of a three-digit number and a letter. In Figure 4, for instance, this is 274w. The first two digits are the work week of the year, or week 27 in this case. The third number identifies on which line the product will be assembled. In this case, the product will be assembled on line four. The letter in the identifier corresponds to the color of the router (w is for white). Router colors vary to assist in quick visual identification of parts on the manufacturing floor.

Their current production system, as stated above, conforms to the needs of the customer. When an order is received, the production manager determines how to incorporate that order into the line. As some products have longer cycle times than the lead times requested by the customer, however, the company holds certain products in finished goods inventory to be able to meet their customers' needs. With this method, products which are not currently requested by a customer must be included in the production schedule. Additionally, issues arise when these products become obsolete and must be reworked before they can be sold. Reworking the products increases product cycle time and costs for the company.

4.2 Current State Simulation Creation

As described in Section 4.1and shown in the VSM in Appendix A, products have seven main processing steps. The process steps encompass fairly low levels of complexity and require manual processing especially at the welding, assembly and quality assurance steps.

The company had little documentation of product routings, product cycle times, or machine changeover times. As there was no electronic tracking system, this information had to be gathered by hand through time studies, direct observation, and interviews with the operators. The manufacturing line was examined at each process step individually, providing more detailed information. This information was compiled to approximate average wait times, processing times, and machine changeover times. Upon gathering the product information, a simulation of the current state of the facility was created using Arena simulation software. This simulation is highlighted in Figure 5.

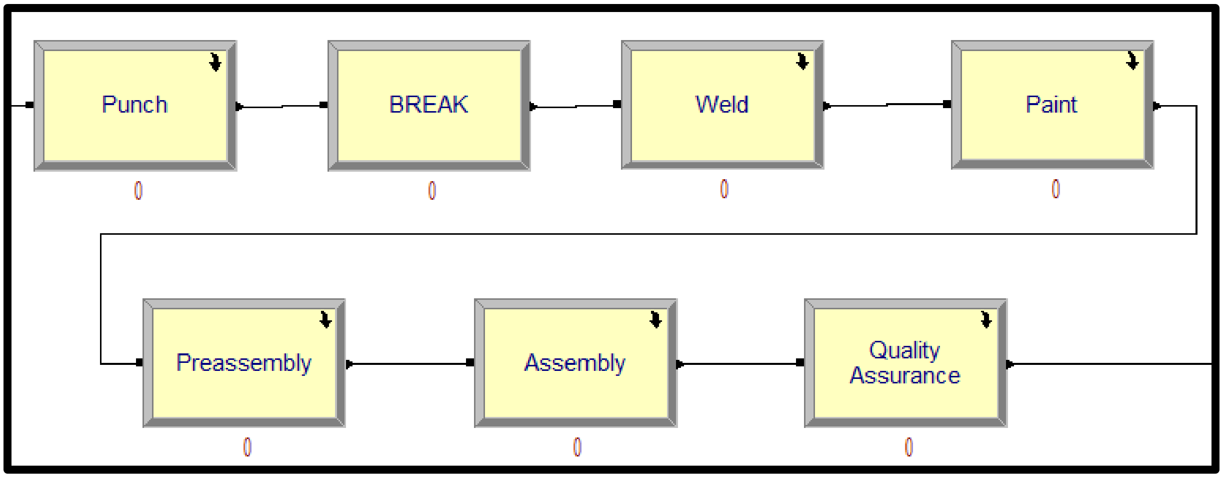


Figure 5: Simulation design of case study process flow from Arena software

In Figure 5, each box represents a process, with the number below each indicating the number of products at that process when the simulation is running. The seven processes contain sub processes which include decision heuristics to guide the material as it would be processed in the actual system. For instance, the assembly lines at the case study company are scheduled by product size and industry type. To ensure material flow emulates the company operation, the simulation contains decisions which step the material through each assembly line until it reaches the one which it would be assigned to. Comparing Figure 5 to Figure 2, one may notice that the pack and ship processes are not included in the simulation. This is because these processes comprise a small portion of the total cycle time, as shown in the value stream map in the Appendix. Additionally, the amount of data that was available and collected on these processes did not yield reliable results.

Products at a given process step at the company are processed on a first-in, first-out (FIFO) basis; this is reflected in the simulation. No products that are given precedence for processing unless indicated verbally by the PM. As mentioned previously, material is batched with like items, not necessarily the exact same model but in the same family. This batching is reflected in the simulation with batches of three units.

In the simulation, one week of production time is considered to be 64 hours, since, the facility nominally operates four days per week and has 16 effective operating hours per day, divided between two overlapping ten-hour shifts. The results from the current state simulation are shown in Table 1.

Table 1: Average cycle time results from current state Arena simulation in hours

Product	Average Cycle Time (hrs.)	Average Cycle Time (days)
1	296.25	18.52
2	259.73	16.23
3	259.16	16.20
4	267.90	16.74
5	255.15	15.95
6	307.18	19.20
7	266.51	16.66
8	280.27	17.52
Average	**274.02**	**17.13**

In Table 1, the cycle time of each product is shown in the second column in hours, which is pulled directly from the Arena simulation. The third column shows the cycle time in days. The cycle times of all the products are on average 17.13 days, or around 2.5 weeks. This is similar to actual cycle times at the company when not considering the packing and shipping processes.

In addition to the quantitative results shown in Table 1, other observations were made from the simulation. The company has the practice of only starting material at the beginning of each day for a process. Therefore, material that arrives throughout the day remains in queue until the following day. Further, material in the welding area begins processing on the first day of the work week (Monday). From the simulation, it was observed that the time in queue was large, although machine utilization results indicated they were not being fully utilized. Thus, there is capacity in the system for higher throughput.

4.3 HDMS Design

To design an HDMS several key steps have been applied in this study, as described in the discussion below.

4.3.1 Express Line Creation

The products that run on the express line are high-running and have comparatively low cycle times to other products. Current and forecasted demand levels, in addition to the insight of the production manager and continuous improvement manager, were used to determine the products. Five products were selected out of around 100 product offerings at the company, or approximately 5% of their total product offerings. While demand fluctuates based upon customer orders, historical data provided insight into approximate monthly demand. The five products and corresponding approximate demand are shown in Table 2.

Table 2: Express line products and estimated monthly demand

Model	Product Description	Monthly Demand
1	Incubator A	11-14 units
2	Incubator B	5-7 units
3	Incubator C	12-14 units
4	Oven A	6-8 units
5	Oven B	4-6 units

Multiple iterations of the express line product list were created and can change again in the future to accommodate fluctuating demand.

For the five selected products, general information was gathered to understand their impact on the company's success and on the manufacturing operations. Information was gathered on the raw materials required (i.e., metal type, gauge and sheet size, and electrical components), the components which compromised each model, and the quantity of each component.

4.3.2 Standard Product Scheduling System

The standard scheduling system uses a set of logic and rules which seek to address the issues currently faced by the facility. For instance, a perception exists that products can only start in certain departments at the beginning of the week. The decision support heuristic developed seeks to eliminate these concerns and address the root issues. Throughout the trial and error process of creating the decision support heuristic, a Gantt chart with each of the products listed was monitored to reveal the effect of logic changes on product cycle times. The heuristic is shown in Figure 6.

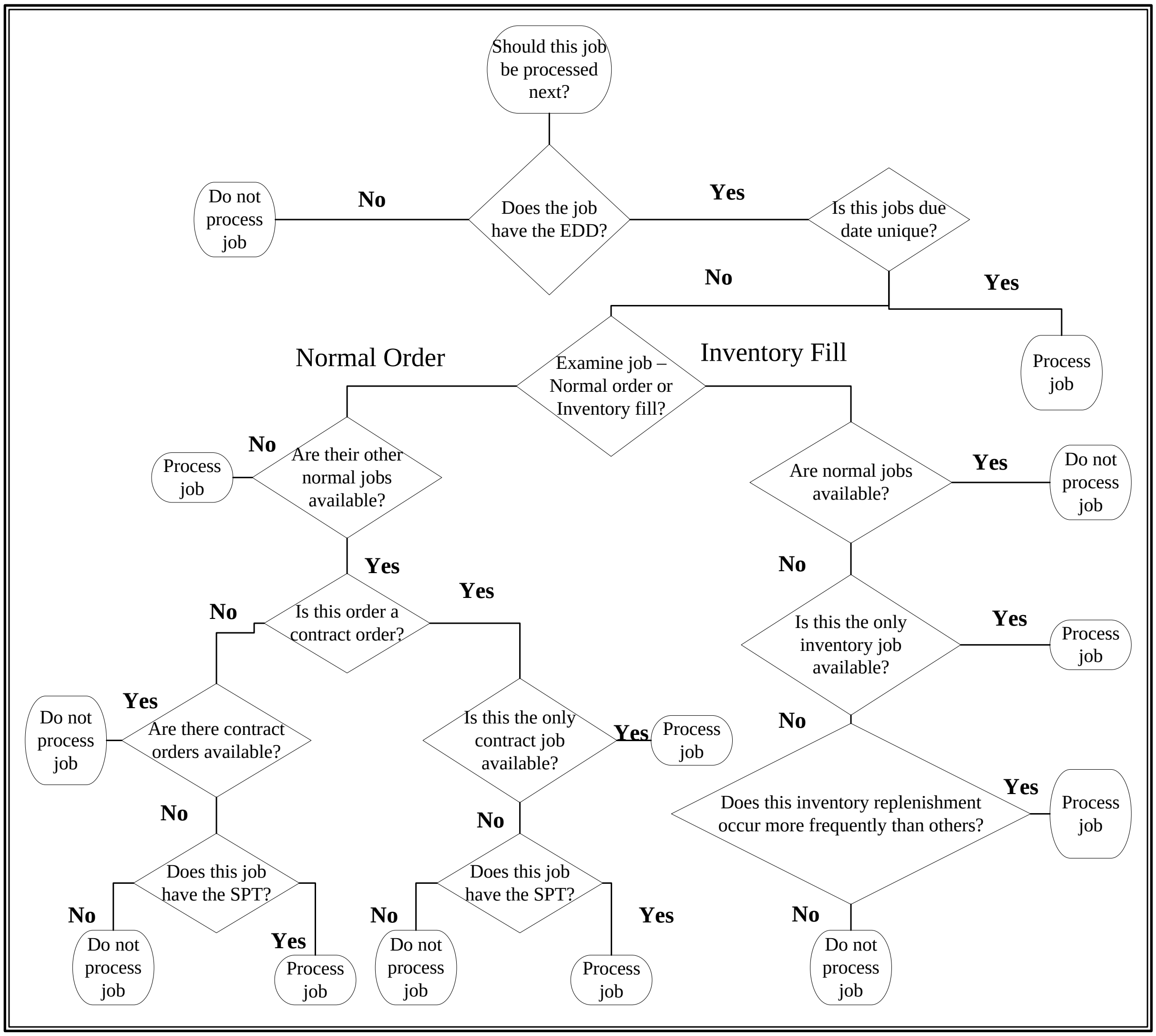


Figure 6: Decision support heuristic for product scheduling at the case study company

The decision support heuristic steps the scheduler through different options. First, the estimated due date (EDD) of the product is examined. If the product has an EDD which is unique (i.e., no other products are due that day), then it is placed on the production schedule. Next, the order is categorized as "normal," one that is requested by a customer; or an inventory fill, a product which will be stored in finished goods inventory, anticipating the customer demand, but that is not guaranteed to be sold. If it is a normal order, it is then categorized as a contract or non-contract order. Contract orders are those for regular customers who have scheduled product order quantities and due dates. The company wants to ensure the needs of the contract customers are met as they comprise a large portion of their business. Finally, products are categorized by processing time. The company has approximate total processing times for each product and these will be ranked to schedule those products which remain. With the use of the multiple criteria for scheduling, the heuristic aims to standardize the way all products are scheduled to increase consistency and reduce product cycle times.

4.4 HDMS Simulation Testing

Once the design of the HDMS was completed, it was necessary to test the design using simulation software. The same software as for the current state simulation, Arena, was used for the future and current state simulations. The HDMS simulation focused on the five high-volume products while also incorporating the standard products into the production flow. The design differences for the future state simulation are described below.

4.4.1 Product Designations and Divisions

Each of the five products was created individually in the simulation with specific processing and machine changeover times. In addition to the five products, three other products were created which represent the standard products divided into low, medium, and high processing times. These processing times were gathered from compiling, analyzing, and averaging sales data for the company from the past six months. The three product categories also simulate the demand level data gathered from the past six months.

4.4.2 Material Processing

In this HDMS simulation, material processing was updated in four ways:

- Product order processing decision making
- Continuous manufacturing
- Concurrent manufacturing
- One-piece material flow

These simulation design changes will be addressed in this section. The product order processing decisions differ from those of the current state. As the HDMS simulation incorporates the standard and express line products, material must be processed accordingly. The products in the express line will take precedence for processing at any given process step. For each process, the queue has two tiers: the first being for the express line products and the second for standard products. Upon arriving at a process, for example at the brake process, the products will be placed at the top of the first tier queue. If a job is currently in process, it will not be interrupted, but once completed, the express line product will be processed. Standard products are selected to begin being processed only when there are no express line products in the queue.

In addition to changes to the order of product processing, the simulation is designed such that material is continuously manufactured. Thus, it is processed at any time of day when personnel are present, should it be at the top of the queue. This eliminates the added cycle time which results from waiting to process products at a new step until the next morning or the beginning of the week.

Next, concurrent manufacturing, which involves parallelizing processes to reduce the total product cycle time, was simulated for the pre-assembly processes. The wiring of control panels, control panel assembly, and door assembly are completed separately from the manufacturing and assembly of the main unit. Thus, while the main unit is at the welding and paint stations, these three processes can begin, reducing the total cycle time for the product.

Finally, the HDMS design simulation processes material as-needed for each product sequentially produced, removing the batching that was present in the current state simulation. The one-piece flow moves the company towards a leaner environment. Removing batching allows for improved flexibility and reduced work-in-process (WIP) inventory.

4.5 HDMS Design Simulation Comparative Results

The results obtained from the simulation of the HDMS design are compared to those obtained from the current state simulation (Table 3). Focus is placed on the changes for the express line products, since reducing the cycle times of these products was a main objective of the research.

Table 3: Comparison of cycle times for express line products from current state simulation to HDMS design simulation

Express Line Product	**Average Current State Cycle Time (days)**	**Average HDMS Design Cycle Times (days)**	**Cycle Time Reduction (%)**
1	18.52	2.80	85%
2	16.23	3.00	82%
3	16.20	3.15	81%
4	16.74	3.45	79%
5	15.95	2.78	83%
Average	**16.73**	**3.04**	**82%**

The comparison of cycle times in Table 3 shows a cycle time reduction of 79-80% for each of the five of the express line products evaluated. The cycle times of the express line products for the HDMS design are on average 3.04 days, or about three-quarters of a work week, for the company, as they operate four days of the week on average. As noted previously, the simulation does not account for the packing and shipping processes, which would be accommodated by the remaining day of the work week.

The results demonstrate the cycle time reductions for the express line products only for the HDMS design. To examine the results more closely, the average cycle times of the individual processes for both express line and standard products were evaluated, as shown in Figure 7.

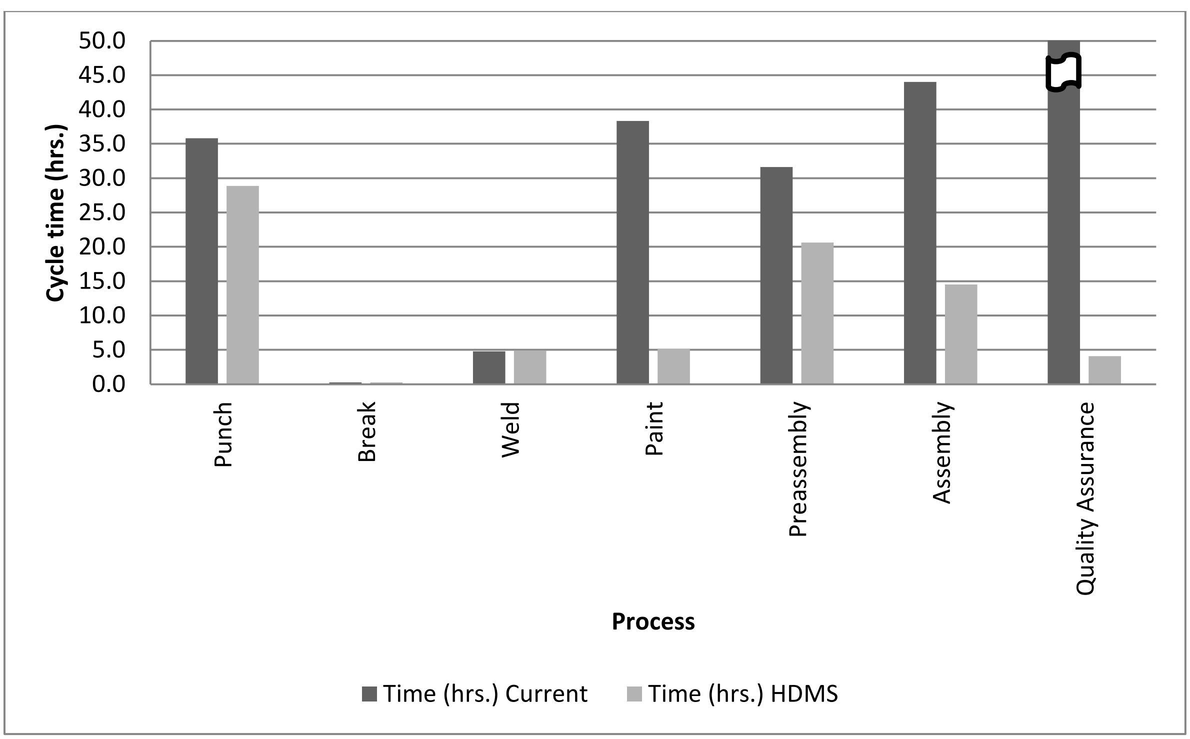


Figure 7: Process cycle times for the current state and HDMS state simulations

Both the express line and standard products were included in the calculation of the average. Values for each process were obtained from the total time, which included the value-added and non-value-added times. It is apparent there is a sizeable reduction in cycle times for each process, except welding. Note, the quality assurance cycle time for the current state simulation was 245.9 hours, much higher than shown in Figure 7, as denoted by the break in the graph. It was not fully included in the graphic to provide clarity at the other processes. The break process has an average cycle time of 0.20 hours. The bulk of the cycle time at the break process is in the set-up time for changing dies, since bending the part takes approximately two to five seconds. Changeover time was not modeled in the simulation. The percent reduction in cycle time when implementing the HDMS design is shown in Table 4 for each process.

Table 4: Reduction in cycle time by process between current state and HDMS simulations

Process	**Reduction in Cycle Time (%)**
Punch	19.40%
Break	0.16%
Weld	-2.20%
Paint	86.58%
Preassembly	34.67%
Assembly	67.04%
Quality Assurance	98.34%

All processes, with the exception of welding, which increased slightly, demonstrated a cycle time reduction from the current state to the HDMS design simulations. The quality assurance, painting, and assembly processes showed the greatest potential for cycle time reduction, 98.34%, 86.58%, and 67.04%, respectively. These reductions would be with an ideal state and it is highly possible that a 98.34% reduction for the quality assurance process, for example, may not be fully attainable. These reductions, however, demonstrate the areas of opportunity and provide guidance to manufacturing personnel about where to focus effort to reduce non-value-added time and support activity time. In reality, there is great opportunity to reduce the cycle time at the welding process due to current processing methods (i.e. only starting new jobs on the first day of the work week). The results from the simulation may not reflect this opportunity for cycle time reduction due to the grouping of welding sub-processes (i.e., spot welding, PEM, and grind) under the welding process heading. Improving upon this portion of the simulation in future iterations is an opportunity to further strengthen the model.

The objective of this research was to create a systemic approach to implement the HDMS at SMEs with an HMLV of products which addresses the long lead times to customers and the issue of varying customer demand levels. The results from the comparison of the current state and HDMS implementation simulations indicate a reduction in cycle times for the express line products. This reduction addresses the long lead times to customers and will reduce this value. Additionally, the two components of the HDMS (express line and standard product scheduling) accommodate the varying customer demand levels. Products which are in high demand and have delivery dates that cannot be met for customers with standard product scheduling can be classified as express line products to reduce throughput time.

4.6 Suggested HDMS Implementation Plan

Now that this HDMS simulation is completed, the next step is to implement the HDMS design at the company. In addition to demonstrating cycle time reductions for products, the simulation highlighted changes which will help the company in other ways. Implementation of concurrent manufacturing, one-piece flow, and continuous manufacturing, for example, will help the company towards reducing cycle times for all products.

This research served as a demonstration to the company for the potential improvements to be gained by implementing the proposed HDMS. If they choose to implement the solution, additional testing and design modifications to the HDMS will be made during the implementation and validation phases. As stated previously, an HDMS can adapt to changing market conditions and is expected to evolve over time. As shown in Figure 1, it is a closed loop system, and results will help to revise future iterations of the HDMS design.

5. DISCUSSION

The design of the HDMS system successfully met the goal of creating a systematic approach to address long lead times to customers, while accommodating varying levels of customer demand for different products. The developed approach must first be reviewed and evaluated at the case study company, and, next, refined as a general model for SMEs with an HMLV of products. These ideas are presented below, as well as a discussion regarding opportunities for future research related to model development.

5.1 Case Study Results Discussion

Based upon the results of the current state and HDMS design state simulations, implementation of the model at the case study company would be desirable. Implementation would result in reduced cycle times (and, subsequently, customer lead times) for the express line products. This reduction in lead time would allow the company to guarantee earlier customer delivery dates, improve customer relations, and possibly increase customer demand levels. Furthermore, by reducing product cycle times, the company would be able to handle increased throughput, should the demand arise.

5.2 Conceptual Model of HDMS for SMEs with an HMLV of Products

SMEs face special challenges when implementing lean manufacturing practices as there is often a scarcity of resources. SMEs with an HMLV of products have an even more difficult time implementing lean principles due to the wide variety of products they manufacture. Additionally, SMEs tend to feel the effects of ever-changing market demand more closely than a large corporation. The hybrid dynamic manufacturing system approach developed provides a solution for HMLV SMEs to be flexible to these conditions. As the design has not been implemented, the results have not been fully realized. Nonetheless, the simulations demonstrate the potential areas for improvement and provide insight into the likely next steps for the company. Further, the simulations support continued research into the development of robust HDMS design methods to facilitate broader implementation of this unique approach in SMEs, or even larger companies engaged in HMLV manufacturing.

5.3 Future Research

The design of the systemic approach to HDMS design demonstrated many opportunities for future research. In the short term, future research could focus on scheduling interactions between express line products and non-express line (standard) products. For instance, alternative methods to create the weekly production schedule or different methods of material processing could be investigated. Another opportunity for future research with this HDMS transition system is how the manufacturer can improve their manufacturing performance from the gained implications. The goal is to reduce unnecessary product varieties by standardizing products and manufacturing components. While the above two opportunities address short-term needs, in the longer-term, this research can lend itself to creating mathematical models for scheduling optimization for SMEs with an HMLV of products. While the current method of scheduling is robust and adapts to changes in customer demand, this method can be verified mathematically to ensure that it is the optimal solution. If it is not, new scheduling systems can be created based upon better solutions. This indicates the further-reaching implications of the HDMS approach within SME organizations, as it helps to improve efficiencies and reveal remaining deficiencies in the system that might not be readily addressed by cycle time reduction.

6. References

[1] B. Obama, Interviewee, *State of the Union Address.* [Interview]. 28 January 2014.

[2] G. Conner, Lean Manufacturing for the Small Shop, Boca Raton: CRC Press; Society of Manufacturing Engineers, 2001.

[3] United States International Trade Commission, "Small and Medium-Sized Enterprises: Overview of Participation in U.S. Exports," United States International Trade Commission, Washington D.C. , 2010.

[4] "Jabil," 2014. [Online]. Available: http://www.jabil.com/highmixlowvolume.html. [Accessed 14 March 2014].

[5] J. M. Araya, "Value Stream Mapping Adapted to High-Mix Low-Volume Manufacturing Environments," *KTH Industrial Engineering and Management*, 2011.

[6] S. Khaewsukkho, "New Approaches for Design of High-Mix Low-Volume Facilities," The Ohio State University, 2008.

[7] J. M. Rheauma, "High-Mix, Low-Volume Lean Manufacturing Implementation and Lot Size Optimization at an Aerospace OEM," Massachusetts Institute of Technology, 2003.

[8] Tooling U, "Quality Training: Process Flow Charting 240," Society of Manufacturing Engineers, 2013. [Online]. Available: http://www.toolingu.com/definition-900240-13470-non-value-added.html. [Accessed 14 March 2014].

[9] "Shel Lab," [Online]. Available: http://www.shellab.com/store/. [Accessed 22 October 2013].

[10] The IRIS Center, University Research Corporation International, "The Role of Micro, Small and Medium Enterprises in Economic Growth: A Cross-Country Regression Analysis," September 2008. [Online]. Available: http://www.bvcooperacion.pe/biblioteca/bitstream/123456789/5824/1/BVCI0005365.pdf. [Accessed 18 January 2014].

[11] J. Orlicky, Material Requirements Planning, New York: McGraw Hill, 1975.

[12] E. M. Goldratt, The Goal, Great Barrington: North River Press, 2004.

[13] Vorne Industries, Inc., "Theory of constraints," LeanProduction.com, 2010. [Online]. Available: http://www.leanproduction.com/theory-of-constraints.html. [Accessed 11 November 2013].

[14] US Environmental Protection Agency, "Lean thinking and methods: kanban," 10 November 2011. [Online]. Available: http://www.epa.gov/lean/environment/methods/kanban.htm.

[15] J.-B. Waldner, Principles of Computer-Integrated Manufacturing, London: John Wiley, 1992.

[16] Rockwell Automation, Inc. , "Arena Simulation Software," 2014. [Online]. Available: http://www.arenasimulation.com/Arena_Home.aspx. [Accessed 19 January 2014].

[17] E. Commission, "The New SME Definition," 20 May 2003. [Online]. Available: http://ec.europa.eu/enterprise/policies/sme/files/sme_definition/sme_user_guide_en.pdf. [Accessed 27 January 2014].

[18] O. Girod, "A Hybrid Dynamic Transition Phase for High Mix Low Volume

Manufacturers," in *Industrial Systems and Engineering Reserach Conference*, Montreal, 2014.

[19] Sheldon Manufacturing, Inc., "Shel Lab," Sheldon Manufacturing, Inc., 2013. [Online]. Available: http://www.shellab.com/store/. [Accessed 22 October 2013].

APPENDIX: CASE STUDY COMPANY VALUE STREAM MAP (VSM)

The VSM below provides detailed information for the current state of the case study company's production system. The data and process layout help to establish a baseline and visual representation of product and information flow from customer order receipt through final shipment.