REAL TIME CONTROL OF MANUFACTURING UTILIZING A MANUFACTURING EXECUTION SYSTEM (MES)

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science in Engineering

Department of Electrical and Computer Engineering

Fort Wayne, Indiana

May 2020

THE PURDUE UNIVERSITY GRADUATE SCHOOL

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ACKNOWLEDGMENTS

The effort required to complete a thesis was more than I ever imagined. From researching to placing everything from my head to a piece of paper seemed to be difficult at times. Therefore, there are individuals that helped me along this journey that need acknowledgment.

First off, I would like to thank my company as they supported be in my endeavors and gave me the means to completing this thesis. My company provided a so-called playground for me to trial out my thesis and to prove aspects of the thesis is a real-life scenario. Of course, the scope of my thesis wouldn't have been selected if there wasn't already a need within my company. In short, thank you goes to my company for their support along the way.

Secondly, I would like to thank the band of guys that supported me along the way: Andy, Ken, Michael, Greg, Robert and Paul. These individuals supported in going through most of this process with me. From the late-night trips to campus, to the idea sharing conversations we had, we all were able to go through the process together. The first class ever left us talking for the 1.5 hour drive home as maybe we were way over our heads. However, we buckled down and were able to understand the concepts and successfully apply them. This support and walk through has been valuable.

Thirdly, I would like to thank my wife and all her support. I know this has been a long process and at many points hard but thank you for staying by my side and providing me encouragement. Your support and understanding is appreciated further than what you know, thank you.

Fourth, I would like to thank Dr. David S. Cochran for the support he has giving me throughout my class work and my thesis. Your insight and feedback are greatly appreciated and allowed me to continue pushing through ensuring that I was on the correct path. From the continually meeting to reading the updates of my thesis, thank you for your continued support.

Finally, I would like to thank God for the faith he has giving me that provided be comfort throughout this thesis process. I know that God provided me the strength to continue along my way throughout the entire process.

Further acknowledgement goes out to those individuals that I may have missed that provided support for me. If I missed your name my apologies and thankfulness go out to you. This thesis took hours upon hours of work and provided headaches as to what information to place into

each chapter. However, through the support of many, I was able to slowly chip away at my thesis and complete it in completion of my degree. I am thankful for all support that allowed me to get this far. Thank you!

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ABSTRACT

Manufacturing facilities need control for sustainability and longevity. If no control is provided for the manufacturing facility, then chaos can be unleashed causing much alarm. Therefore, it is essential to understand how control can be utilized to support the manufacturing facility and the corresponding manufacturing processes. This thesis will walk through a tool to help provide control and that tool is a Manufacturing Execution System (MES). This thesis will start with research to define MES and its implications, then will work into the development of MES from the ground up. The design process will be systematic and utilize the Collective System Design (CSD) approach with the aiding tool of the axiomatic decomposition map. Then examples will be given for the implementation and execution of the decomposition map as it relates to inventory and traceability. Final work will show the 7 FRs of manufacturing and how they are applicable to MES with given examples. Throughout the entire design and implementation, the initial hypothesis will be evaluated to determine if MES can provide the control required for a robust manufacturing facility.

1. PROBLEM STATEMENT AND HYPOTHESIS

1.1 Introduction

Companies exist to make money so that they can pay their employees and contribute to the local community through either the intentional contribution to their local community or through the spending of their employees in that local community. It is understood that there are additional benefits in having a long lasting company in a community and are outside the scope of this thesis. This thesis will look for those hidden costs that are associated with manufacturing processes housed inside a manufacturing facility. By exposing these hidden costs, the manufacturing facilities' management team can continually improve until those hidden costs are brought down to an acceptable level if not eliminated altogether.

This thesis will look at designing a system that will provide management with the appropriate data that is timely managed to expose the hidden costs of that manufacturing facility. Management will then have the proper information to make decisions based off actual situations and therefore resulting in the reduction of overall costs. The system will be designed utilizing axiomatic design principles along with collective system design and will show the process of: determining what items to look at, the collection of data and utilization of the data collected.

This system will be designed for a manufacturing facility in Findlay, Ohio that provides braking system parts to tier 1 automotive OEMs with case studies being performed on a recently built manufacturing facility along with a new product design and manufacturing process. The case study will provide a comparison of a previously establish manufacturing facility with mature management information systems and active products to the new manufacturing facility, product and process. The contrast from the existing manufacturing facility to the new will be gross in nature and provide insight into controlling costs.

1.2 Problem Statement

The design and implementation of a management information system must be approached and analyzed in a systematic manner. An effective management information system will exist to provide benefits that are both tangible and intangible to a manufacturing facility. Turning a profit for a manufacturing facility allows for longevity and a source of steady income for its employees.

By incurring hidden costs by the manufacturing facility, the longevity could affect the company's future depending on how severe the costs are. These hidden costs need to be exposed and visible for management and the appropriate individuals to provide effective solutions for the reduction of those hidden costs. If these hidden costs continue to be covered up, the result could be detrimental leaving individuals without employment and a source of income.

This chapter will serve to review the research question to the depths of what a research question is in additional to its application. When performing any type of research, the individual performing the research needs to have a question in mind that will be the guide. This research question will provide guidance in the terms of knowing where to start and additionally, what other questions may be asked in support. However, the research question is just the place to start and leads to the research hypothesis which is utilized throughout the research process. The research question guides the researcher while the research hypothesis is what the researcher is expecting to find during the research process.

1.3 Research Question

In performing any type of research, it is essential to develop a research question that will help guide the research. The first step of developing a research question is to identify the subject of interest and provide preliminary research. Then additional research should be conducted off what was found during the initial research and then continually to be iterative until the subject is properly defined to a narrow scope [Ratan & Anand, 2019]. Once the subject has been narrowed to a refined subject topic, additional research should be considered until every aspect of the subject has been explored and the researcher is comfortable with their level of understanding.
For this thesis, my research question was evaluated and was narrowed down to the following:

"Are there financial benefits to investing company resources to reveal hidden costs with a management execution system?"

This research question will tackle the financials for deploying and maintaining a management information system. When attempting to deploy the manufacturing execution system, capital investment needs to be inclusive and will be aided through additional research. After the deployment of the management information system, the cost of maintaining the system and the

additional resources such as manpower needs to be considered. Once the costs are evaluated for deploying and maintaining, the cost effect of revealing hidden costs and providing a continual method of improving will need to be cross examined to analyze the financial benefit of the management information system.

1.4 Research Hypothesis

For the pre-described problem statement and research question, a research has been generated to tackle the concept of hidden costs within a manufacturing facility. The research hypothesis utilized in this thesis will utilize the hypothesis terminology used within statistics. The research hypothesis will provide both a null hypothesis and an alternative hypothesis which can be properly testing and evaluated. A null hypothesis is known as the commonly accepted fact in which researchers work to nullify, or discredit [Null Hypothesis Definition and Examples] and is denoted by H_0. On contrary to the null hypothesis, the alternative hypothesis seeks an outcome that it opposite of the null hypothesis and is denoted by H_a.

In response the research hypothesis to this thesis, a null hypothesis and alternative hypothesis have been defined as the following:

H_0: The time allocated and capital invested in implementing and maintaining MES does not expose hidden cost and enable continual improvement.

H_a: The time allocated and capital invested in implementing and maintaining MES does expose hidden cost and enable continual improvement.

With the null and alternative hypothesis, the first step is to start conducting research as it relates to MES. The research will be conducted to determine benefits and to understand if its implementation and maintenance is truly beneficial. If research uncovers that MES is not beneficial, then there is no need to further design and implement MES. However, research could determine MES beneficial and provide insight to the effective working parts which could support the design and implementation processes.

1.5 Research and Thesis Outline

This thesis will go into the design and implementation of a MES to provide the tools necessary to provide management with the information to make changes for the best of the company. The information that will be provided from MES will be real-time and allow for immediate reaction and further enhancing the control of the manufacturing facility.

This thesis will serve as a tool to support the design, implementation and validation of a manufacturing execution system and support in the documentation of the details of the product system. Individuals down the road will have ample information to understand how MES works with respect to the target manufacturing execution system. Other individuals outside of the target manufacturing facility will also prove to gain insight from this thesis. Of course, not all items within this thesis will work for all manufacturing facilities but will provide a base line for how MES can be utilized for a better manufacturing outcome.

Chapter 2 will present literature material as it relates to MES. The literature survey will present an overview of what MES is and what the benefits are for implementing and maintaining MES. Chapter 3 will then touch on Collective System Design (CSD) and the process that is needed for completion. CSD will start by understanding the stakeholders, then setting the proper tone for the system and then into the design methods utilizing axiomatic design. Chapter 3 will also explore the method of implementing and maintaining. Chapter 4 will then move into some of the motivations for MES as it relates to the need of control. Control will be explained and then related to inventory and traceability. At this point, the need for control will be quantified and actual costs will be presented for both inventory and traceability. With this need for control, chapter 6 ushers in the development of the decomposition map where design decisions are made for the system in design. Chapter 6 will start off with establishing design decisions and then will move into creating a top-level decomposition map that will then further decompose to both the inventory and traceability aspects of MES. Chapter 7 will take the decomposition map as designed in chapter 6 and provide the method of implementation. Chapter 8 will explore the control that MES will provide and correlate this control to the 7 FRs while chapter 9 will summarize this thesis and provide insight into the lessons learned and what items can be improved upon when additional features are added to the pre-established MES.

2. LITERATURE SURVEY

2.1 Introduction

Manufacturing Execution Systems (MES) are becoming more and more common throughout industries, especially the automotive industry. However, MES can bring about many challenges that can affect not just a company's profitability and efficiency, but also the key stakeholders of the Manufacturing Execution System. Other core systems of a company can become fully reliant on MES that any glitch in the system, the company could start into a spin and take a while to recover. Therefore, it is essential to provide a systematic approach to understanding what MES is and how it can be used to better a company's profit from the bottom line to sales while fully understanding the key challenges in implementing and maintaining MES. This chapter will walk through what MES is, how it is currently being used, and the benefits that can come from its utilization.

2.2 Literature Survey Approach

The approach taken to understand the current state of MES was performed with an open mind and was derived from both, available and relevant published material. In having a fully comprehensive understanding of how MES is being utilized today, MES can be tailored to meet any company's needs for improving the bottom line. Certainly, MES at the core will be common among various companies across various industries, but each company will have their specific and unique requirements that will be additional to what will be found here. It was essential then to take published material from different industries to gain a fully comprehensive understanding.

2.3 What is a Manufacturing Execution System?

In looking at a MES, it is very important to gain an understanding of what a MES does at a system level, in addition to where it fits into a company. In looking at MES at a stand-alone system level, it could provide valuable information that could help drive decision for a company but could drive a company in a non-value-added direction. However, just looking at MES from a company level, MES key aspects could very well be overlooked. Therefore, the following will work through

what MES does and its connection with other systems in a company along with ensuring MES is beneficial.

Systems such as Enterprise Resource Planning (ERP) and the Control Layer which directly governs a manufacturing system are common to many companies where MES is something that is continuing to gain acceptance. MES, or Manufacturing Execution System is as it says, supports the execution of a manufacturing process. A basic understanding of MES is, it "stands in between the business-related information and the workshop level of production." [Farzan, Yachubipoor, Hekoui, 2017, 2017] Even though Farzin, Yachubipoor and Hekoui provide a simplistic definition of MES, it does allow for an understanding that MES provides a link between the business-related information and production.

Further research into MES provides additional insight to what MES is and its connection within a company. According to Ivey, "MES systems are computer systems that relay plant floor data from the operator and process control system to the company's enterprise business systems" [Ivey, 1991] while Zhen-kui states that "MES is one of manufacturing systems that are used to bridge the data between the gap of the bottom layer and the enterprise system layer [Zhen-kui, 2013] In both definitions of MES, reliance is on creating a link from the production layer to the ERP layer, where a computer system is deployed. The data that is transferred from the production layer to the ERP layer is a little vague and does not include the data which would be transferred. Zhou expounds of this by providing some examples of data transfer in "MES lies between management layer and control later, obtains orders and basic data from ERP, gives optimization instruction to PCS and real-time monitors production process." [Zhou, 2013] Zhou's explanation provides more insight into MES by giving the understanding that it can provide a real-time monitor of a production process at the production layer.

Figure 2.1 explicitly shows the link of MES from the control layer to the management layer. The control layer includes PCS but could also provide connections to PLCs, HMIs, and various other instruments such as sensors while the management layer is the Enterprise Resource Planning (ERP) layer where all the key metrics for financials occur in addition to order management. For connecting the control layer to the management layer, the figure provides various examples of items that would be inclusive to MES. The elements in the MES layer are comprised of 3 main items, the MES server, MES database and a manufacturing process. It is crucial to understand that MES needs to provide a single connection to the Management Layer and multiple connections the

control layer. Multiple connections at the control layer would include all manufacturing processes that would be affected.

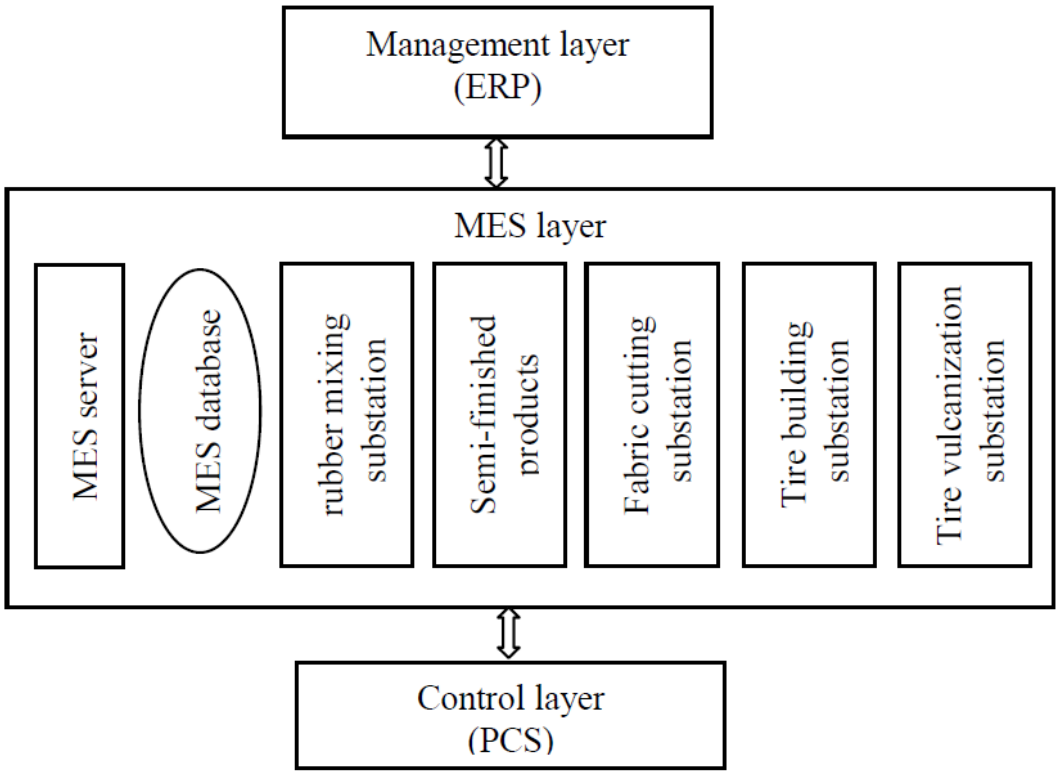


Figure 2.1 MES linkage between the control layer and management layer (Zhou, 2013)

When looking at a link that is created and maintained by middleware software, the interaction is essential to understand. Shen-koi provides a diagram for software middleware acting as an active link in Figure 2.2. The diagram shows that the middleware is broken into parts named as such: model, control and view. The model portion is the building block for where transactions occur between the middleware software and control layer and are registered in the database. The model portion is then connected to the control layer which would allow the model portion of the software to execute based upon a watch dog situation. Then the top layer would be the view portion which shows the software transaction through HTML for which a user can see what is occurring. With bi-directional connections being created from the database to web browser and ERP system, the user can see both real-time and historical transactions.

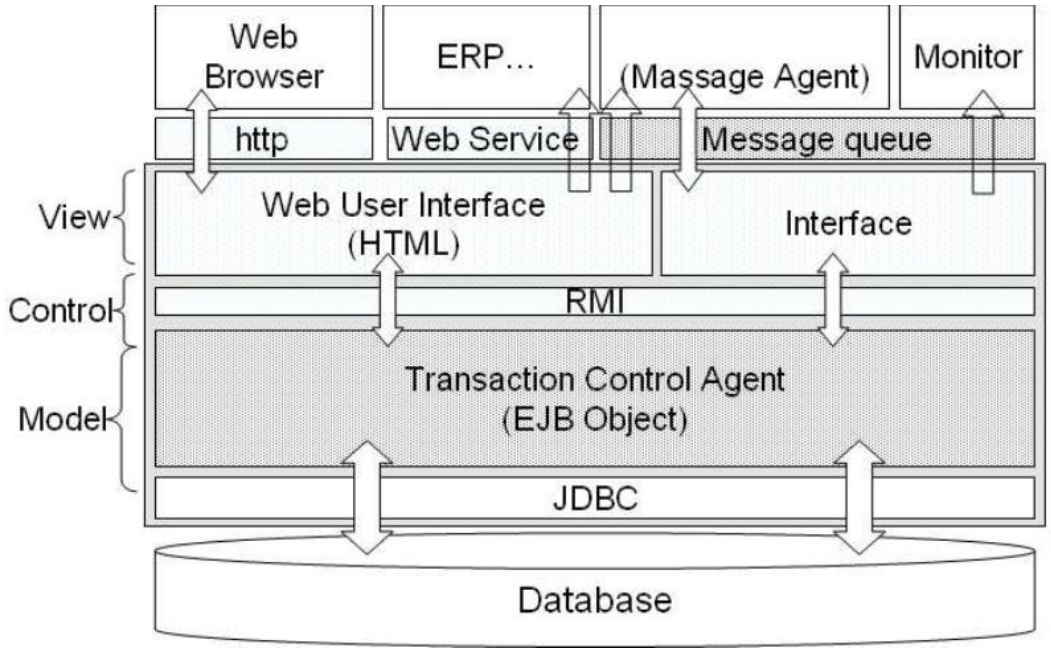


Figure 2.2 Middleware Software Connectivity

2.4 Benefits of MES

While connecting the ERP system to the control layer can prove to be beneficial at a gross level, it is also important to look at all benefits for MES. If a company does not feel that the benefits of implementing MES outweigh the cost of capital to implement and maintain, then that company may feel no need for MES. Therefore, it is of the upmost importance that the benefits of MES are clearly defined and understood. With this importance as priority, additional research was conducted to provide the benefits of MES entirety and not specific to a single company or industry.

According to Farzin, Yachubipoor and Nekoui, "access to immediate and exact data at the factory level in order that they prove helpful in making decisions at the managemental level." [Farzin et. al, 2017] The main concept would be the immediate and exact data to provide real-time decisions for how to progress with the manufacturing process(es). However, this real-time data cannot be achieved through the means of a manual process. Farzin, Yachubipoor and Nekoui go on to say that "MES can link with automation equipment to record relevant information automatically and control the quality of work in process (WIP), statistics analysis, production scheduling and the maintenance of equipment and instructions, etc." [Farzin et. al, 2017] Without a link to the automation equipment, real-time data would be out of the question. Furthermore, the real-time decisions were expounded upon to state the control of work in progress, provide the

ability for statistical analysis and even better production scheduling which would have otherwise been unachievable without MES's interaction.

Additional research was also performed and found various other benefits for the implementation and utilization of MES. Ivey stated that "benefits include reduced paperwork, better control of inventory levels, allowing for better overall production planning, increased employee effectiveness, better quality management, and reduces manufacturing costs" [Ivey, 1991] These benefits as defined by Ivey elude to providing better control which is applicable to inventory and production planning which can further derive better quality of products and the reduction of manufacturing costs. Of course, the benefits of MES can be further expounded upon. Zhou went through the process of implementing MES and came to conclusion of MES benefits to be the following [Zhou, 2013]:

- Order execution speed was increased by more than 10%
- Speed of obtaining statistical data was improved more than 10 times
- Scheduling efficiency was improved higher than 20%
- Equipment failure rate reduced significantly
- Complete storage of data to assist in data analysis and product traceability

Additional benefits of MES include the following [Cerra, 2015]:

- Capture costs more accurately
- Reduce waste, scarp and overages,
- Decrease downtime
- Reduce Costs and Inventory

In conclusion, there are many benefits for the implementation of a Manufacturing Execution System. Especially when looking at the return on investment, companies can certainly return their investment and much more with a properly vetted and implemented MES. The ability to have real-time data that is accurate, companies can gain a better understanding of their current condition and plan appropriately to steer their company in the direction that they are planning. It is typical to see companies that do not have MES to perform monthly reviews of processes and plant performances. If something were to be negative in the prior month, of course correction can be made. However, correction occurring a month too late repeatedly can prove devastating. Therefore, it is essential for companies to increase their bottom line to turn a high profit margin for better successful and longevity.

2.5 Summary

The purpose of this chapter was to review material on manufacturing execution systems and the continuing evolution within various industries for which research will continue to be required. The explanation of MES proves simplistic in nature with its main responsibility of connecting the control layer to the management layer. As with anything else and especially the rapid advancement of technology, IT systems including MES will further expand and provide better results and various obstacles. Current and upcoming goals are for machine learning and artificial intelligence. As these are things that will continue to shape the industrial climate, big data is needed. Therefore, MES is becoming more and desired to provide real-time data that is accurate which can be further analyzed and used for items such as machine learning and artificial intelligence. Therefore, it is essential to understand where MES currently stands and be open to possibilities that will show themselves in the future.

2.6 Literature Survey Synthesis

From the research conducted on manufacturing execution systems, I found that MES provides various amounts of information that would prove to be beneficial to any company whether actively engaged in manufacturing or not. MES provides the ability to capture massive amounts of data that can be further compiled in easy to read reports that will help to drive operations within any company. For manufacturing line specific information, benefits of reducing downtime, reducing inventory concerns, gaining better visibility of traceability and even capturing costs more accurately; help to facilitate action plans the will help combat issues. The most valuable thing for consideration with MES is the ability to have real-time information. Real-time information allows for decisions to be dynamic and changes to be implemented many times over before a massive amount of resources are allocated. In conclusion, MES allows for real-time information to shape how a company does business and to react to concerns before concerns get out of hand. Without MES, companies are only looking backwards at some frequency and makes it very difficult to be dynamic to ever changing environmental circumstances.

3. COLLECTIVE SYSTEM DESIGN

3.1 Introduction

The purpose of collective system design is to fully understand the requirements of stakeholders respective to the design and to provide a method of systematically deriving requirements to provide the best solution for each item. As for the stakeholder requirements, the scope of the design application is also to be considered so that all requirements are fully understood and there is little to no requirements creep after the kick off the design. This process of defining the best solutions for each requirement is essential as it can take the most complex system and create bit size chunks that allow for an effective implementation and further maintenance of the specified design. The lack of the smaller design chunks required through the system would create a severely complex system that would inevitably fail. Furthermore, the simplistic of designs can allow for better engagement of stakeholders in the design implementation process as each stakeholder can participate in their respective role.

With respect to the designer, there are additional benefits with one being a full understanding of what requirements are desired of the system and the scope to which the design is to function. “The ultimate goal of axiomatic design is to establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools.” [Suh, 1990]

With the development and design of any system, there are certainly many approaches that can be taken. The varying approaches will provide varying degrees of effectiveness depending on the initial to final design concepts. The most effectiveness is to provide an initial design that is as close to the result as possible. The additional amount of tweaking to the initial design will require additional rework and extend the design and validation timeline. Therefore, a systematic design approach will be utilized particularly through Collective System Design which utilizes concepts of Axiomatic Design.

The framework for Collective System Design utilizes the following five elements [Cochran & Swartz, 2015]:

1) The Flame Model
2) The CSD Language
3) The CSD Design Map
4) Standard Work
5) The Plan-Do-Check-Act (PDCA) Learning Loop

The flame model works to "to express design relationships that the leadership team establishes" [Cochran & Swartz, 2015] while the CSD Language works to "align design objectives and proposed solutions and performance metrics to ensure that desired outcomes are being achieved" [Cochran & Swartz, 2015]. The CSD Design Map assigns Physical Solutions to Functional Requirements to provide a simple solution that can easily be implemented and managed. Standard Work is "to define the work process for normal conditions" [Cochran & Swartz, 2015] while the PDCA learning loop continues to make improvements the system over time.

3.2 Collective System Design Process

The process for design with use of Collective System Design, includes 12 steps. The 12 steps start when a conscious choice is made and is not completed until the designed item is no longer valid. This process therefore starts before design even starts and flows through the design process, design implementation and then through a continual process of improving the design. This process works for the design of products, services and even systems.

The steps for Collective System Design (CSD) can be seen in Figure 3.1. The first two steps include on boarding the leadership team and gaining resources. Step 3 requires establishing the appropriate tone and values which is done through the flame model. Steps 4, 5, and 6 is where the customer needs are identified, Functional Requirements and Physical Solutions are determined, and the Decomposition Map is created according to axiomatic design principles. Step 8 then talks about the organization structure to ensure there are enough resources to accommodate the new design. Moving out of step 8, step 9 established standard work through utilization of the PDCA cycle. Step 10, 11 and 12 then isolate the gaps and associates cost with not achieving Functional

Requirements and then sets forth a plan for closing gaps and providing feedback for a more robust design.

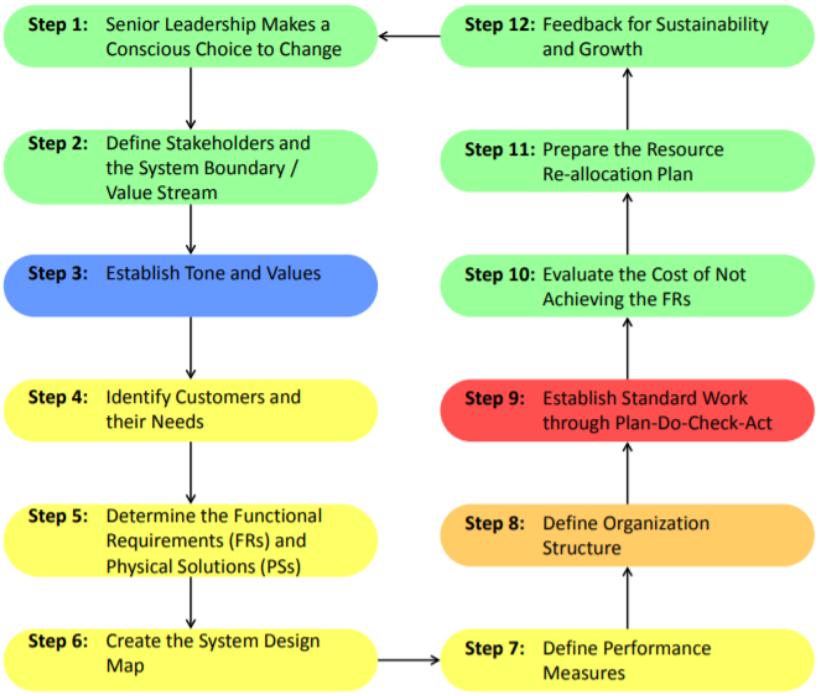


Figure 3.1 Steps of CSD [Cochran, 2015]

In conclusion, the 12 steps of CSD provide a method of ensuing all aspects from the conception of an idea to the maintenance of a system is robust. The 12 steps facilitate the design by walking through each step of the process. Each step additionally has supporting material that provides support. The additional content will be explained for each step in the following sub chapters.

3.3 Definition of Stakeholders and System Boundary

A main item to be considered when looking to make a change and therefore looking into designing a new system, it is crucial to look at the stakeholders of the system. A stakeholder is someone who has either an interest or concern with the specific design. The stakeholders will be the individuals who will help to gain perspective of the design in the beginning and will help to ensure that is continues along a path of a success design that is robust in the end. The stakeholders

will help to facilitate the design process by providing the scope to which the design will be implemented, also known as the system boundaries.

In having a list of customer requirements that encompasses all customers of the system being designed, it is also important to cross check those customer requirements to ensure that they are all applicable to the system. A method of ensuring all customer requirements are applicable to the system is to perform system boundary analysis. Figure 3.2 shows an example of system with the grey portion laying inside the system boundary while the white space around the system boundary lines are items outside of the system boundaries. These items that lay outside of the system boundary are items that will not be controlled whether purposeful or they are not able to be controlled.

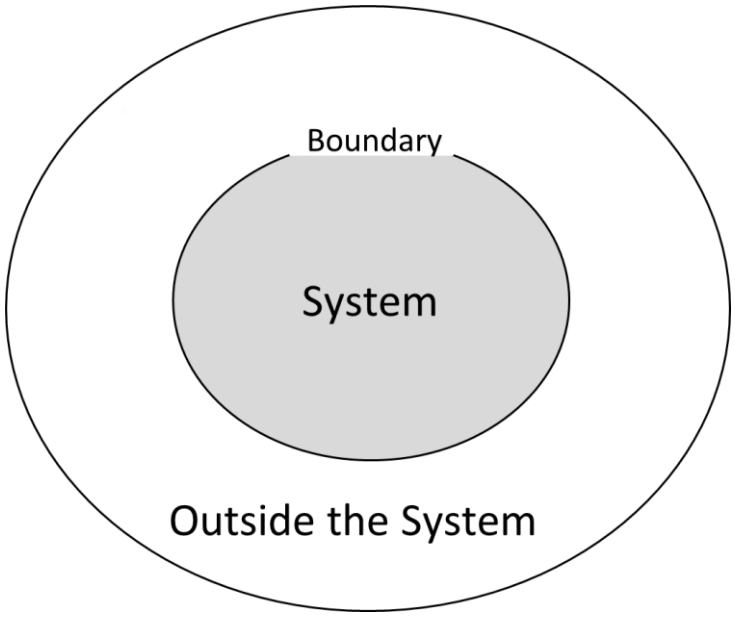


Figure 3.2 System Boundary

If the system boundaries are not known, the design will have one of two effects, either the design does not capture enough scope, or the system is so complicated requiring for the capturing of too much scope. However, there will be a slightly different effect during the design process. Without having the system boundaries defined, the system could grow dramatically through the design process through the receiving of additional requirements. Additional requirements during

the design process are considered requirements creep and only add complexity and additional cost. In conclusion, it can be said that a design needs well established boundaries so that the system ends robust upon completion.

3.4 Flame Model

A complex system is that of any system that has inputs from human beings due to decision making and actions that are unpredictable and inconsistent. To simplify a complex system, one needs to first recognize that the tone and mindset of the people acting within a system creates the system itself [Cochran & Swartz, 2015]. Setting a positive tone or an attitude within an organization is crucial to the success of the CSD. Figure 3.3 below illustrates an understanding that a system design requires understanding the actions, the business structures, the thinking about that system and the tone within that system [Cochran & Swartz, 2015]. The flame model of system design is a logical systematic approach from the bottom in the order of: tone, logical design, physical system and then work.

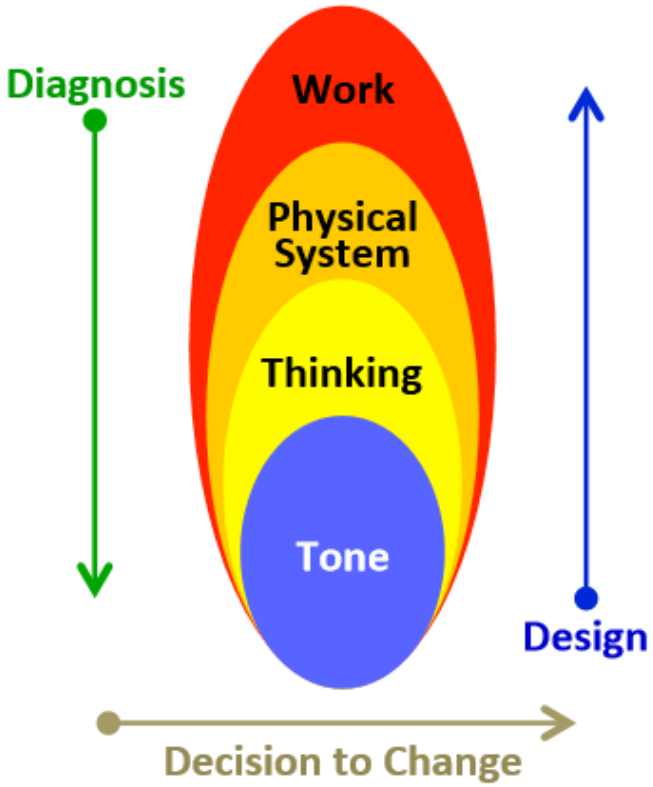


Figure 3.3 Flame Model [Cochran & Swartz, 2015]

When designing a new system, the design should start from the bottom and move upwards. The tone is the first step and requires the system designer to start designing with respect to the users of the system. The users include those actively using the system and those who seldomly use the system. Never the less, the system needs to have the correct tone so that users are excited and not pushed away through discouragement. After the tone, thinking needs to occur for how the system with be designed as it needs to be logical. The thinking portion is where the CSD Language is applied to facilitate the conversion of a complex system into a logical system that provides predictability. Once the thinking portion has been completed, the physical system is the next step where the implementation of the CSD Language and primarily the decomposition map is implemented. In attempts to developing a predictable system, the use of standard work is created and facilitates an understanding of normal versus abnormal. From the utilization of standard work, the work phase is entered and provides the necessary actions for the system to function. The work phase is post implementation of the system where gaps can be isolated and the PDCA cycle utilized to continuously improve.

In summary, the flame model is very useful for the design and implementation of any system. Within the various phases of the flame model, aspects of: CSD, Standard Work and the PDCA cycle are utilized. Additional information will be provided for the elements utilized with the flame model.

3.5 Design Domains

Collective System Design utilizes four domains to systematically go through the process of what is desired to achieve to the point of the satisfaction of that need. These design domains encompass the CSD Language portion of Collective Systems Design to help facilitate information transfer through the system design process. Design domains for CSD are utilized in steps where the customer needs are identified along with the Functional Requirements and Physical Solutions are determined. The various domains of Axiomatic Design were established to create distinct definition the various design activities. These domains include the customer domain, the functional domain, the physical domain and the process domain. It is also imperative to know that the domains require sequencing. As Figure 3.4 shows, the customer domain is determined with the customer requirement and is then mapped to the functional domain which includes the Functional Requirements. Then the functional domain is mapped to the physical domain where Physical

Solutions are explored while finally the physical domain is mapped to the process domain. For the mapping of each domain, the mapping type will vary. The mapping from the customer domain to the Functional Requirement domain will hold a one to many relationships where most customer requirements will require multiple levels of Functional Requirements. This one to many relationships is contrary to the mapping of the functional domain to the physical domain. It should be noted that it is important to ensure that each Functional Requirement is expounded in a hierarchy method where a single Physical Solution from the physical domain accomplishes a single Functional Requirement.

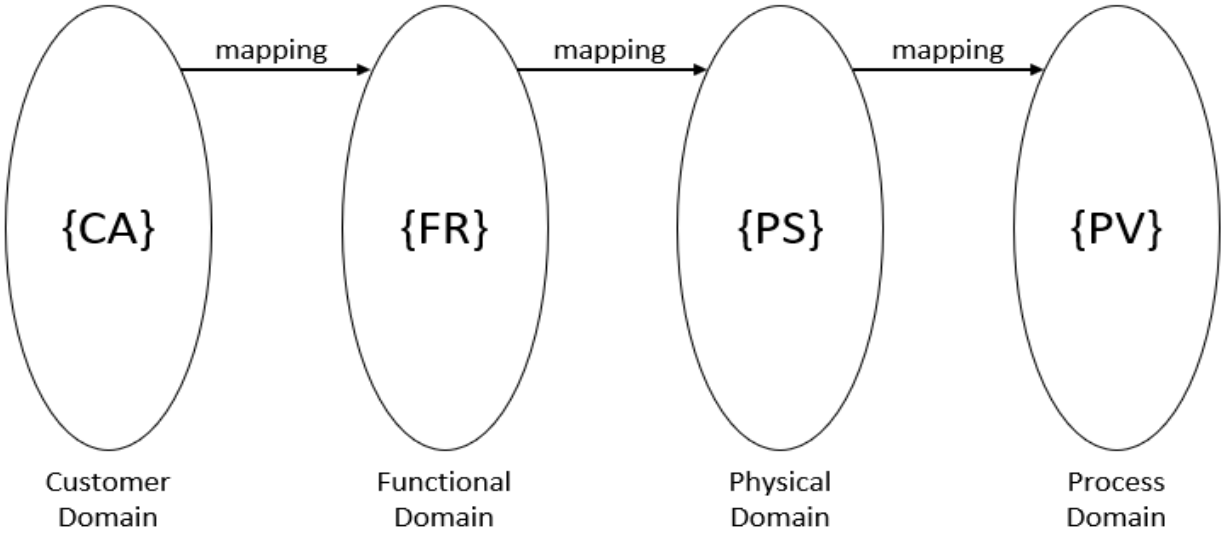


Figure 3.4.Design Domains [Suh, 1990]

In support, figure 3.5 shows a high-level overview of passing requirements through the axiomatic design process. The customer domain includes items such as customer needs, expectations, specifications, bounds and laws while the functional domain looks at the what while the physical domain is the how. All items within this mapping process is essential to ensure that all customer domain elements are pushed to achievable elements that can be implemented. If even one of the process steps are missed, then there is no correlation to whether the system will achieve want the customer wants.

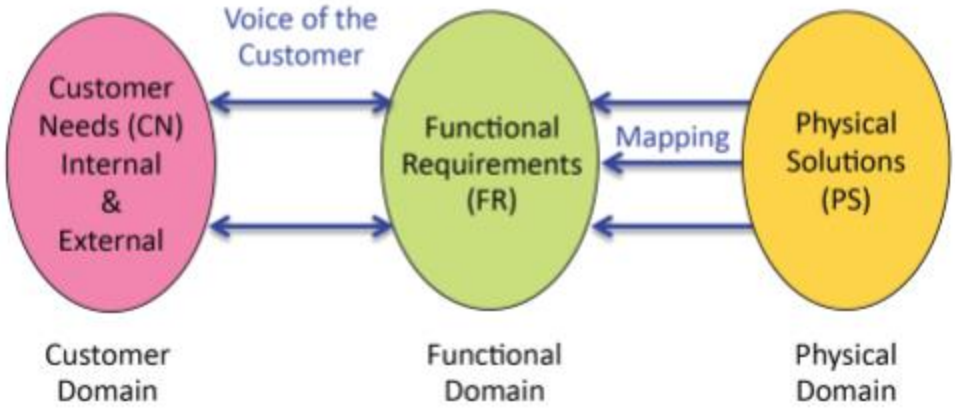


Figure 3.5.System Design Domains [Cochran, 2019]

3.5.1 Identify Customers and their Needs - Customer Domain

No matter what system, there will always be individuals who hold stake in the system and can be considered as stakeholders or even simpler, customers of a that system. The expectations of each customer will vary as the expectations will align with a need. Therefore, it is essential to look at each customer of the system and to determine what specific expectation there is. The various expectations of each customer are considered customer requirements within axiomatic design. Furthermore, a more complex system will provide additional customer requirements as there will may be additional customers and even overlapping expectations from one customer to another. These customer requirements need to be fully explored and a simplistic list created without missing any, as the additional complexity of customer requirements will provide a more complex system overall.

An item that also needs consideration when working in the customer domain are those items that affect the system in which cannot be changed. These non-changeable items are considered constraints. Constraints for the system can come in many forms such as time for the system to be implemented, the money allowed for the system design and implementation or even an input from outside the proposed system that cannot be changed. It is essential to document these constraints to ensure that the system to function in a manner respective to those constraints. Of course, there will most likely be constraints on a system that are not advantageous but is something that needs to be accommodated for.

System design could be affected greatly if the scope of the system, with respect to system boundaries, are not evaluated. Only the customer requirements that are within the scope of the system, or the system boundaries should be explored. Exploring additional customer requirements that are very far out of the system boundary or that are not controllable, such as the stock market can bring a heavy burden to the system design and the eventual function of the system. Therefore, only the customer requirements that are within the defined system boundaries should be considered when designing the system. In addition, the system boundaries will greatly help the system designers in understanding their responsible requirements and can help to prevent requirement creep in the future.

3.5.2 Functional Domain

In having an established list of customer requirements from the customer domain, the next step is to convert the customer requirements into a form that will in result, drive the system. The customer requirements need to be converted into a set of Functional Requirements for how the system should perform. It is difficult to state the need of Functional Requirements until the term Function Requirement is defined. “Function Requirements (FRs) are defined as the minimum set of independent requirements that completely characterizes the design goals.” [Suh, 1990]. If the Functional Requirements do not characterize the design goals, then the system will not be successful and meet the expectations of the customer. Without the Functional Requirements matching up with the customer requirements, then the customer will not like the system and therefore creating an ineffective system no matter how well the system was designed. In the end, the Functional Requirements are essential and need to be accurate to ensure customer acceptance of the system and therefore allowing the system to be utilized to its fullest.

Functional requirements need to be defined in a way that they make sense and are achievable. A Functional Requirement may not make sense if it is extremely vague where there are various kinds of ambiguity. This level of ambiguity will not allow for the Functional Requirements to truly reflect the customer requirements and result in a system that is not what the customer really wanted. In addition, Functional Requirements need to be achievable. There is no point of establishing Functional Requirements where it can never be achieved. Functional Requirements may be complex or even difficult to articulate, however Functional Requirements need to consider constraints such as time, money, physical space, and more for the design to be

effective. In conclusion, Functional Requirements are a key element for axiomatic design and need to be thoroughly thought through for the design process and ultimately the design to be effective and robust.

3.5.3 Physical Domain

After the functional domain has been explored and the Functional Requirements mapped back to the customer domain's customer requirements, there is a need to derive a solution for each Functional Requirement. The solution for achieving a Functional Requirement happens in the physical domain with a Physical Solution. For each unique Functional Requirement, there is a uniquely defined Physical Solution that is designed to fulfill the Functional Requirement. Figure 3.6 shows the relationship of Functional Requirements are Physical Solutions through mapping. Without having a unique one to one relationship from Functional Requirements to Physical Solutions, the system will not be able to accomplish the customer requirements of the system. Therefore, to have a system that is well received and utilized by the end customer, it is essential to ensure that all Functional Requirements are achieved with a Physical Solution.

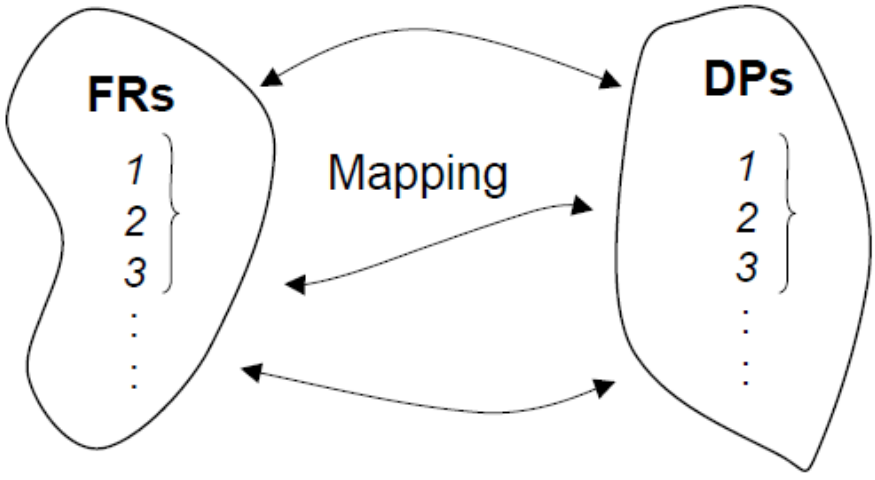


Figure 3.6 FR and PS Mapping [Cochran, Linck, Won 2001]

Physical Solutions are very important to the system design and allow for an implementation of a system, one Physical Solution at a time to be successful. The Functional Requirements mapping to each Physical Solution allow for small segments of a system to be implemented and debugged before introducing additional elements of Physical Solutions that could cause for frustration as

isolating the trouble spots could prove difficult. Therefore, the most simplistic Physical Solution should be chosen to satisfy a Functional Requirement. The more complex the Physical Solution are, the more complex the overall system will be in the end. Keeping it simple at the Physical Solution will keep it simple at the system level.

3.6 Axioms within Axiomatic Design

Axiomatic design has its unique reason not just because it sounds good, but because of the structure. Axiomatic within axiomatic design is the key word as it encompasses axiom, where "Axioms are truths that cannot be derived but for which there are no counterexamples or exceptions." [Suh, 1990] Axiomatic design includes two axioms with the first being the independence axiom while the second being the information axiom. Therefore, it should be without saying that when designing a system with axiomatic design, the design process with encompass the two axioms.

3.6.1 The Independence Axiom

The independence axiom to ensure that the system has independence amongst its relative parts. Independence is important when deriving Functional Requirements and Physical Solution as it ensures a simple and effective design. With respect to the independence axiom, there are several design types of axiomatic design where some are acceptable, and some are not. The types of designs as defined by Axiomatic Design include: uncoupled, path dependent, coupled, incomplete and redundant. The acceptable design types are uncoupled and path dependent where the coupled, incomplete and redundant are not acceptable.

The first design type uncoupled, allows for a predictable outcome allowing for one Physical Solution for each Functional Requirement, where there is no relationship from one Functional Requirement to another. Figure 3.7 shows the uncoupled design where each Physical Solution is mapped to a unique Functional Requirement.

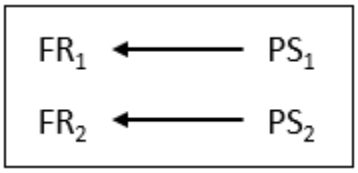


Figure 3.7 Uncoupled

The second design is path dependent meaning that one Functional Requirement must meet a Physical Solution before the next Functional Requirement can be met, allowing for a predictable outcome. Figure 3.8 shows the path dependent design where PS_1 is used to achieve FR_1 and FR_2 yet PS_2 is only used to achieve FR_2 and not a backwards reliance for FR_1.

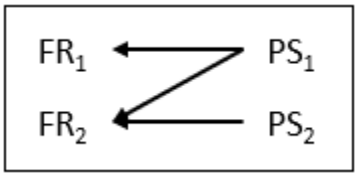


Figure 3.8 Path Dependent

The coupled design type does not allow for a predictable outcome as PSs are used for to accomplish multiple FRs in a crossed manner. Figure 3.9 shows a coupled design where PS_1 is used to achieve FR_1 and FR_2 and PS_2 is used to achieve FR_1 and FR_2. This coupling creates a very complex matrix and requires multiple PSs to interexchange with multiple FRs.

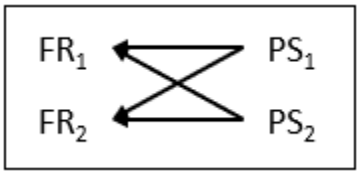


Figure 3.9 Coupled

Another design type is incomplete with not all Functional Requirements are achieved with a Physical Solution. Figure 3.10 shows an incomplete design where FR_2 is not achieved by PS_2.

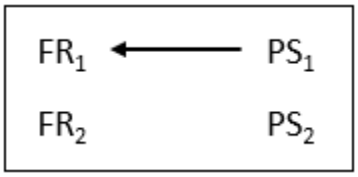


Figure 3.10 Incomplete

Then the last design type is the redundant type where there is still a one to one link from a Physical Solution to a Functional Requirement but where a Functional Requirement is being achieved by multiple Physical Solutions. This design type is not beneficial as it adds additional time and cost

to the system. Figure 3.11 shows the redundant design type where FR_1 is being achieved by both PS_1 and PS_2.

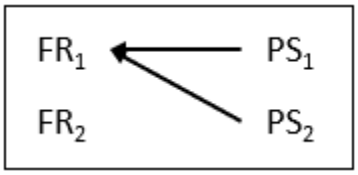


Figure 3.11 Redundant

In exploring all design types in axiomatic design, the uncoupled and path dependent methods hold true to be the best options. Without creating additional constraint on the system for being unpredictable or adding additional cost or time, the other design types should not be considered. Independence within axiomatic design is an important step when going through the method of defining Functional Requirements and Physical Solutions as it was seen above. Therefore, adherence to the first axiom, the independence axiom is important as the system is being defined.

3.6.2 The Information Axiom

The second axiom within axiomatic design is the information axiom and the intent should be to minimize the information content once the independence axiom has been achieved. “Among all the designs that satisfy the Independence Axiom, the design that has the least information content is the best design” [Suh, 1998]. In having several designs for a FR that successfully achieve the independence axiom, the information axiom is to be evaluated to ensure the best and most robust design is chosen. Suh states benefits of the information axiom as, “the Information Axiom provides a quantitative means of measuring the merits of a given design, which can be used to select the best among those acceptable.” [Suh, 1996]

The information axiom serves within axiomatic design to understand which design allows for the least amount of information content. Simply stating, the information axiom pushes towards the simplest design. A simpler design is beneficial as it allows for easier implementation and is easier to control once a system has been implemented and is being utilized. If additional information is required, the system will become complex and have a higher probability of failing

at some in time. Therefore, the information axiom is sequenced after the independence axiom and should be considered in the design stages for a robust system that will endure the test of time.

3.7 Creation of Design Decomposition Map

Exploration was made previously in this chapter with respect to the domains associated with axiomatic design. The next step is to start pulling pieces together into a visual display called the decomposition map. This mapping process has steps that need to be accomplished in a unique sequence and will be explored in more detail following. The decomposition map is the physical act of establishing a Physical Solution in consideration to a Functional Requirement and will start at the functional domain.

Figure 3.12 illustrates the process for designing and completing a decomposition map. The first step can be found as the customer needs. The customer needs should be pushed to a Functional Requirement so that it helps drive the design. As previously mentioned, there is no point in designing a system that does not consider the customer and their needs. The second step then is to assign a Physical Solution (PS) to each individual Function Requirement (FR). The main concept here is that each PS MUST achieve the FR. If the PS does not achieve the FR, then the design will not work. Once a PS is assigned to each FR, the next step is to provide a Functional Requirement Metric (FRm) to FRs that require it. A FRm serves to provide information as to how each FR is performing. Therefore, the FRs that may be critical or even hard to control should have an assigned FRm to continual evaluate how that FR is doing. Likewise, step 4 is to assign a Physical Solution Metric (PSm) to each PS to provide information to how a particular PS is performing. In likness to FRm, PSm is not required for each PS, just where it is needed to provide input to the designer.

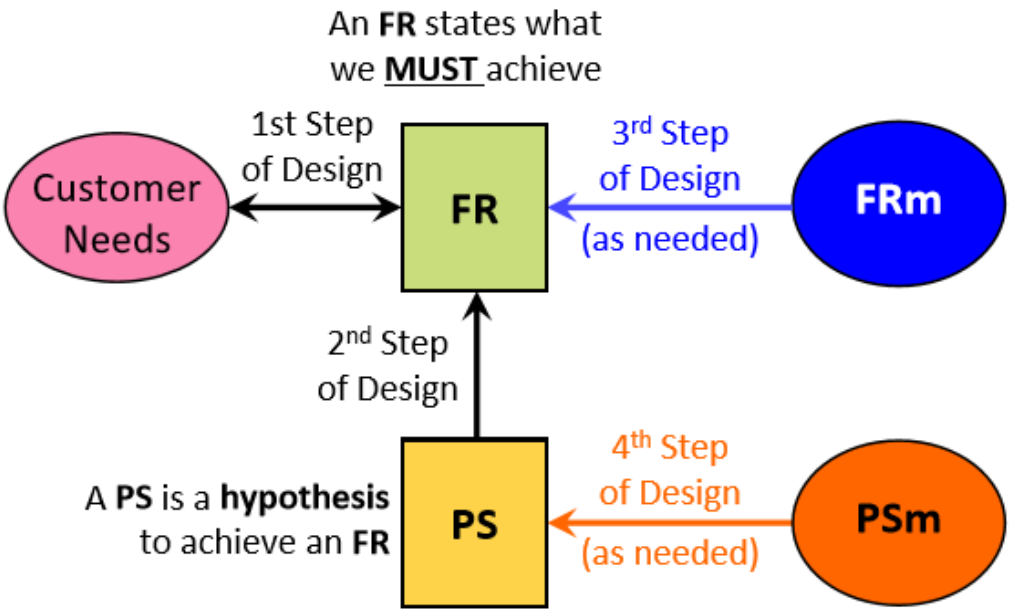


Figure 3.12 CSD System Design Language [Cochran, 2017]

As the steps to designing a decomposition map were discussed, there are some items that need to be considered during that process. When assigning a PS to a FR, it is essential to evaluate the design's application to axiom 1 or the independence axiom. As each PS is assigned to a FR and the current design is coupled, then the PS that is in contradiction, needs to be redefined. However, if the current design is not coupled then there is no concern and the process can continue with assigning additional Physical Solutions to Functional Requirements. The information axiom allows for the best set of Physical Solutions to achieve each Functional Requirement. Once the information axiom has be evaluated for each case of PS to FR mapping, the design itself needs to be evaluated to see if it is complete. If the design is in fact complete, then the decomposition map is complete. However, a design may require additional information to support a PS in which another layer of decomposition may be required. At this point, the designer would go forward with establishing a new set of Functional Requirements and continue through the process on the next layer. This iterative process of defining Functional Requirements and then Physical Solutions to achieve the Functional Requirements can happen as many times as the designer feels comfortable until the design is complete and able to be implemented.

As explained through the process of creating the decomposition map, Figure 3.13 provides an example of zigzagging from Functional Requirements to Physical Solutions. In the example,

the first element created is the top-level FR in the functional domain. Then that FR is mapped to the top-level PS in the physical domain which goes through the decomposition process. Then another layer is added with FR_1 and FR_2 with PS_1 and PS_2 being mapped according. This process continued until the fifth iteration where the design stopped at FR_{1231} and FR_{1232} and their corresponding Physical Solutions of PS_{1231} and PS_{1232}. It can also be seen where the branches of the decomposition map end with a thick outline around each Functional Requirement and Physical Solution. This thick outline indicates that the decomposition progression is no longer needed and is complete.

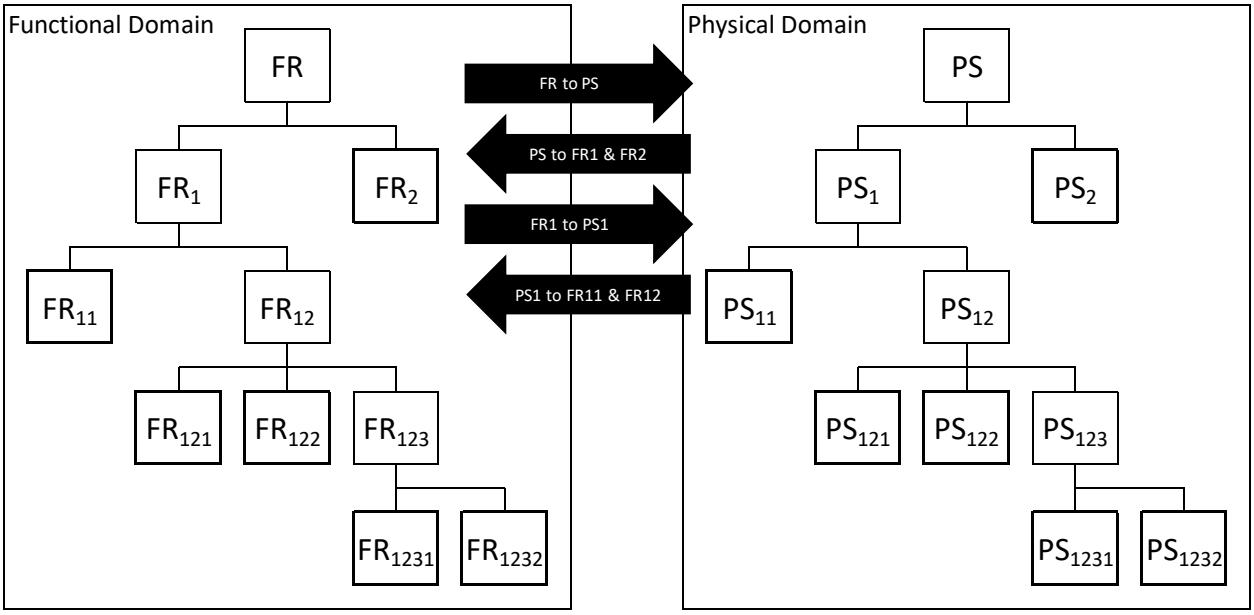


Figure 3.13 Zigzagging [Suh, 1990]

3.8 Application of Axiomatic Design to Manufacturing

At this point within the design process, the requirements from the customer with respect to the customer domain have been established and mapped to high level Functional Requirements in the functional domain. Furthermore, each high-level Functional Requirement has been mapped to a Physical Solution in the physical domain through the decomposition process where additional work was completed, and the decomposition mapping process was decomposed to the lowest level. Now it is time for the implementation of the decomposition map to deploy the design. The process for implementing the decomposition map is illustrated in figure 3.14 where the Physical Solutions are implemented from left to right then bottom to top.

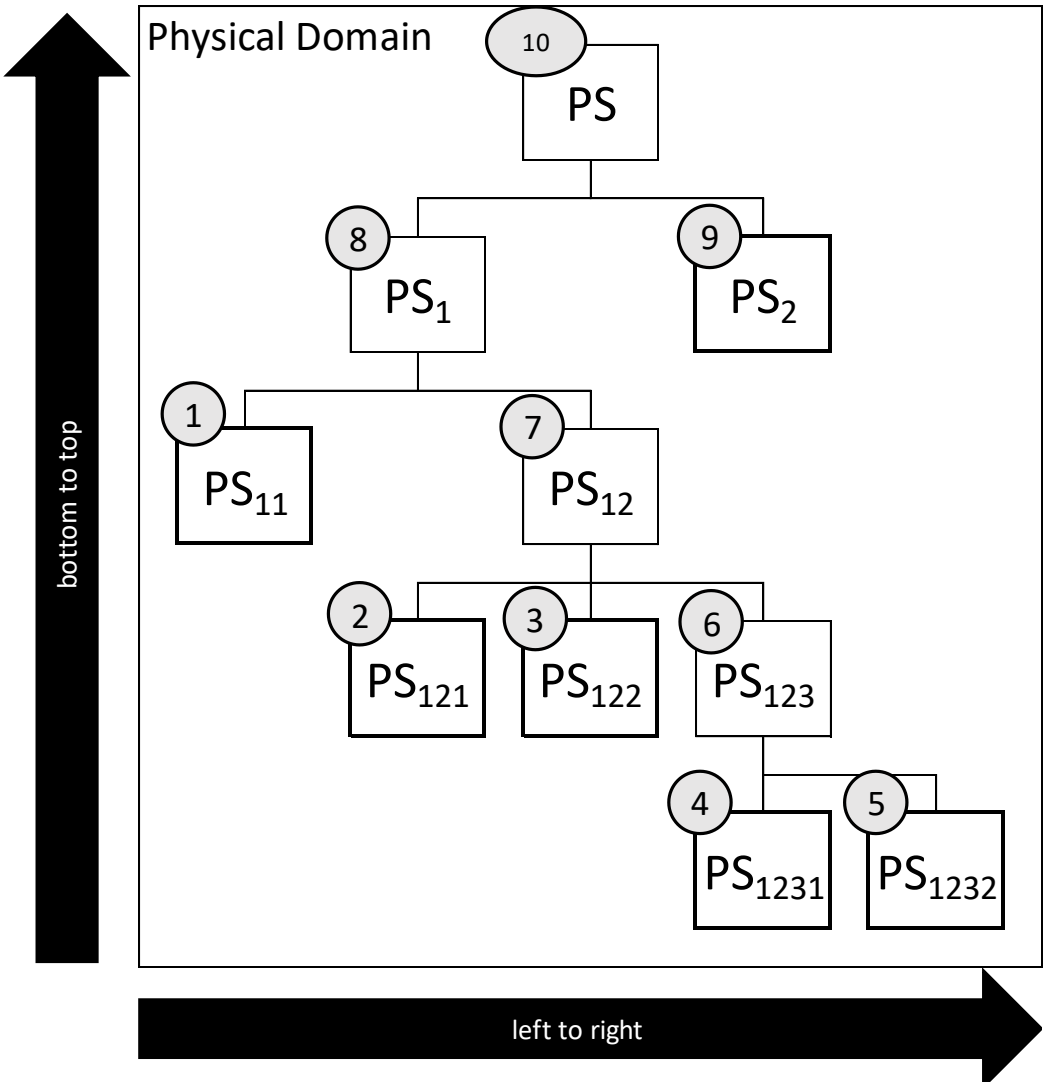


Figure 3.14 Decomposition Map Implementation Process

The numbers on Figure 3.14 shows the sequence for Physical Solution implementation. The reason for this implementation is that it allows for the simplest elements to be implemented and in a manner that doesn't affect other Physical Solutions. The first, second and third elements on the figure do not have dependencies and will make for a smooth implementation. Once the first three Physical Solutions have been implemented, the fourth and fifth Physical Solutions need to be implemented a layer down for a successful implementation of the sixth element. This sort of back and forth working the way up the decomposition map will help for a smooth implementation and successful have all lower level mapped Physical Solutions.

3.9 PDCA Cycle

In having the system implemented and executing successfully, the time comes for continual system maintenance. It is not always that the system needs to be updated, however it is essential to have some sort of health measurement of the system. A health measurement will allow for management at a quick glance how the system is operating and plan any changes if something were to dictate it. If something were to happen and the requirements change making the system not as successful anymore, the PDCA cycle in Figure 3.15 helps to ensure any changes made to the system will be successful.

Figure 3.15 Plan Do Check Act [ASQ.org]

The PDCA cycle is broke into four phases: the plan phase, do phase, check phase and the act phase. The plan phase is where there is recognition that there is a need for change and those changes are planned in detail. This plan phase would be a revision of the decomposition map based upon new findings and then planning what would be required to modify the system to match the newly defined Functional Requirements and Physical Solutions with respect to the decomposition map. After the plan phase, the next step is to move into the do phase. The Do phase encompasses a test that is conducted on a small scale to test the designer's hypothesis and all system level changes. The intent from the test is to gain insight into how the changes will affect the overall system before a mass introduction of change points. Once the test has been completed, the check phase is where the test results are reviewed and analyzed so that insight can be gained. Any insight from the test should be fully understood and pushed back into the plan phase with a re-run of the

test and analysis of the results. Once there is a comprehensive plan with favorable results from the Do and Check phase, the last phase is the Act phase. The act phase is the mass introduction of all changes to the system. Each change point should be implemented separately as to validate the successful implementation until all change points have been fully implemented.

The PDCA cycle is not something that should be just reviewed from time to time, it will help with the smallest to largest modification of the system through its entire life and should be iterative. There could be many requirement changes as time goes on and there needs to be a way to manage changes to the system. The PDCA cycle is a good methodology for ensuring changes are managed adequately and that the system continues to be robust through its expected life time.

3.10 Standard Work

An essential element within Collective System Design is Standard Work. Standard Work is the starting point of implementation for the decomposition map as it is the means to which the requirements are pushed to the individuals who are performing the work. The decomposition map continues to break down complicated requirements to the simplest level. With the lowest level Physical Solutions being the simplest, it allows these Physical Solutions to be implemented through standard work. Therefore, standard work is very crucial as it is the building blocks for the decomposition map.

When looking at standard work, there are two types. The types of standard work in white sheet and green sheet standard work. When the design is performing as expected and the PS is properly achieving the FR, the white sheet standard work is utilized. White sheet standard work "defines normal operation" [Cochran, 2019] while green sheet standard work "defines how to identify and resolve abnormal conditions in a predefined manner." [Cochran, 2019]. This means that green sheet standard work is utilized when the design is abnormal, or not functioning as intended. It is essential to have each white sheet standard work and green sheet standard work to ensure that no matter what inputs are given into a design, the design can handle those variables without disrupting the entire design. If the abnormal situation continues to occur and become normal, then green sheet standard work can move to white sheet standard work with the modification of those Functional Requirements and Physical Solutions. Figure 3.16 shows the use of standard work within collective system design.

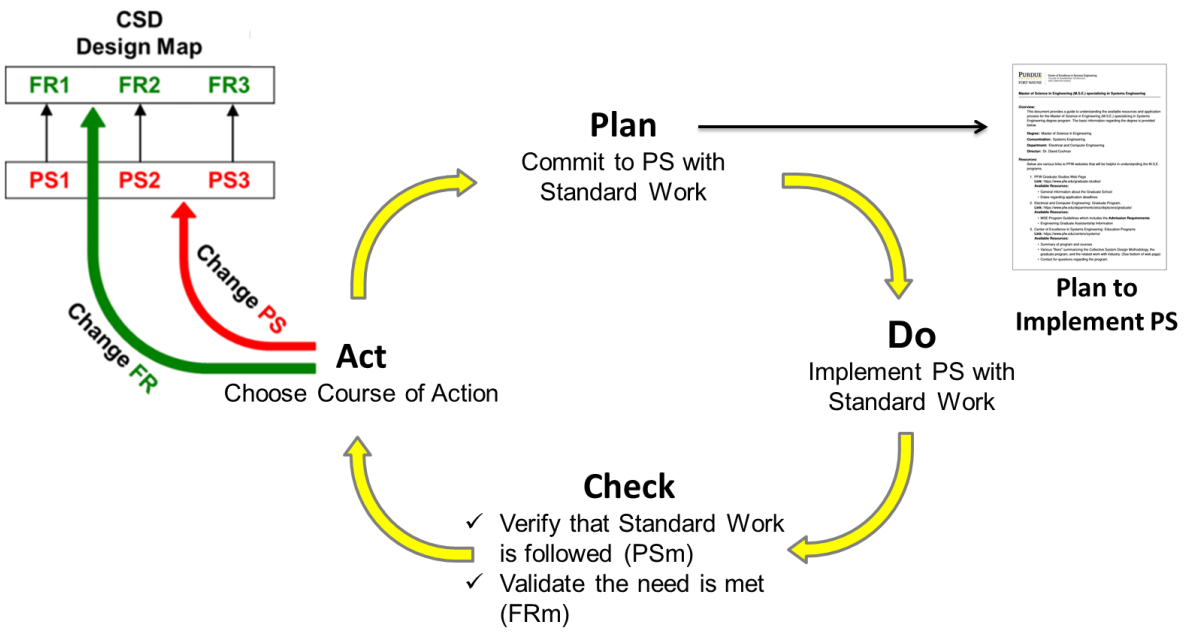


Figure 3.16 PDCA Learning Loop

Continual analysis of Figure 3.16 shows standard work and the modification through the PDCA cycle. The plan phase takes a PS from the design map and then aligns it with standard work. The do phase then takes that derived standard work and implements it, thus implementing the already defined PS. It is at this point that the standard work is validated through the FRm or Functional Requirement Metric and PSm or Physical Solution Metric that has already been defined in the CSD language design step. The PSm is first evaluated to determine if the standard work is being followed. Then the FRm validates if the standard work that was implemented, effectively achieves the FR. The decision for the FRm and PSm are then carried to the act phase where there are several options. Depending on the evaluation of the FRm and PSm, there may be a need to change an FR or PS in the CSD design map. If there is a change required, then the design map is to be updated and this process to continue again. However, if there is no need to change an FR or PS, then the cycle will continue through the CSD design map until all FRs and PSs are evaluated.

With a new design, this process will occur several times until the designer is satisfied with the outcome. The design should then be continually monitored to ensure that the current standard work is effective. If at any point, the standard work is no longer effective, the analysis process should be executed to maintain the design functioning in a robust manner.

4. NEED FOR CONTROL

4.1 Introduction

The need for control of a manufacturing facility through all manufacturing processes can stem deep while being viewed from different angles. With facts remaining facts, all companies (excluding non-profit) exist to make money. The intentions of making money may vary from one company to another. Companies, outside of non for profit, exist primarily to make money, or technically to turn a profit. There are secondary items such as influencing a community, allowing for a return on investment and more, but truly exist to make a profit so that the company can continue to exist. Therefore, if a company fails to make money then individuals working at that specific company may be forced to lose their employment, a town or city could be put into shambles from an excessive amount of people seeking employment, loss of life changing product of innovative solutions addressing a current need and many other effects could arise. Therefore, it is essential that all companies continue to stay in the black as the accountants would say, to maintain longevity and provide a good or service to those individuals seeking.

To maintain profitability, control is needed. Control is needed from the accounting perspective, the management perspective and ultimately the production or manufacturing process. But how can control be implemented in a manner that all individuals within the company can be satisfied? A Manufacturing Execution System (MES), is a very valid solution to achieving a high degree of control in which all individuals from the shop floor to the top-level executive can be satisfied with. Depending on the configuration of a company's MES, the resolution of control can greatly vary. Resolution could be set to a 30,000 feet level or down to the ground where every element is tracked to it entirely. Nevertheless, the main control lies in the fact that MES ties the control layer where the value-added manufacturing is performed all the way to the financials of a company comprised within the ERP system.

This chapter serves as understanding the need for control as included within MES as it relates to inventory and traceability. Data will be presented to understand the cost effectiveness that MES would have provided if it were to be implemented. The data shown is historical but relative to current manufacturing and justifiable by nature.

4.2 What is Control?

Control is very important across manufacturing facilities as individuals within the manufacturing facility can adequately respond to a situation that is not desirable. Yet, to get to the point of controlling a system, there are elements that need to be defined as they relate to control. According to Merriam-Webster, control means "to exercise restraining or directing influence over" [Control]. When tying this concept of control into a manufacturing facility, system control can implicate directing influence over a manufacturing process whereas individuals continuous monitor a process and continually guide it to the desirable output state. Without control, a manufacturing process could output elements that are undesirable.

Now that control has been define, it is essential to know how control can be utilized in a practical sense. System control allows the continuous flow of information to be provided and evaluated against a trigger point. When the information being provided goes outside of the desired window of operating, a trigger is sent to the appropriate individuals to respond. It is then the individual's responsibility to correct the underlying issue to bring the undesirable condition back into a desirable condition. In order to do this loop of correction, there are three basic functions required [Cochran, 1994]:

1. Data acquisition and sorting function(s)
2. Information flow function
3. System control function

Incorporation of the three basic functions allow for

Function 1 allows information to be collected and sorted so that only the essential information is provided while functions 2 and 3 provide meaning to the information which incorporates feedback. [Cochran, 1994]

In conclusion, control is beneficial yet there are criteria that need established for control to be efficient. First, normal needs to be defined so that triggers can be established. Secondarily, information flow is required so that the object of control can be monitored. Thirdly, information needs to be sent to the appropriate people while finally there needs to be a response. The response portion is the most critical point and requires the appropriate individual to assimilate the situation and determine the effects causation. As said, 'an appropriate response requires knowledge of the error, that is, the difference between the input (the desired result) and the feedback (the actual

outcome) [Cochran, 1994] In knowing the difference, action can be taken to place the undesirable situation back into a desirable one.

4.3 Control with Respect to Inventory

To truly understand what it means to control inventory, the term inventory needs to be expounded upon. “Inventory is the term for the goods available for sale and raw materials used to produce goods available for sale” [Kenton, 2019]. In this definition, inventory can be looked at from the part perspective or even the product perspective. Parts consist of raw materials that are needed to produce a good that is available to sell while a product is the good that is available to sell. Not only does inventory cost and is considered as an asset on the company’s financials, inventory can also cause additional costs when parts are not available to produce a product of a product is not available to sell. Both inventory as an asset and inventory causing additional costs will be explored in further detail.

An analysis for the cost of inventory was conducted where information was gathered for only one month. This information came from where the manufacturing facility’s asset management system stated a certain level of inventory that could not be physically found. These “lost” parts could not be found and thus required depletion from the asset management system and therefore introduced great cost to the overall profit of the company. Figure 4.1 shows the one-month information with 26 various part numbers. The gray bars show the total cost in USD for each part number while the blue line shows the cumulative cost of the parts from left to right. For the one-month time period, $31,359.08 was depleted from the asset management system with one hundred percent allocation to excess costs. The cost presented here for inventory deficits over a one-month period are just the part level costs and doesn’t include the intangible cost of individuals searching for product and line stoppage due to part shortage.

Inventory management needs control as it plays a large impact of the financials of the company. However, there are additional items that stand to require control especially with respect to inventory management. A situation that can very well happen during the manufacturing process is the manufacturing line running out of components. With some products requiring over 60 different component parts, control is most certainly required to ensure the manufacturing line does not face any stoppages. A lack of inventory at the manufacturing line would require the line to stop producing parts are could very well lead to impacting customers. Once the snowball starts to roll,

there is no telling what all will be impacted. Therefore, control is required to ensure that operations on the manufacturing line can signal for additional parts to be brought to the line. The operations themselves do not have the time to get their own parts as it is not part of their standard work or will fit within the required cycle time. The operators are dependent on others to deliver product and if they are getting low, they need a method of stating their current condition. This level of control is essential to having a robust manufacturing process and even manufacturing facility. In designing MES correctly, MES can provide a solution of signaling for additional product and in return not allowing for the manufacturing line to run out of product.

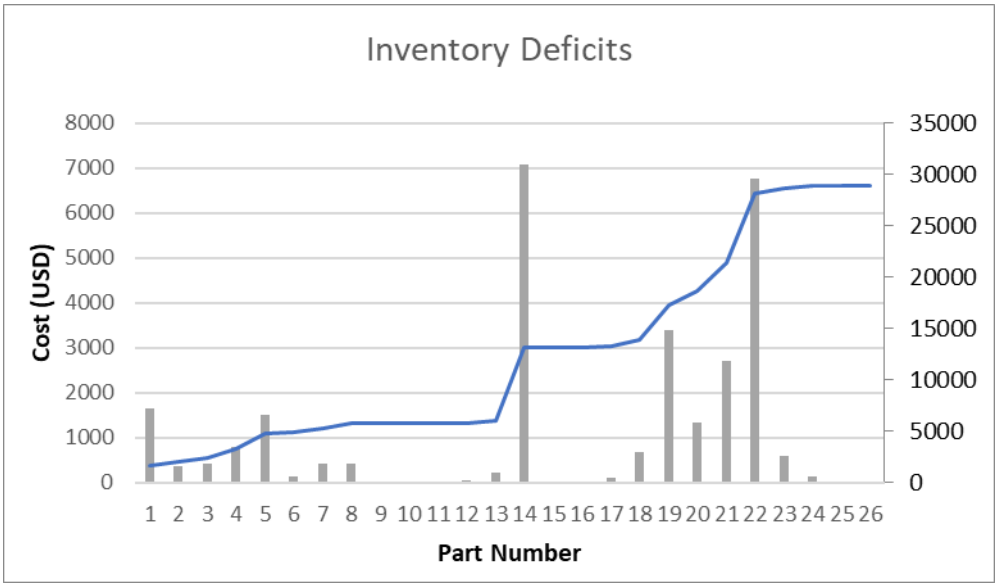


Figure 4.1 Inventory Deficits

4.4 Control with Respect to Traceability

Control in an important aspect when it comes to any manufacturing facility and can range from component parts to products. Traceability is a large contributor to control and allows for the collection of both process and product data for a finished product. When a product comes off a manufacturing process, there is a need to understand all the component parts that went into that product and the specifics for how that part was processed. Both process and product data are essential to have when something abnormal happens on any manufacturing process throughout a value stream. If an abnormal event were to occur, there is a need to determine the suspect parts and provide containment. This isolating of suspect parts is where the traceability data is most

important. If the traceability data does not have enough resolution, then additional parts will require containment and therefore consuming additional resources.

A scenario will be provided which constituted the need for control as it relates to traceability. The scenario that will provided was a real instance and had the occurrence of once. The times requiring traceability are unknown and will occur without warning therefore requiring the need for traceability all the time. The scenario entails a manufacturing process where a component part was produced via the method of machining. This machined component part then went into a varying levels of assembly states. For a clearer understanding of the process, refer to Figure 4.2. The process flow shows a machining process where a component part is produced. That component part is then moved to the assembly 1 process where it is assembled as a sub-assembly. Once the sub-assembly is complete, the sub-assembly is further processed at the assembly 2 process and is then shipped to: customer 1, customer 2 and customer 3.

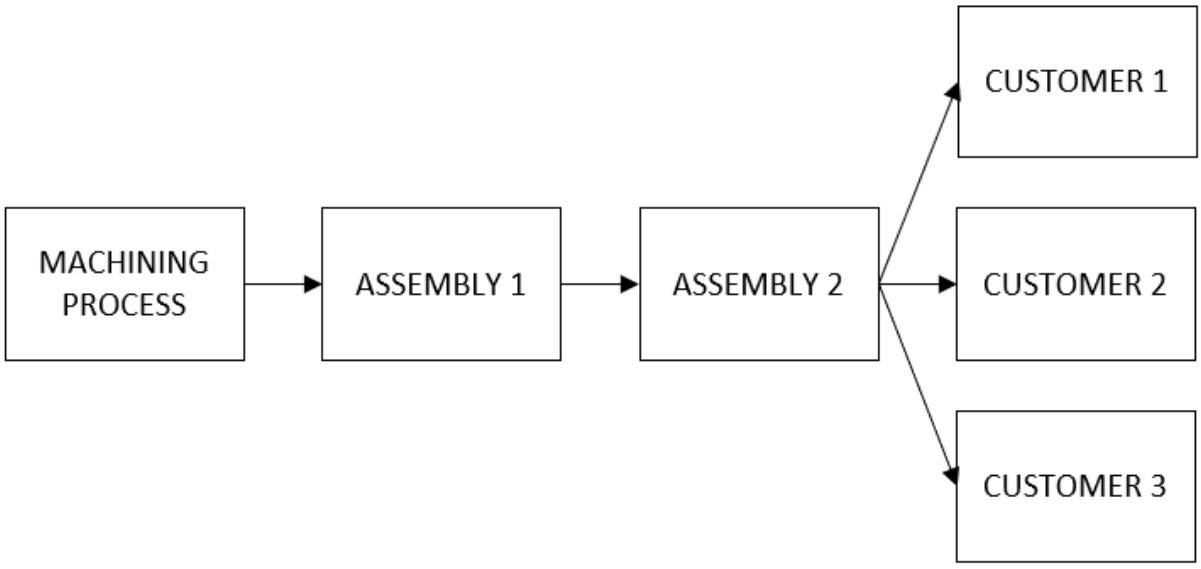


Figure 4.2 Manufacturing Process Flow

The component part that was manufactured at the machining process was manufactured with a Physical Solution that was outside diameter that did not meet the design specifications. This occurrence happened due to some measurement gauge setup and was isolated to a certain day and shift until it was realized and could be contained. Containment was performed and resulted in containing additional products than required. The machining process was determined to produce 3,424 component parts that were outside of the design specification limits. However, the level of

traceability was poor across all manufacturing processes and required containment of 13,748 finished products, over four times the required containment needed. To further complicate the issue, most of the suspect parts had already been shipped to each of the three customers. Table 4.1 further shows the number of parts that were contained equaling 13,748 parts with 3,424 (24.91%) being truly suspect and 10,324 (75.09%) requiring containment even though they were not suspect but needed to be contained due to a loss of finite traceability.

Table 4.1 Containment Results

Suspect Parts	3424	24.91%
Non-Suspect Parts	10324	75.09%
Total Containment	13748	100.00%

With the vast number of parts that were considered suspect and needed containment, the cost associated was also vast. The customers were contacted and made aware of the situation and started to implement containment on their end. The customer containment included performing physical sorts both on and off vehicles. With parts being already assembled to a vehicle, the unit required removal which took much more resources. It was not just the need to contain parts, it required investigation to find the root cause and fix the issue while making additional parts to replace the parts that were at the customers. Therefore, the issue on not be able to distinctly decipher which parts no longer met specifications was very difficult.

To provide additional detail on the traceability concern and its magnitude, it is time to look at the data associated with the event. Figure 4.3 shows the costs associated with the concern as it occurred. This means that the information is provided with all 13,748 parts. The blue bars show the cost for each supplier while the grey line is a cumulative cost with the addition of customers when moving from left to the right. As the figure shows, there is a great deal of cost associated with each customer resulting in a total of $633,466.18 dollars.

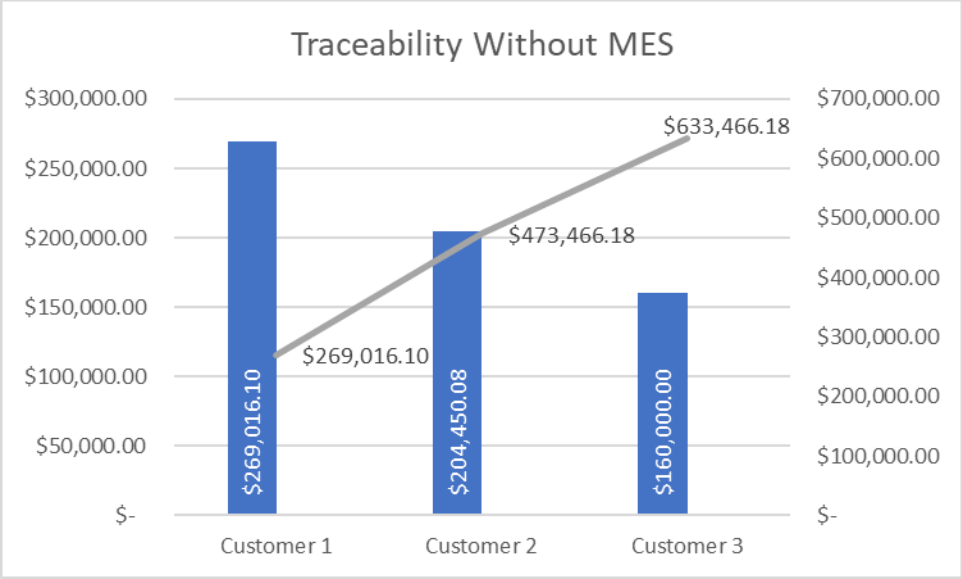


Figure 4.3 Traceability Cost – Without MES

Of course, the cost for this one concern was monumental and could have been avoided with more control in the manufacturing facility, including control on the manufacturing line for processing in additional to overall traceability. Yet, it would be interesting to see what would have happened if the suspect parts would have been known and distinguishable. Therefore, the costs were re-evaluated with the assumption that each part had a unique serial number so that it could be distinguishable in addition to each serialized part maintaining tracking throughout the entire manufacturing facility.

Figure 4.4 shows the costs associated with the modified level of traceability and includes only the 3,424 that were truly suspect for being manufactured outside of the specification limits. The costs were broken down and the costs that were fixed and not dependent on several parts remained the same while the costs for parts was modified. With having a fraction of the parts being suspect, there wouldn't have been a need to remanufacture as many parts. Figure 4.4 shows the cost for each customer within the blue bars and a cumulative cost on the grey line. The total estimated cost for having traceability in place and effective for this one concern was $155,395,68 dollars, a drastic contrast to not having traceability implemented.

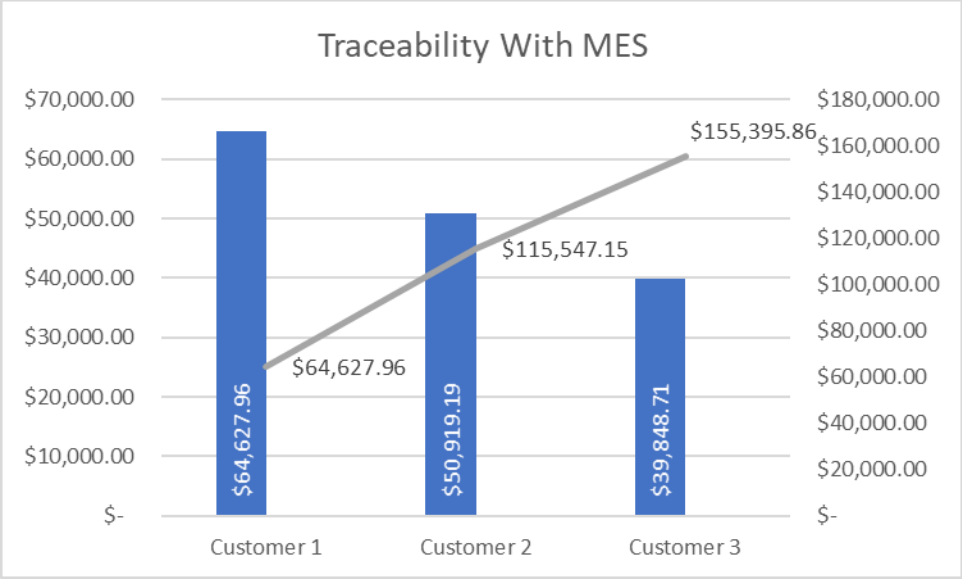


Figure 4.4 Traceability Cost – With MES

To better illustrate the difference between the cost of an actual traceability concern with and without MES, Table 4.2 shows the total costs and the delta cost associated. As it was presented already, the total cost without MES was $633,466.18 dollars while the cost analysis with MES was $155,395.86 dollars, this brought the delta to $568,838.22 dollars in favor of with MES.

Table 4.2 Cost Comparison for MES and Traceability

	Without MES	**With MES**	**Cost Savings**
Customer 1	$269,016.10	$64,627.96	$ 204,388.14
Customer 2	$204,450.08	$50,919.19	$ 204,450.08
Customer 3	$160,000.00	$39,848.71	$160,000.00
Total	**$633,466.18**	**$155,395.86**	**$568,838.22**

There will be times when the need for traceability information will be required to help isolate parts sent to customer(s). The example given is just one example of where a lack of control with respect to traceability can lead to a substantial cost to be incurred. With the focus remaining solely on traceability and isolating suspect parts, this is not the only element that needs to be addressed. The small level of control associated with traceability doesn't prevent the issue from occurring again which incurred a cost of $155,395 [Company Proprietary Document]. Further analysis and control are required at the manufacturing line to prevent creating suspect parts which leads into the quality aspect of MES. Further control will need to be established at the manufacturing facility

to control the manufacturing of products so that failures are prevented so they don't occur in the first place. This additional control needs to be addressed but is outside of this thesis and will be conducted separately. In conclusion, control is needed with multiple aspects to ensure that additional costs are not incurred. It is essential to have control within the manufacturing facility to eliminate the excessive costs of a lack of traceability. As the cost was heavily focused and a key element for validation, the customer satisfaction and trust are also an essential element leading to establishing and validating the need for control and in this instance, traceability.

4.5 MES Cost and Analysis

After understanding the costs associated with isolated incidents dealing with both inventory and traceability, a cost justification needs to be provided with the estimated costs of MES creation and implementation calculated. For the cost of MES, Table 4.3 shows the costs associated with software and hardware. The software includes the software licensing and programming costs to creating and implementation a MES solution. In adding all the content up, the total cost for MES implementation was found to be $528,000 dollars.

Table 4.3 Cost of MES

Software Cost	$ 512,000.00
Hardware Cost	$ 16,000.00
Total Cost	$ 528,000.00

With a value as large as calculated for the total cost of MES, additional analysis is to be provided to determine the return on investment based upon historical data. In using the information already provided for a month cost of inventory costs and a one-time estimate of excessive cost due to traceability, the cost justification can be completed. Table 4.4 summarizes the previous information provided with the cost of the single month inventory costs along with the one-time traceability cost and the cost for MES. It is essential to note that the cost used for traceability was calculated assuming the difference between the cost of the one-time occurrence difference between with MES and without MES, the delta cost. Furthermore, the table then provides the percentage of MES Cost divided by the Total Cost which provides a value of 87.97%. This percentage

therefore states that the cost to develop and implement MES is only 87.97% of the cost for a one-month inventory deficit and a one-time traceability concern.

Table 4.4 Cost Justification for MES

Inventory	$ 31,359.08
Traceability	$ 568,838.22
Total Cost	$ 600,197.31
MES Cost	$ 528,000.00
MES Cost / Total Cost	87.97%

In conclusion, the cost that can and is being occurred for inventory deficits and traceability concerns are substantial and take away from the bottom line of the company. In developing and implementing MES, there is cost justification instituting benefit on the side of MES. Therefore, development of MES can be started so that there can be control over both inventory and traceability. It is also noteworthy to state that there are other benefits with the design and implementation of MES outside the scope of inventory and traceability. However, this thesis will only focus on inventory and traceability with the assumption that the other benefits of MES will already be justified.

5. MES OVERVIEW AND APPROACH

5.1 Introduction

Customer requirements and constraints are present when developing a system and this chapter will serve to define and place context around the customer requirements while understanding and dealing with constraints. These customer requirements and constraints will deal directly to the design of a real-life application of MES. Information will be provided relative to the overall approach to both the design and implementation of MES along with the constraints placed onto the design of the system. The constraints that were placed onto the system were determined and are as follows:

- Limit User Access According to Roles
- Implement Only Portions of MES Based Upon Need
- Provide User Access to View MES Data Anywhere

With these constraints documented, MES needs to be compliant and therefore requires design consideration with respect to compliance of the various constraints. During the axiomatic design process, these constraints will be addressed and how they can align with the customer requirements.

For a better picture of the approach taken to the design of MES, it is essential to remember what purpose MES serves. MES is an information system that serves to connect, monitor and even control simple to complex manufacturing systems and data flow on the plant floor. The intent and goal of MES is to ensure effective execution of various manufacturing operations, improve production output and provide management level information for process performance [Margaret, n.d.]. Undoubtably, MES provides massive amounts of data that can be very cumbersome to navigate through and expensive to store. However, a properly designed MES will provide move benefit for knowing how a manufacturing process is operating along with providing feedback to where the process can be improved.

5.2 Customers and Requirements

The first domain in axiomatic design is the customer domain where the designer is to understand the customers of the design and the requirements that come from those customers. The

customers for the design of MES were considered and were broken down into the categories of both direct and indirect customers. The requirements that come from both categories will be explored in more detail.

5.2.1 Indirect Customers

The category of indirect customers includes those individuals within the manufacturing facility that serve to see the system wholly and are not active participants of system execution. It can also be said that the indirect customers serve to control a portion of the manufacturing facility and monitor performance through the means of MES data. Table 5.1 shows the indirect customers and the assigned customer requirement that was gathered during the customer domain portion of axiomatic design for MES. The main indirect customers were determined to be: plant manager, production manager, quality manager, logistics manager and engineering manager.

Table 5.1 Indirect Customer linkage to Requirements

Customer	Customer Requirement
Plant Manager	Wants to have an overall picture of how the manufacturing facility is performing
Production Manager	Wants to know how the manufacturing process is performing according to orders
Quality Manager	Wants traceability from a product and part level
	Wants the capability of marking product suspect
Logistics Manager	Wants to track inventory within the manufacturing facility
	Wants to fulfill customer orders
	Wants to ensure correct parts are being sent to the customer with correct labeling
Engineering Manager	Wants to understand how the production line is performing
	Wants to understand repairs and machine upgrades to the production equipment
	Wants to track production specific tooling.

Each indirect customer and the associated customer requirement are the top-level requirements that need to be achieved for creating an effective system that the customers will welcome. If the system doesn't into account the customers and their requirements, then the MES will not be welcomed and most likely will not be utilized. Therefore, it is very essential to have a high-level understanding for the design of MES before going any further.

5.2.2 Direct Customer

The indirect customer was defined as a non-execution role where the direct customer can be defined in a direct execution role. The direct customer will the individuals within the manufacturing facility that will interact daily with the system of MES as its primary users. These users are on the plant floor and will handle the transactions within MES that will provide data for the indirect customers to view. Some examples of the direct customers include:

- Logistics User who receives product in the manufacturing facility and moves it to the appropriate location
- Production Line User who receives orders for product that needs manufactured
- Tooling User who manages the production tooling and builds tooling assemblies for the machining line to consume
- Tugger User who is picking up component parts to deliver to the manufacturing line and then picking up completed product to be delivered to the shipping area
- Shipping User who pulls completed product to ship to the various customers
- Quality User who is responsible for measuring manufactured product to ensure that it meets the print
- End of Line User who pulls the part off the manufacturing line, checks for specific items and then packs the completed product into a container
- And more…

As the primary users for MES, the direct customers have their own set of requirements that should be included in the overall design of MES. For a vast majority of the direct users, time is of the essence and therefore requiring work to be completed in a set amount of time. Therefore, the user cannot pay too much attention to MES and neglect a function that should be performing. In result, the following list are the requirements that come from the direct user of MES:

- The interface for MES needs to be user friendly and intuitive allowing for a seamless interaction
- MES needs to be robust so that all aspects of work can be executed, even the non-standard items
- MES needs to be reliable and trustworthy

5.3 MES Hierarchy

When thinking through the design of MES, first consideration was put towards the overall hierarchy. Constraints were placed onto the system to limit a user's access to certain functionality. The constraints for limiting user access was boiled down into: configurating the various aspects of MES, executing MES activities and then providing management and others with information about how a manufacturing process is performing all the way to the overall performance of the manufacturing facility. Therefore, the hierarchy was established according to the following: configuration, execution and reporting.

Figure 5.1 shows the hierarchy structure for MES with consideration to configuration, execution and reporting. The configuration portion allows for a user to create or modify some setting that will be dependent for the execution process to occur. This configuration portion includes items such as maintaining storage locations, supplier parts, manufacturing products and much more. Then moving up the hierarchy, the next stage is the execution process. The execution process includes roles for users to perform actions with respect to the items that were already configured. The execution stage includes performing tasks such as moving inventory, shipping parts, capturing process data and much more. These actions are the core elements that provide data from the plant floor. Now with having data respective to actual tasks performed, the next stage is the report stage where a read only copy of information is provided to management and other key individuals to gain insight into a manufacturing process or facility performance.

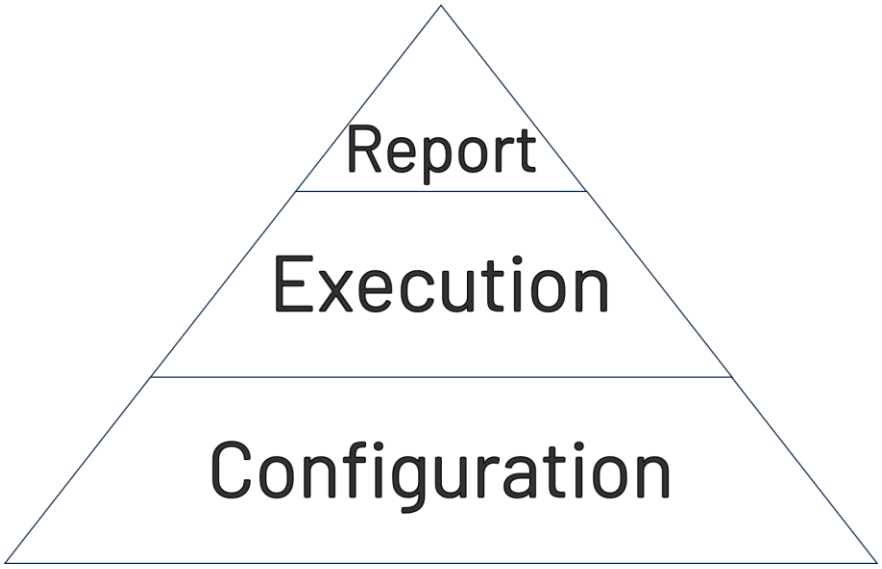


Figure 5.1 MES Hierarchy

User management is a key element of MES and ensures that only certified individuals can perform tasks based upon their role. Without having a MES hierarchy in place, users could very well make changes to MES that would result in inaccurate data. This constraint of having limitations for users was understood before starting the design process for MES and proved to be beneficial from many fronts.

This hierarchical method will be explored in more detail in chapter 6 when developing the decomposition map for both the execution and configuration of inventory and traceability. Additional work with reference this hierarchical method in chapter 7 where evidence is provided for the implementation of the inventory and traceability modules. As it has been stated, chapter 6 and 7 rely on a firm understanding of the MES hierarchy and will prove to be beneficial in the development and implementation of MES.

5.4 MES Design with a Modular Approach

A constraint that was brought forth before the design process was the desire to implement only portions of MES when desire. Therefore, a modular design was found to be fitting. Modularity in software development is becoming ever more prevalent and provides many benefits such as concurrent engineering. With respect to software engineering such as the design of MES, “modularity refers to the extent to which a software/Web application may be divided into smaller

modules. Software modularity indicates that the number of application modules are capable of serving a specified business domain" [what is modularity?]. With this approach, the design of MES was considered and broken into several pieces or modules that would allow for implementation based upon certain needs of a manufacturing process.

The first step to determining the modules to be developed is to map the customer attributes to a Functional Requirement. The Functional Requirement allows the customer attribute to be phrased in a manner that can be achieved. Table 5.2 presents the customer, customer attribute and the mapping to each Functional Requirement. By mapping the customer attribute to the Functional Requirement, the customer domain is being linked to the functional domain.

Table 5.2 Customer to Functional Domain Mapping

Customer	**Customer Attribute**	**Functional Requirement**
Plant Manager	Wants to have an overall picture of how the manufacturing facility is performing	Provide method of seeing all level operation details
Production Manager	Wants to know how the manufacturing process is performing according to orders	Provide method of seeing manufacturing process to order completion
Quality Manager	Wants traceability from a product and part level	Provide bottom up and top down traceability
	Wants the capability of marking product suspect	Ensure All Parts Maintain Quality
Logistics Manager	Wants to track inventory within the manufacturing facility	Provide Control over Component and Finished Goods
	Wants to fulfill customer orders	Provide Link from Customer Orders to Production Line
	Wants to ensure correct parts are being sent to the customer with correct labeling	Provide Customer Correct Parts with Customer Defined Labeling
Engineering Manager	Wants to understand how the production line is performing	Provide Production Performance Detail
	Wants to understand repairs and machine upgrades to the production equipment	Provide Repair and Upgrade Tracking
	Wants to track production specific tooling.	Maintain Tracking of Production Specific Tooling

In having a mapping from the customer domain to the functional domain, the next step is to create mapping from the functional domain to the physical domain. Table 5.3 shows the direct linking from the functional domain of the Functional Requirement to the physical domain and the physical solution.

Table 5.3 Functional to Physical Domain Mapping

Customer	**Customer Attribute**	**Functional Requirement**	**Physical Solution**
Plant Manager	Wants to have an overall picture of how the manufacturing facility is performing	Provide method of seeing all level operation details	Reporting Module
Production Manager	Wants to know how the manufacturing process is performing according to orders	Provide method of seeing manufacturing process to order completion	Pack Out Module
Quality Manager	Wants traceability from a product and part level	Provide bottom up and top down traceability	Traceability Module
	Wants the capability of marking product suspect	Ensure All Parts Maintain Quality	Quality Module
Logistics Manager	Wants to track inventory within the manufacturing facility	Provide Control over Component and Finished Goods	Inventory Module
	Wants to fulfill customer orders	Provide Link from Customer Orders to Production Line	Order Management Module
	Wants to ensure correct parts are being sent to the customer with correct labeling	Provide Customer Correct Parts with Customer Defined Labeling	Shipping Module
Engineering Manager	Wants to understand how the production line is performing	Provide Production Performance Detail	Production Tracking Module
	Wants to understand repairs and machine upgrades to the production equipment	Provide Repair and Upgrade Tracking	Maintenance Module
	Wants to track production specific tooling.	Maintain Tracking of Production Specific Tooling	Tooling Module

With the design of MES being modular, the proper steps have taken place to allow for the modularity. As already discussed in Table 5.3, the modules for MES were broken down into the following: reporting, pack out, traceability, quality, inventory, order management, shipping, production tracking, maintenance and tooling.

5.5 Data Collection and Accessibility

The last constraint to be considered is the ability to allow users to view MES data no matter where the user may be. With the advancement of technology, this is becoming easier and provides many platforms to perform. The current buzz word that truly encompasses this constraint is IIoT of the Industrial Internet of Things where are information is readable accessible.

The first step to complying with this constraint is data collection and its storage. As a company policy and standard practice, Microsoft SQL Server will be used to store the data collected throughout the manufacturing facility using MES. Once the data is collected, another company standard is to use Microsoft Power BI to provide users access to the data no matter where they may be.

In conclusion, the constraint for allow user access to data reveals additional company constraints of utilizing MS SQL Server and MS Power BI. These solutions can be utilized effectively but need to be considered throughout the design process.

5.6 Conclusion

In understanding additional information about MES and its applicability toward the design process, many elements were discussed. The first step eluded to the constraints that would need managed that were to be placed on the system. Once these constraints were addressed with MES hierarchy and a modular approach, the customers were identified along with their requirements in the customer domain. Then the functional domain was explored isolating the proper Functional Requirements and finally moving into the physical domain and the mapping to physical solutions.

6. DECOMPOSITION MAPPING PROCESS

6.1 Introduction

This chapter will focus on the decomposition mapping process as it relates to inventory and traceability functions within MES. Decomposition mapping will take a Functional Requirement (FR) and then assign a Physical Solution (PS) that will achieve the desirable requirement. Even more so, the decomposition mapping process will allow for a systematic process as this requirement to solution concept will be worked layer by layer starting at the top simplest requirement. However, to even start the decomposition process, there are certain design decisions that need to be made. Once the design decisions are established, this chapter will start the decomposition process starting with the high-level requirements. These high-level requirements will form the basis for the decomposition map starting with the top-level decomposition map and then leading into the second level and third level decomposition maps. It is only after this point of establishing design decisions and developing the top-level, second level and third level decomposition maps that the inventory and traceability modules can be explored. The inventory module decomposition map will be explained first and will include a configuration and execution. Then this chapter will move into the traceability module and will also be broken down into configuration and execution. In following the above-mentioned steps for this chapter, the decomposition process can be completed for both inventory and traceability as it relates to MES.

6.2 Design Decisions

Before design can occur at any point, there are some design decisions that need to be made. Design decisions can range depending on what the design includes. For this thesis and the design of MES, the design decisions will accordingly align. There are really two main categories for design decisions as it relates to MES.

The first category includes the technology that will be utilized and is applicable to the inventory module. This technology includes items such as PCs, mobile devices, data collection and more. For MES, the design decisions were to stay with PCs in certain areas and for other areas where PCs would be cumbersome, iPads will be used as it is the company’s standard tablet. Therefore, PCs will be used in all static locations and iPads will be used for locations that continue

to move, especially in the moving of inventory. Moving inventory requires associates to pick up inventory at one location and then drop is off at multiple locations. If the technology PCs were to be used, the act of moving inventory would become very difficult due to the requirement of physical movement and ergonomics.

Then the second category for design decisions include what the output should be information as it relates to traceability. There are many requirements when it comes to traceability that are enforced by customers, internal standards and in addition the Automotive Industry Action Group (AIAG) which is a governing body for the automotive industry. Therefore, traceability needs attention as to what information will be required. As it turns out, the company's standards for traceability are more stringent than both the AIAG and customer so those internal standards will be used. Traceability requirements include both a bottom up and top down approach which is required in 8 hours timing. The bottom up approach takes a supplier component and then tracks all serialized product manufactured at the manufacturing facility and where those top-level products are. In addition, the top down approach takes a product and then back tracks to find all component parts that went into that serialized part including part numbers and batch numbers. If this is not enough, there is an additional time constraint requiring all this information to be supplied in less than 8 hours.

As the design starts, these design decisions need to be taken into consideration. It is not that these design decisions are constraints placed on the system, they are merely decisions made to allow for a robust system that accommodates standards and best practices. These design decisions will be utilized in the following portion of this thesis and will be given proof throughout the completion of this thesis.

6.3 Top Level Decomposition Map

The first place to start in the axiomatic design decomposition map is the very first Functional Requirement. Figure 6.1 shows the top level of the decomposition map where the Functional Requirement or FR1 has been stated to "Connect and Monitor the Manufacturing Facility." FR1 is the requirement to connect and monitor the manufacturing facility and has the purpose of improving manufacturing processes. This purpose of improving manufacturing processes is aimed towards delivering the correct product to the customer at the correct time while minimizing costs within the manufacturing facility. The intent of improving the manufacturing processes result in

increasing overall profit in addition to increasing customer confidence. To connect and monitor the manufacturing facility and providing benefit for the manufacturing facility, a solution is needed. Therefore, FR1 is achieved through the solution of PS1 and a "Manufacturing Execution System (MES)." MES is a solution to connecting and monitoring the manufacturing facility but is yet only a tool. There are additional requirements that will need to be established to support MES and will be found when going through additional decomposition levels.

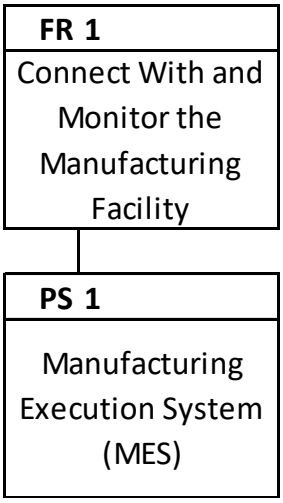


Figure 6.1 Top Level Decomposition Map

With the first level of the decomposition map already being defined, PS1 of MES needs additional information where new Functional Requirements were developed with their corresponding physical solutions. Figure 6.2 shows the decomposition map up to the second level. The Functional Requirements defined under MES are FR 1.1, FR 1.2, FR 1.3, FR 1.4 and FR 1.5 where each FR has a corresponding PS.

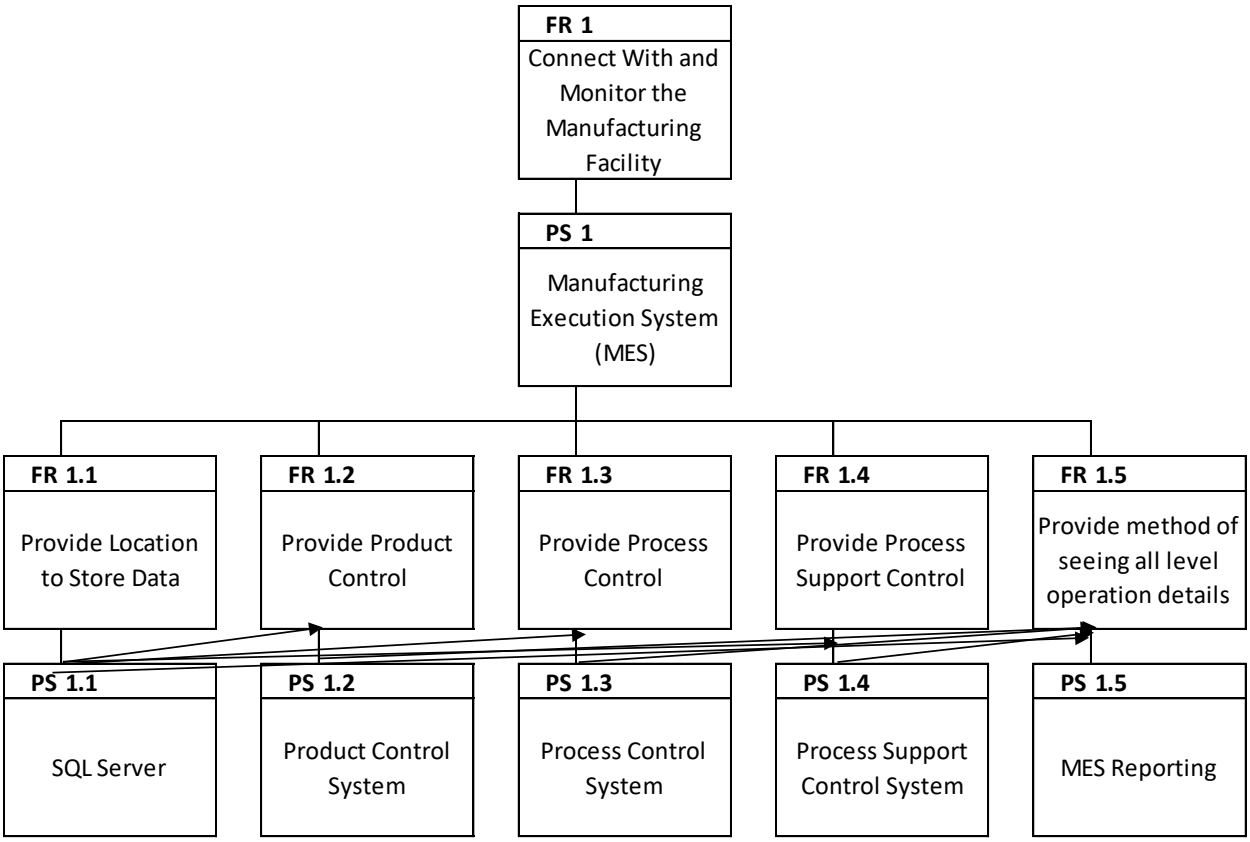


Figure 6.2 Second Level Decomposition Map

The first functional requirement, FR1.1 is to provide a location to store data that will be collected within the manufacturing facility. The solution that is to achieve FR1.1 is through a SQL server. There are many different methods that can be utilized to store data, however the decision was made to utilize a database and furthermore, SQL. Then moving to FR1.2, the requirement is to provide product control. Product control looks at controlling all items within the manufacturing facility that correspond to either a component, work in process or product. The solution that achieves this functional requirement is a product control system. As it will be explained in more detail, both inventory and traceability lay under the product control system. Additionally, FR1.3 has a requirement of providing process control. Process control includes giving control over all the processes within the manufacturing facility including the manufacturing processes and the supplement processes that provide support to producing a product. The solution of a process control system was established to achieve FR1.3 by providing control amongst the processes within the manufacturing facility. FR1.4 has a requirement to provide process support control

which is to provide support for all support processes that take place for a product to be produced. An example of a support process is maintenance which is needed for all manufacturing processes to continue running at their optimal level. The solution to achieve FR1.4 is a process control support system and will control all support processes to ensure quality and on time delivery. Then moving to the last function requirement in the second level decomposition map, FR1.5 states to provide a method of see all level operation details. This functional requirement provides the visibility to all information contained with MES. This information includes real-time and historical data among all product, process and product support elements. The solution to achieve this functional requirement is MES reporting.

It is key to note that the arrows on the figure determine path dependency where PS 1.1 is required for all FRs and PS1.2 is required for all except for FR 1.1. Figure 6.3 shows the design equation where the FRs are list to the side and the PSs on top and then the path dependency where they meet.

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \\ FR_{1.4} \\ FR_{1.5} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ X & X & X & O & O \\ X & X & X & X & O \\ X & X & X & X & X \end{bmatrix} \begin{Bmatrix} PS_{1.1} \\ PS_{1.2} \\ PS_{1.3} \\ PS_{1.4} \\ PS_{1.5} \end{Bmatrix}$$

Figure 6.3 Second Level Design Equation

With a complete level 2, the decomposition map can be continued to level 3. Figure 6.4 shows the decomposition map to level 3 and is really where the MES modules lay. The MES modules fall within the level 3 content with the customer requirements forming the Function Requirements for each module. The reason for pushing the MES modules to the third level is dependent on separating the process data from the product data. Process data is something that is not able to be taken off a product after the manufacturing process is complete while the product data is something that can be pulled off a product after the product has completed the manufacturing process. Instances of process data include the data collected during the manufacturing process and include items such as a load to install a component or a machining tool speed. In contrast, product data is something that can be taken from a part and include items such

as screw torques and finished dimensions. In looking at the third level decomposition map, PS 1.2.2 shows the inventory module while PS 1.2.3 shows the traceability module. With the inventory and traceability module falling under 1.2, they are included in the product control system.

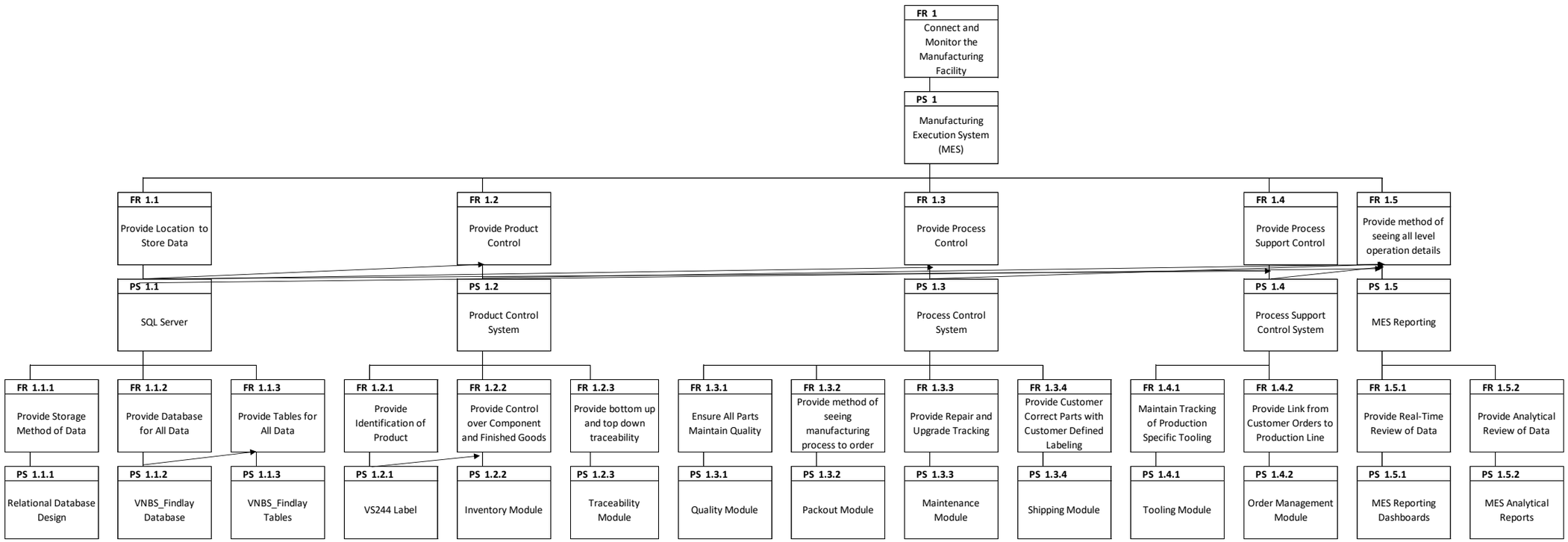


Figure 6.4 Third Level Decomposition Map

A deeper look into the third level decomposition map in Figure 6.4, there are many elements that need expounded upon. These elements will be expounded on in more detail so full comprehension can be gained. The flow of expounding will be from left to right on the third level as the previous two level's content is above.

The first section lays under PS 1.1 which has a physical solution of a SQL Server where the following are required of the SQL Server: FR1.1.1, FR 1.1.2 and FR 1.1.3. FR1.1.1 states to provide storage method of data and is achieved through PS 1.1.1 of a relational database design. A relational database design is a method of storing data flat which requires less hard disk space. The concept is using primary and foreign keys to link one element to another. FR 1.1.2 then states to provide a database for all the data and is achieved by PS 1.1.2 which is VNBS_Findlay database. This database is on the SQL server and is the central location for all MES table. Then diving a little deeper, FR 1.1.3 states to provide tables for all the data which is achieved by PS 1.1.3 and the VNBS_Findlay tables. The path dependency from PS 1.1.2 to FR 1.1.3 is due to tables falling under the database in which tables cannot be generated without the database.

Moving on, the next section is PS 1.2 and a product control system. For this physical solution to work, FR 1.2.1, 1.2.2 and 1.2.3 need to be in place. FR 1.2.1 has a functional requirement to provide identification of product and is relevant to the confines of the manufacturing facility. This functional requirement is then achieved by PS 1.2.1 and a VS244 label. A VS244 label is a company specific standard for what information needs to be defined in both human readable and scannable formats. Then once there is a VS244 label, the next functional requirement is FR 1.2.2 to provide control over component and finished goods. FR 1.2.2 is achieved by PS 1.2.2 and the Inventory Module. The inventory module will use the VS244 label and track components, WIP and products as they flow through the manufacturing facility. Lastly, FR 1.2.3 is to provide bottom up and top down traceability. FR 1.2.3 is achieved through PS 1.2.3 and the traceability module. The traceability module will keep track of all component information as it goes in WIP and then into a final product. All these functional requirements and corresponding physical solutions are required for the product control system.

For PS 1.3 and the physical solution of a process control system, there are functional requirements which include FR 1.3.1, FR 1.3.2, FR 1.3.3 and FR 1.3.4. FR 1.3.1 states to ensure all parts maintain quality. This functional requirement of maintaining quality is respective to all manufacturing processes across the manufacturing facility. Assurance of quality happens during

material transportation and processing. This requirement of maintaining quality is achieved through the PS 1.3.1 physical solution. The next functional requirement is held by FR 1.3.2 and is to provide a method of seeing a manufacturing process to order. This functional requirement allows the appropriate individuals within the manufacturing facility to see all manufacturing processes and to place an order for a product with a defined quantity and timing. To achieve this functional requirement, PS 1.3.2 has the physical solution of the pack out module which allows for the tracking of parts against an order. Furthermore, FR 1.3.3 calls to provide repair and upgrade tracking. This functional requirement focuses on equipment so that all equipment is tracked and maintained. In response, PS 1.3.3 is the physical solution to achieve FR 1.3.3 and is stated to be the maintenance module. The maintenance module will allow users to track equipment as it relates to repairs and replacements. Then the last functional requirement is FR 1.3.4 and to provide customer with the correct parts and with customer labeling. This functional requirement has elements that come directly from the customer and therefore require additional consideration. However, PS 1.3.4 and the shipping module allow for customer orders to be scheduled and shipped with the correct customer labeling. Therefore, all functional requirements established to achieve

After PS 1.3, the decomposition map moves to PS 1.4 and the process support control system. PS 1.4 requires only two functional requirements of FR 1.4.1 and FR 1.4.2. The first functional requirement is FR 1.4.1 and is to maintain tracking of production specific tooling. This requirement is a little differnet than seen above in FR 1.3.3 as FR 1.4.1 looks at the specific identification of all tooling and therefore provides all historical information as it relates. Examples of specific information include elements that went into the build up of a tool such as all tooling component traceability information along with assembly information such as a preset height. This functional requirement is achieved by PS 1.4.1 and the tooling module. The tooling module allows the tooling individuals to build up tools that will be used on the manufacturing lines and then when utilized to produce a product, provides full traceability. Then the second functional requirement is FR 1.4.2 and to provide a link from customer orders to the production line. This realy of information include standard products, prototype products or even component parts. To achieve this, PS 1.4.2 and the order management module work to gain customer orders and then properly assign them to the production line that will be fullfilling that customer order. It is in essence that the order management module is the line of communication from the customer to the individual locations with the manufacturing facility. It is therefore appropriate to say that these functional

requiremetns of FR 1.4.1 and FR 1.4.2 work to achieve PS 1.4 and the process support control system.

The last physical solution in level 2 of the decomposition map is PS 1.5 and MES reporting. There are many elements that can be included under MES reporting yet it is very important to continue with the decomposition method. In doing so, the first functional requirement under MES Reporting and PS 1.5 is FR 1.5.1 which is to provide real-time review of data. A real-time review of data allows the appropriate individuals at the manufacturing facility to respond to any types of issues that may arise before further harm can be done while also serving as a holistic overview. The way this functional requirement will be achieved is through PS 1.5.1 and MES reporting dashboard. A dashboard allows for specific information to be continually streamed for a real-time status. With moving away from real-time, FR 1.5.2 is also needed and relates to providing analytical review of data. This type of analysis requires historical data to build statistical models that will work to improve each manufacturing process. A good way to look at this is to vew the real-time information as a gross level reporting with alerts established while the analytical method helps to isolate the minute issues and provides a much more in depth look. For the analytical review of data, PS 1.5.2 serves to achieve FR 1.5.2 with MES analytical reports. These analytical reports require additional decomposition as to understand what statistical methods will be required in addition to provide customer specific inputs.

In going through the third level decomposition map, path dependency is essential to understand as there are inputs from one physical solution to another functional requirement. To better understand path dependency relative to the third level decomposition, Figure 6.5 shows this information via the design equation. Path dependency can be seen to lie between PS 1.1.2 and FR 1.1.3 in addition to PS1 1.2.1 and FR 1.2.2 while no other path dependency exists.

$$\begin{Bmatrix} FR_{1.1.1} \\ FR_{1.1.2} \\ FR_{1.1.3} \\ FR_{1.2.1} \\ FR_{1.2.2} \\ FR_{1.2.3} \\ FR_{1.3.1} \\ FR_{1.3.2} \\ FR_{1.3.3} \\ FR_{1.3.4} \\ FR_{1.4.1} \\ FR_{1.4.2} \\ FR_{1.5.1} \\ FR_{1.5.2} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} PS_{1.1.1} \\ PS_{1.1.2} \\ PS_{1.1.3} \\ PS_{1.2.1} \\ PS_{1.2.2} \\ PS_{1.2.3} \\ PS_{1.3.1} \\ PS_{1.3.2} \\ PS_{1.3.3} \\ PS_{1.3.4} \\ PS_{1.4.1} \\ PS_{1.4.2} \\ PS_{1.5.1} \\ PS_{1.5.2} \end{Bmatrix}$$

Figure 6.5 Third Level Design Equation

6.4 Inventory Module

As mentioned previously, MES was broken down into modules based upon a constraint of allowing for functionality based upon need. These modules were considered and arranged according to the customers and their customer attributes. Each module has their own set of Functional Requirements and physical solutions for successful completion. The first module that will be discussed in the inventory module.

6.4.1 Inventory Module Overview

A module of interest is the inventory module and has been well warranted due to great deals of inventory adjustments due to lost product. The customer for this module is the Logistics manager where the need was portrayed to provide control over components and finished goods. Control was needed at the manufacturing facility to control all components or what is also considered supplier parts to ensure that there is enough product in house to make production. The level of control on component parts entailed tracing all component parts to a specified location and providing information for when product was under a low limit. Then in moving to the product side, the need was to track all products manufactured off the production line to ensure that there were enough products to ship to our customer. This need of product control also entailed providing information when a product part number was under a low limit.

With all the customer needs on inventory, the inventory module seeks to achieve all customer needs. The inventory module itself includes the elements needed from the execution side to provide the proper information as a report to management. However, there are items that need to align with the MES hierarchy model to restrict individuals based upon user role. Therefore, both configuration and execution were utilized in the decomposition mapping process.

The inventory module is just a portion of the entire MES design but is worthwhile to explain. Figure 6.6 looks at the entire MES decomposition map while highlighting in green the portion as it relates to the inventory module.

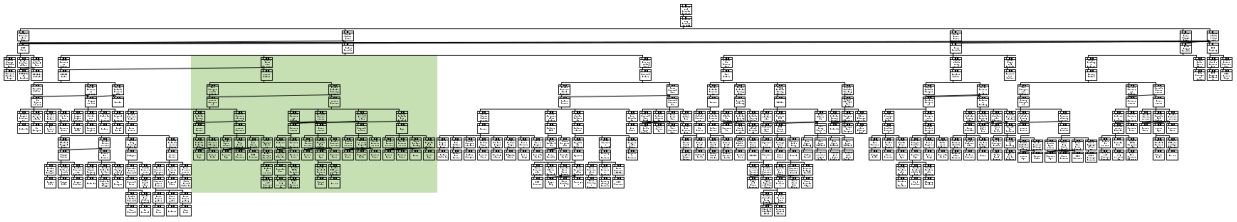


Figure 6.6 Inventory Module

6.4.2 Inventory Configuration

For a user to properly execute an inventory action, configuration of the inventory module needs completed including items such as part numbers, suppliers and more. In requiring configuration to perform execution, axiomatic design path dependency was utilized. Figure 6.7 shows the inventory module decomposition portion where the inventory module PS 1.2.2 requires the ability to configure (FR 1.2.2.1) and execute (FR 1.2.2.3) where path dependency is driven from configuration to execution which can be seen in Figure 6.8 as the design equation.

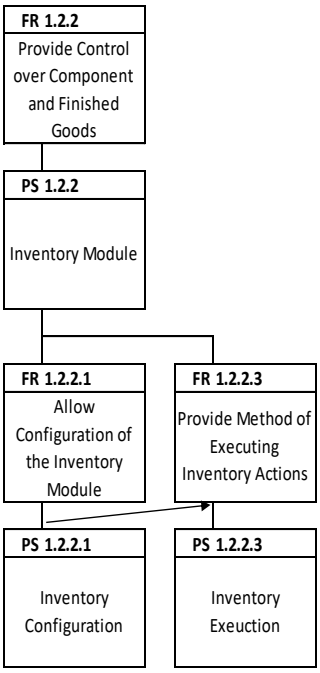


Figure 6.7 Inventory Module

$$\begin{Bmatrix} FR_{1.2.2.1} \\ FR_{1.2.2.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} PS_{1.2.2.1} \\ PS_{1.2.2.2} \end{Bmatrix}$$

Figure 6.8 Inventory Design Equation

Further decomposition was performed to understand the additional function requirements and physical solutions required for both the inventory configuration and inventory execution. Figure 6.9 shows the inventory configuration decomposition map when PS 1.2.2.1 of inventory configuration is expanded into Functional Requirements:

- Provide Definition of Products (FR 1.2.2.1.1)
- Provide Method of Defining Various Types of Inventory (FR 1.2.2.1.2)
- Provide Locations for Place Inventory (FR 1.2.2.1.3)

Each Functional Requirement is assigned a physical solution and is further configured to the point were no more branches could be formed.

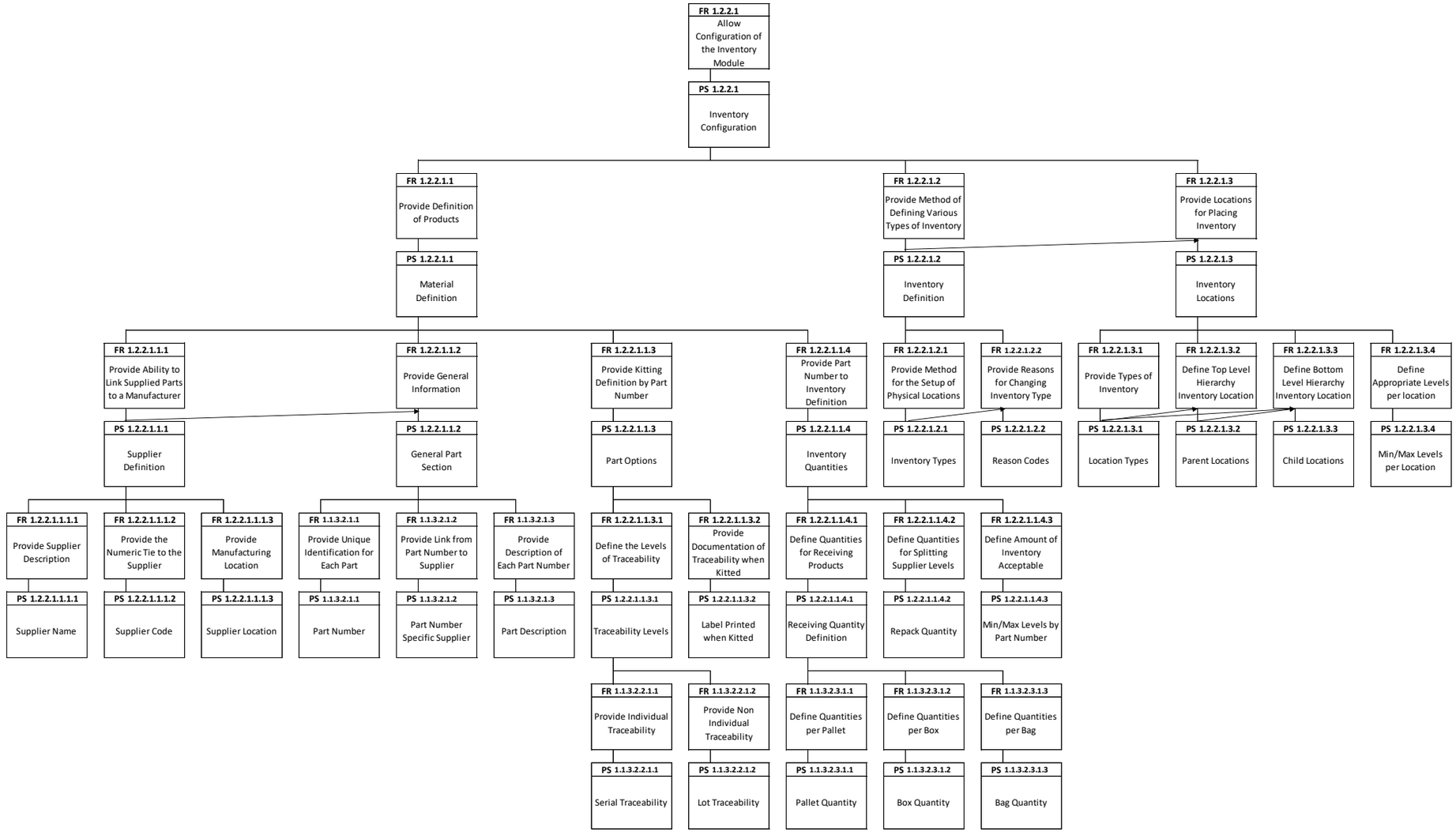


Figure 6.9 Inventory Module – Configuration

6.4.3 Inventory Execution

The inventory configuration decomposition mapping process includes all Functional Requirements and physical solutions that need to be defined before an inventory execution can be performed as previous noted by path dependency. Figure 6.10 shows the execution decomposition map for the inventory module. FR 1.2.2.2 states to provide a method of executing inventory actions in which PS 1.2.2.2 achieves using inventory execution. Additional Functional Requirements were driven from the inventory execution physical solution resulting in allowing for receiving parts, moving inventory around, bag from box removal and even inventory to non-standard amounts. Each Functional Requirement is then achieved through the following: receive inventory, move inventory, unpack inventory and split lot. The receive inventory solution allows for parts to be received when entering the manufacturing facility with the appropriate supplier information of part number, supplier code, batch number, pack number, quantity and supplier manufacturing date to a define location. Utilizing company standards, a label is required from all suppliers with the desired information in addition to a data matrix which allows for a single scan to record all information. Once parts are inside the manufacturing facility, there are multiple options that can happen to parts. The move inventory execution allows for parts to be moved from one storage location to another with the full quantity that was received. Some suppliers however will send in a certain quantity for a box with bags inside that will hold different quantity of parts where the requirement is to remove bags from boxes. The solution for removing bags from boxes is through the unpack inventory execution. Unpacking requires MES users inside the manufacturing facility to scan the box label, then scan the bag label and then the destination location. Then the last inventory transaction is to allow for non-standard quantity removal of parts from either a bag or a box. This execution will be utilized if parts are damaged or someone requires a part for some activity. For splitting a lot, a user is required to scan the source label, enter a quantity for how many to remove and then scan a destination for where the desired quantity is to go. As seen in Figure 6.10, there is path dependency especially from the high-level execution level where parts need to be received in inventory before they can be moved, unpacked or split.

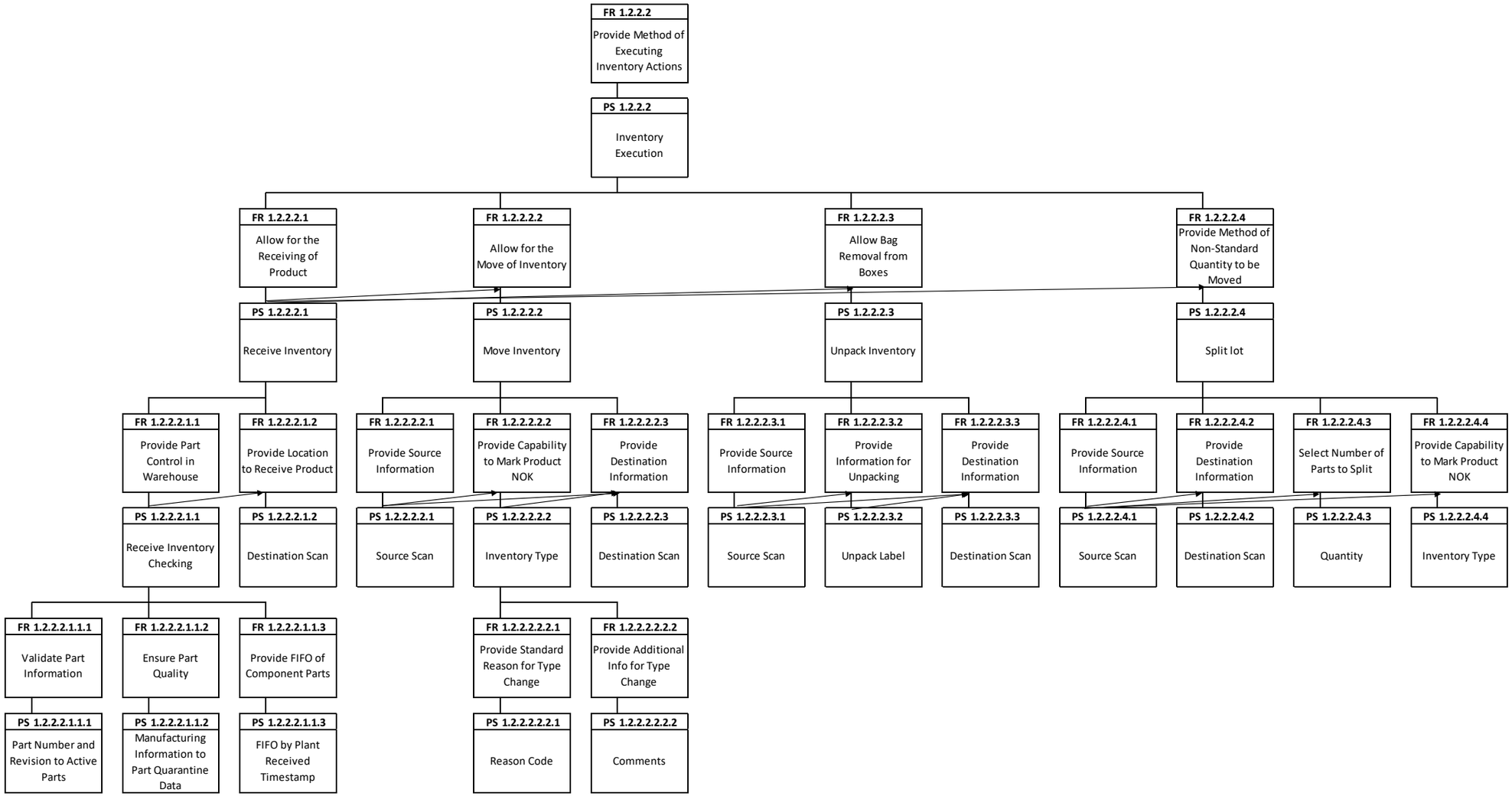


Figure 6.10 Inventory Module – Execution

6.4.4 Inventory Module Conclusion

In exploring the customer requirements for the tracking of both parts and product within the manufacturing facility, there was a need for a solution. With additional constraints and the design decision of making the system modular, the inventory module concept was created. Further breaking down the inventory module took shape of the configuration and execution portions. The process continued in alignment with CSD and Axiomatic Design to provide the appropriate elements for the system. These elements have all formed together to take shape of the decomposition map which provides the Functional Requirements and Physical Solutions for the overall system. This decomposition map is great and provides a ton of benefit in systematic thinking, however is worth very little solely in concept. Further steps in the CSD process will show the decomposition map in action as it is implemented to see just how robust the Physical Solutions are in achieving each Functional Requirement.

6.5 Traceability Module

It is very crucial to understand and have historical records of what parts were built into a final product. As with many if not all tier one OEM automotive manufacturers, the traceability of both parts used to make a product and the product itself are critical. Therefore, the traceability module within MES will be broken down and discussed in a systematic method. The traceability module will consist within the MES hierarchy that has already been explained and furthermore show the benefits that will arise from the systematic design.

When looking into collecting and maintaining traceability information, many fronts are required to be reviewed for compliance. The various fronts to be reviewed include:

- Original Equipment Manufacturer (OEM) Specific
- Industry Standards
- Federal Safety Requirements

Each item as listed above have their own unique requirements in addition to some overlap between entities. However, before each element is broken down, it is important to understand what it really means when traceability is talked about. Traceability allows for either a part or a product to be understood to its full intent. Traceability can be found to be defined as the “ability to trace the application, location, and/or history or item by means of recorded data” [What is traceability?,

n.d.]. This means that at any point within the lifetime of the product, the ability exists to pull up all process information and product information. The process information would include items such as when the part was manufactured, the specific values that went into manufacturing the part and much more. To contrast this, the product information would allow for a part to be pulled and a list generated for all the parts that were used to manufacturing the product. Yet for all of this to happen, there is a requirement that the product itself must have an identifiable mark indicating the starting point for going back into history to find all information. With this new understanding of what traceability means, the entities can now be gone through to see their implications on the manufacturing facility.

When it comes to OEMs, each OEM has their own requirements when it comes to traceability, yet the baseline tends to be similar. It is only the additional requirements that may differ such as how long to maintain traceably records or the level that traceability is required. Some OEMs only require traceably to a manufacturing day while other OEMs require traceability at a serial level. In addition to OEMs, industrial standards require an additional set of requirements and within the automotive industry, industrial standards flow from both the Automotive Industry Action Group (AIAG) and International Automotive Task Force (IATF). AIAG have minimal traceability requirements and state that manufactures need to maintain traceability as their customer dictates. IATF takes this a little further and requires manufactures to adhere to core standards and customer specific requirements. Furthermore, IATF requires bi-annual certification of compliance where AIAG does not. In addition to OEM and industry standards, the next item are federal standards. The federal standards aim to maintain safety for all consumers of vehicles and thus say little about traceability. However, Federal standards require that all safety critical parts need physical traceability that will last the lifetime of the part.

As the above mentions, traceability is highly critical in the automotive industry and even more so with safety critical products. OEMs have their specific requirements while automotive industry tack onto those requirements and finally Federal standards tack on additional. It is therefore essential that manufactures comply with all standards.

6.5.1 Traceability Module Overview

Like the inventory module, another module that will be evaluated and discussed is the traceability module. The traceability module stems from the customer requirement of providing traceability of both parts and products. For the sake of this thesis, the term part has been synonymous with components parts received from suppliers while the term product is anything that is manufactured within the manufacturing facility. Thus, the traceability of parts include understanding what specific component parts went into a product. The specific component parts include both part number identification along with supplier information such as the manufacturing date and lot date. In looking at the traceability of a product, traceability includes understanding defined process parameters that were used to manufacturing the product in additional to tracking when and what customer that product was shipped to.

As depicted in Figure 6.11, the traceability module was derived as a Physical Solution for the Functional Requirement of providing bottom up and top down traceability. In attempts to achieving the bottom up and top down traceability, both the parts and product need to be tracked. The traceability module includes a concept like configuration and execution which was used with the inventory module. The configuration portion of the traceability module includes a Functional Requirement of providing definition for each manufacturing product in which the Physical Solution of product definition is to achieve. In moving to the execution side, the Functional Requirement was defined to collect traceability data where the Physical Solution states traceability execution. Figure 6.12 then shows the design equation for the traceability module and is indicative of the setup needing to be complete before execution can occur.

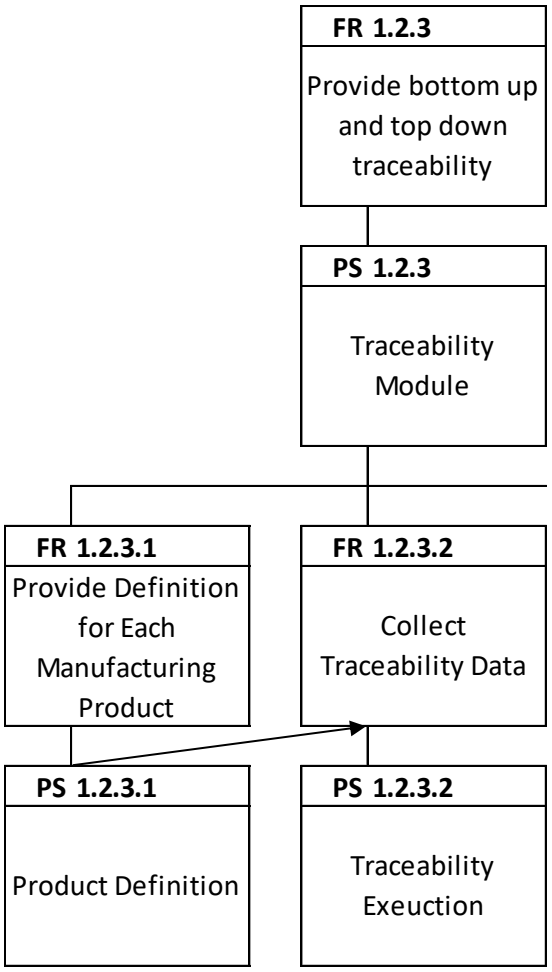


Figure 6.11 Traceability Module

$$\begin{Bmatrix} FR_{1.2.\mathbf{3}.1} \\ FR_{1.2.\mathbf{3}.2} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} PS_{1.2.\mathbf{3}.1} \\ PS_{1.2.\mathbf{3}.2} \end{Bmatrix}$$

Figure 6.12 Traceability Module Design Equation

6.5.2 Traceability Module – Product Definition

The first step in the traceability module as found in PS 1.2.3.1 on the decomposition map is the product definition. The product definition includes all relative information to a product that is to be manufactured by the manufacturing facility. Figure 6.13 shows the product definition portion of the decomposition map with subsequent decomposition levels. As for the production definition Physical Solution, the following are included: general information, bill of materials, production route and quality route. The general information for a product includes items such as the product number and revision, a description, how many parts per container and much more. This information is important as it will be used at later points within the process. Moving on from the general information, the next item is the Bill of Material or BOM. The BOM includes all the

component parts and sub-assemblies that go in the product. Then the Production Route is required to be setup which tells the processes for which the product can go through. The production route includes the operations, the dunnage locations and the definition of the frequency of part testing. Once the production route has been defined, the quality route needs to be defined. The quality route defines the process for which a part must go through and pass for all other products to be shipped.

Additionally, the product definition allows the user to select a set of tags that provide information for all process data that is to be collected. The process data tag list of PS 1.2.3.1.3.1.3 attempts to achieve the Functional Requirement to define the process data to collect at each operation. The formation of the process data tag list fall under the manufacturing process creation where tags from the manufacturing line PLC are made available to collect. There are two methods of collecting the process data which includes a direct connection to the manufacturing line PLC and the use of an OPC UA connection in which the manufacturing line PLC updates network available tags. These two methods are used based upon the equipment capabilities and would be applicable to new or pre-existing equipment.

As it seems as is surely a lot of informant to fill out, the product definition is the key step that needs to be taken to understand what goes into a product, where the product can run and what additional work needs to be completed for the assurance of quality. The traceability module hinges off this information and is required to confirm product that is manufactured and its adherence to the specifications.

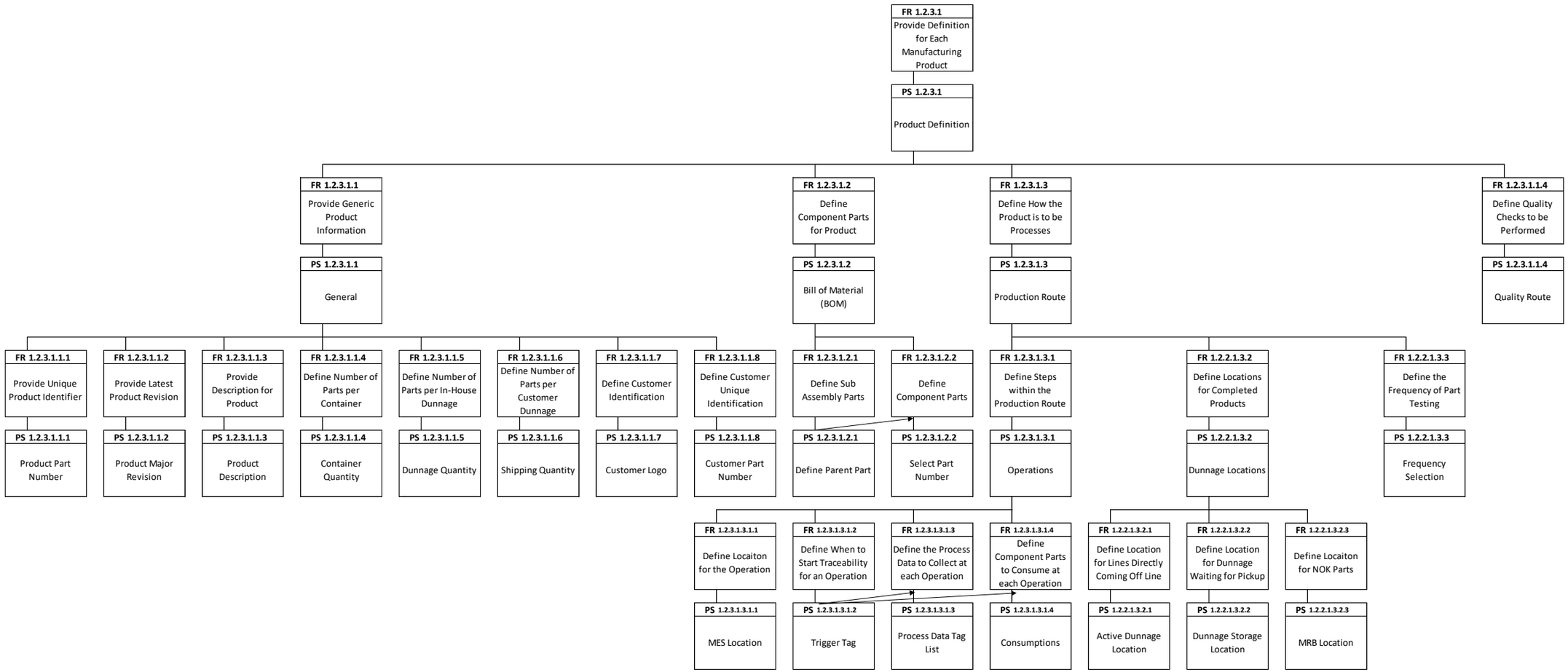


Figure 6.13 Traceability Module – Product Definition

6.5.3 Traceability Module – Execution

Since the setup portion of traceability has been completed, it is essential to understand how the setup items will be utilized. The utilization of the setup items take shape in the execution portion of the traceability module. The execution side of traceability allows for the collection of data once the defined trigger is established. Furthermore, the traceability holds valid for each product as defined in the traceability setup and allows for multiple triggers to be established on different manufacturing lines for the collection of data. This means that if there are three manufacturing lines running a product that has all setup information established, then there will be three triggers allowing for the collection of all manufacturing line data independent of each other. The collection of traceability data is essential to ensure that all products ultimately shipping out the door and to a customer, is fully known by the system.

As for the execution of traceability, Figure 6.14 shows the decomposition map with the Functional Requirement of 1.2.3.2 stating to Collect Traceability Data while the Physical Solution to achieving that FR is the Traceability Execution System. The traceability execution system includes items of determining the start point of traceability of each serialized product, establishing the production route, collecting the process data and then collecting the product data. The first item is FR 1.2.3.2.1 which is to determine the traceability start point for each serialized product which has PS 1.2.3.2.1 of serial number trigger monitoring. As it was explored in the product definition, the trigger point for traceability start is continually monitored and when a new serial number is introduced into the manufacturing process, the traceability process is started.

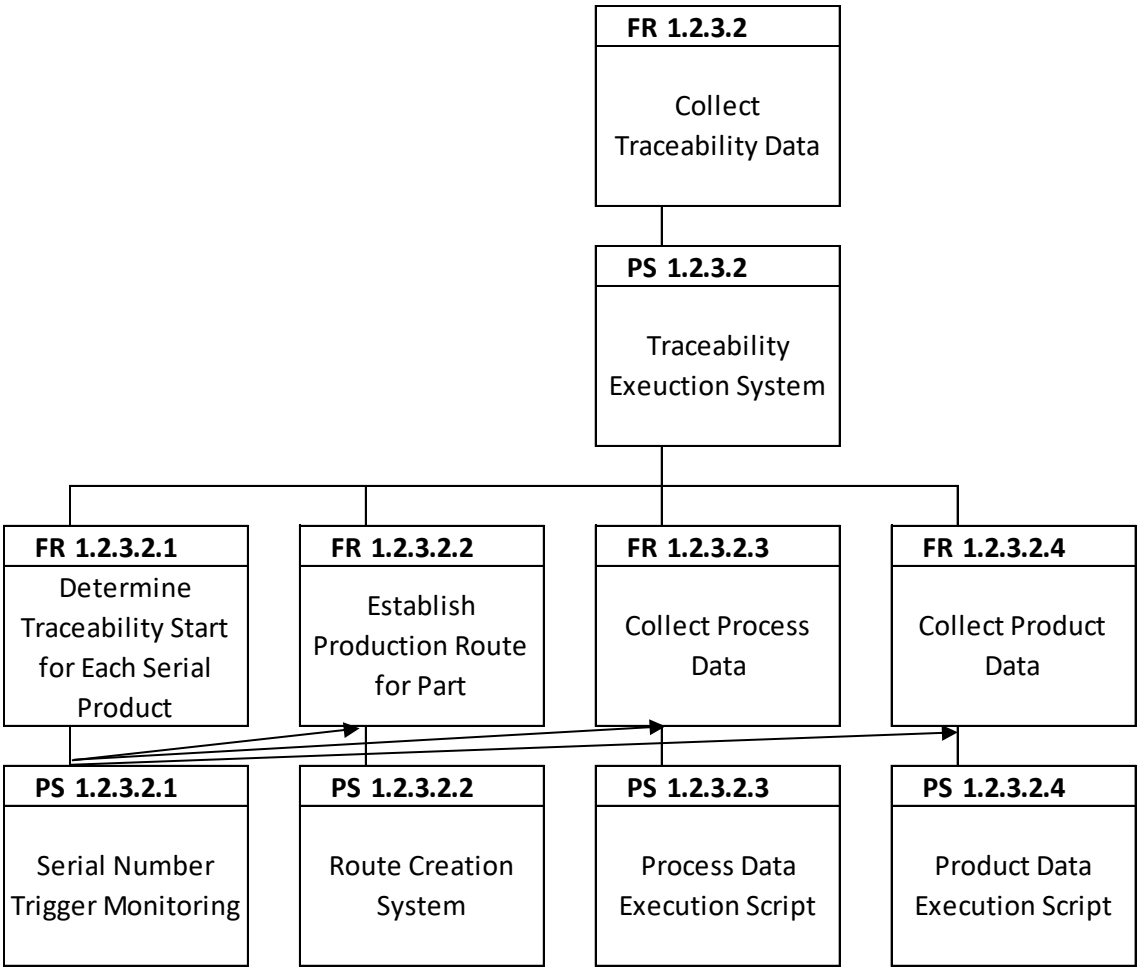


Figure 6.14 Traceability Module Execution

In addition to the decomposition map for the execution of traceability, the path dependency also needs to be understood to understand what is required for each functional requirement to be achieved. For the execution, Figure 6.15 shows the design equation where PS 1.2.3.2.1 is required for all functional requirements via path dependency. This path dependency is evident as the physical solution is the trigger point for the starting of traceability. If the start of traceability is not kicked off, then the following Functional Requirements cannot be achieved by their Physical Solutions.

$$\begin{Bmatrix} FR_{1.2.\mathbf{3}.2.1} \\ FR_{1.2.\mathbf{3}.2.2} \\ FR_{1.2.\mathbf{3}.2.3} \\ FR_{1.2.\mathbf{3}.2.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ X & O & X & O \\ X & O & O & X \end{bmatrix} \begin{Bmatrix} PS_{1.2.\mathbf{3}.2.1} \\ PS_{1.2.\mathbf{3}.2.2} \\ PS_{1.2.\mathbf{3}.2.3} \\ PS_{1.2.\mathbf{3}.2.4} \end{Bmatrix}$$

Figure 6.15 Traceability Module Execution Design Equation

6.5.4 Traceability Module Conclusion

In exploring the customer requirements, the customer requirement of wanting traceability from a product and part level formed to a functional requirement of providing bottom up and top down traceability. As it was explored with respect to the traceability portion of the decomposition map, there are many branches that need taken into consideration for the traceability module to be fully complete and align with CSD and Axiomatic Design. Therefore, the Functional Requirements and Physical Solutions were systematically formed with taking consideration for traceability configuration and traceability execution. With implementation remaining the next step after the development of the decomposition map, further steps in the CSD process including implementation, will show the decomposition map in action and therefore will show the robustness of the Physical Solutions achieving the Functional Requirements.

6.5.5 Decomposition Map Conclusion

As it was already shown, the decomposition mapping process requires consideration to ensure that all elements are adequately covered, Functional Requirements are properly formed, and the Physical Solutions are derived to achieve those Functional Requirements. This process of going through the decomposition and systematically developing Physical Solutions for each Functional Requirement was performed for both inventory and traceability. The decomposition maps for both inventory and traceability were comparable with establishing segment for configuration that would be path dependent to execution. The proper elements need to be defined at the configuration stage before any element can be acted upon during the execution stage. Furthermore, the splitting up of configuration and execution allow the restriction of users based upon credentials. It is therefore fitting to state that a limited number of individuals will have access to the configuration portion while many more may have access to the execution portion. For the

inventory module, the roles of inventory admin and materials admin are allowed access to the configuration portion while the execution portion is limited to an inventory user and inventory super user. By establishing these restrictions based upon roles and then assigning individuals to specific roles, assurance can be had that only the proper people are performing their proper tasks.

In conclusion, there are many elements that are required of MES and only the inventory module and traceability modules were focused on in this chapter as it relates to the decomposition map. However, it was seen that the decomposition map hinges off the relationship of Functional Requirements and Physical solutions. Functional requirements are utilized at each level of the decomposition map with the corresponding physical solutions assigned to achieve each functional requirement. With this method of decomposition, the overall system can be defined systematically so that it may become robust. As with anything, small tweaks may need to be made to the decomposition map in the future to continue its robustness as the external environment may change. This systematic approach was applied to MES and was found to be beneficial when going through the multiple levels of decomposition.

7. IMPLEMENTATION OF THE DECOMPOSITION MAP

7.1 Implementation Overview and Process

In having a complete decomposition map and standard work, the next process is the implementation of the decomposition map. The implementation process is essential as it will not only provide essential feedback, it will drive operations with respect to MES once all individuals are exposed to the new system. For the implementation of the MES decomposition map, many individuals will be affected as MES will be the life line for manufacturing. If the implementation process causes many individuals to be taken back, then the system will need to overcome many challenges for acceptance. Implementation needs to occur in a systematic manner with starting at the bottom left of the decomposition map and working left to right and bottom to top. For the segregation of MES, there are various modules at different branches of the decomposition map. Therefore, implementation will occur one module at a time.

To supplement the implementation of the MES decomposition map, a value stream map will be utilized. A value stream map details all process steps within a defined scope and provides important information needed at each step in the process. In short, a value stream map shows the flow of a part and information. A value stream map will be utilized for the implementation of the decomposition map so that all the appropriate information can be captured at the correct process step and to ensure that all process steps are completed in their correct sequence. Therefore, it would be evident to show a value stream map for the both the inventory and traceability module. Both value stream maps will lay out all process steps throughout the manufacturing facility to aid in the proper implementation of the decomposition map.

The first module for implementation is inventory. From the decomposition map, the inventory module is a physical solution to achieve the requirement of providing control over components and finished goods. Further decomposition shows that the inventory module will be further broken down into configuration and execution. In support of the inventory module's need for configuration and execution, Figure 7.1 shows the value stream for inventory which includes both execution and configuration.

The left portion of the value stream shows configuration portion of the inventory module while the right portion of the value stream shows the execution portion of the inventory module.

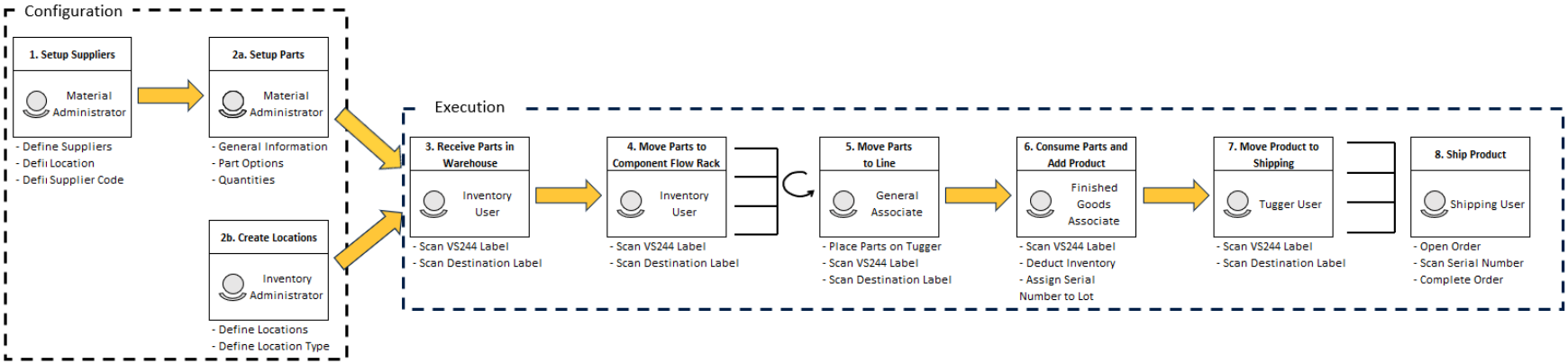


Figure 7.1 Value Stream Map – Inventory

7.2 Inventory Module - Configuration

For the inventory module to be successful and furthermore, to even start, the configuration portion needs to be completed. The decomposition map showed path dependency between the configuration and execution under the inventory module. The left-hand side of the value stream map in Figure 7.1 shows configuration needed for the inventory module. The configuration portion has two flows that need to be completed with the first flow setting up of suppliers and parts while the second for the creation of locations. The first flow does have path dependency and requires suppliers to be established before parts can be inputted. This requirement is due to the parts portion requiring a selection for a supplier. For the setup of suppliers, step 1 is to define the supplier name, step 2 is to define the supplier's location and step 3 is to input the supplier code. The supplier code will be key as this will be the information gathered from all supplier labels. Once suppliers are setup, parts can then be setup. To set up parts, the starting point lies under the general portion where the supplier is chosen, and a part number and part description is giving. The next step is for part options where the part is defined a traceability level of lot or serialized and if a label is required during a future process. Then the last step in the setup of parts are the inventory quantities. The inventory quantities are where pallet, box and bag quantities are defined in addition to the inventory thresholds. With respect to the second flow, locations are required throughout the manufacturing facility. Step one for setting up locations is to create a location name in the correct hierarchy position as deemed necessary by the individual inputting the information. Once this new location name is created, the user is then required to select an inventory type that can go to that location. Inventory types are static within MES where standard means good parts, MRB means suspect and scrap being no good parts. These inventory types will be utilized in the future to restrict the incorrect inventory types.

7.2.1 Inventory Configuration – Suppliers and Part

For Inventory Configuration, both the suppliers and the parts need to be created. It is the materials administrator who is responsible for the setup of both suppliers and parts. For the establishments of suppliers and parts, there are steps that need to be completed. In looking at the supplier creation, the steps include the setting up the supplier name, the supplier location and the

supplier code. Figure 7.2. shows an example of setting up a supplier with each date populated in each field.

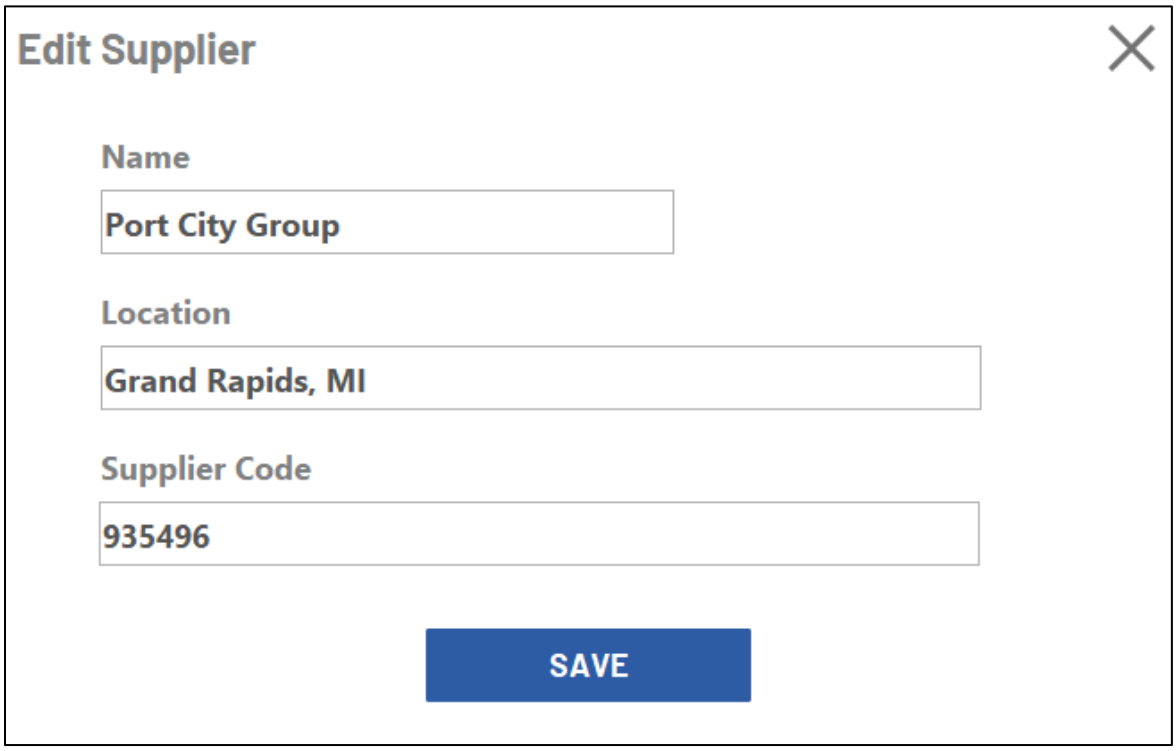


Figure 7.2 Supplier Configuration

Once the supplier is setup, the parts need to be setup and is the next step in the process. The setup of parts is a little more in depth than the setup of suppliers. The steps of setting up parts include a general potion, part options portion and an inventory quantities portion. Figure 7.3 shows the general portion of setting up parts. The general portion requires the selection of a supplier that is already in the system, the part number to uniquely identify parts and a description for each part.

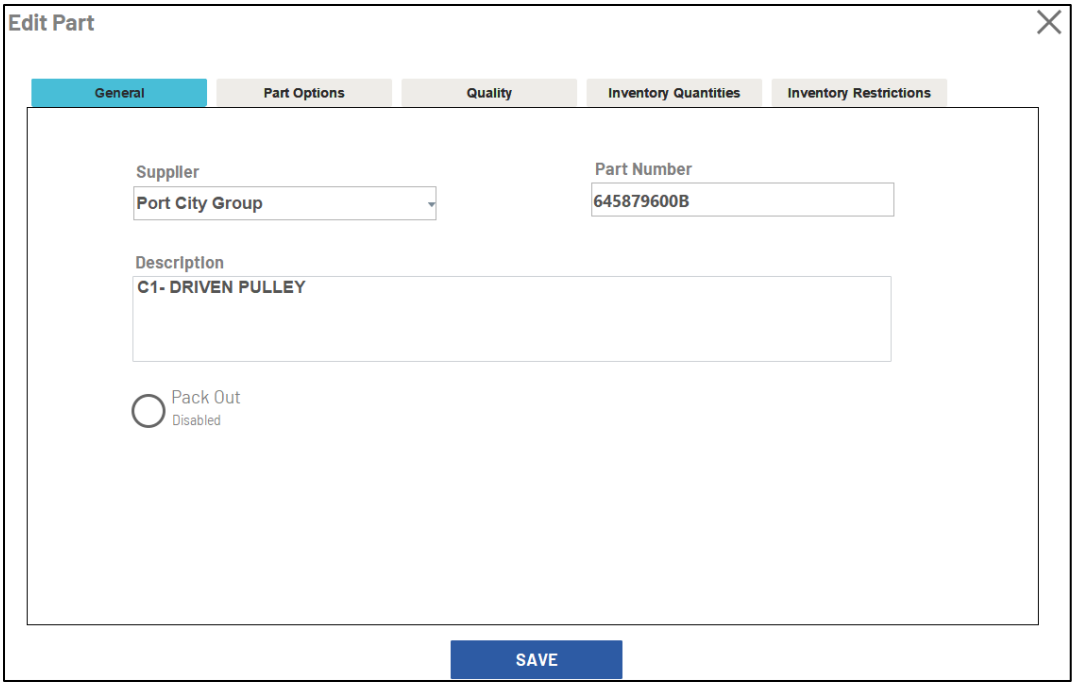


Figure 7.3 Part Configuration – General

The next step in setting up a part is the part options portion. The part options portion allows the materials administrator to first setup the traceability level of the part and then if a label should be printed to travel with the parts for identification. Figure 7.4 shows a part that has selected traceability by lot and to print a label when the part is kitted; or is separated from the original lot based upon quantity size.

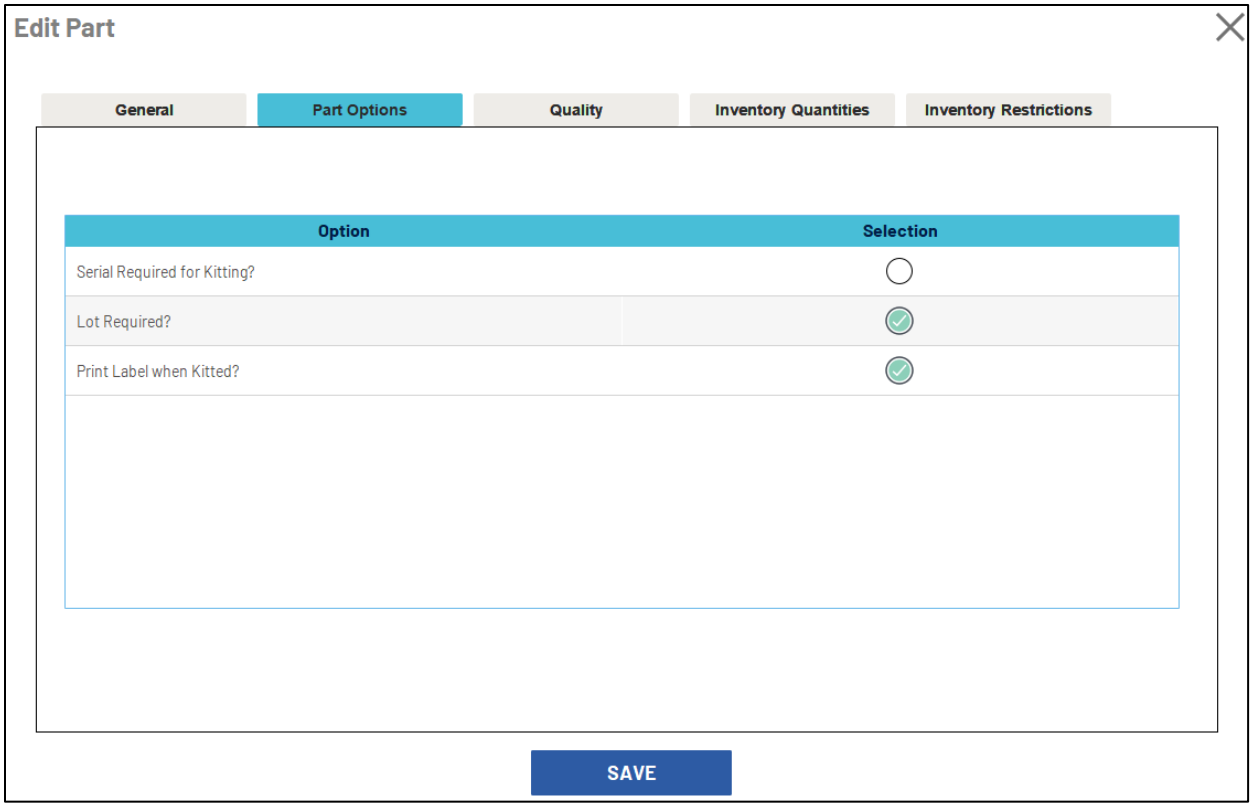


Figure 7.4 Part Configuration – Part Options

Then the last step to be completed when setting up a part is the inventory quantities portion. The inventory quantities portion of the part setup defines the quantity of parts to be received, the ability to repack and inventory levels. Figure 7.5 shows an example of the inventory quantities portion of setting up a part. The part was given receive quantities of 90 pieces on a pallet, 30 pieces in a box and 30 pieces in a bag. These levels will be used later to ensure that the quantity of parts received meet the already established requirement. Therefore, the inventory levels allow for checking the suppliers inventory. Furthermore, the example provides the ability to repack with a default quantity of 1 piece. The ability to repack allows for parts already in the house to be split to different quantities based upon the need. Then finally the inventory quantities portion of setting up a part includes the inventory thresholds. The min level is for the minimum level of inventory while the max is for the maximum level of inventory. These levels allow for the manufacturing facility to either order parts or to hold off on ordering parts. Too little of inventory will not allow the manufacturing lines to run as often as they should

while too much inventory includes a lot of waste such as space to store the parts and transportation of the extra parts.

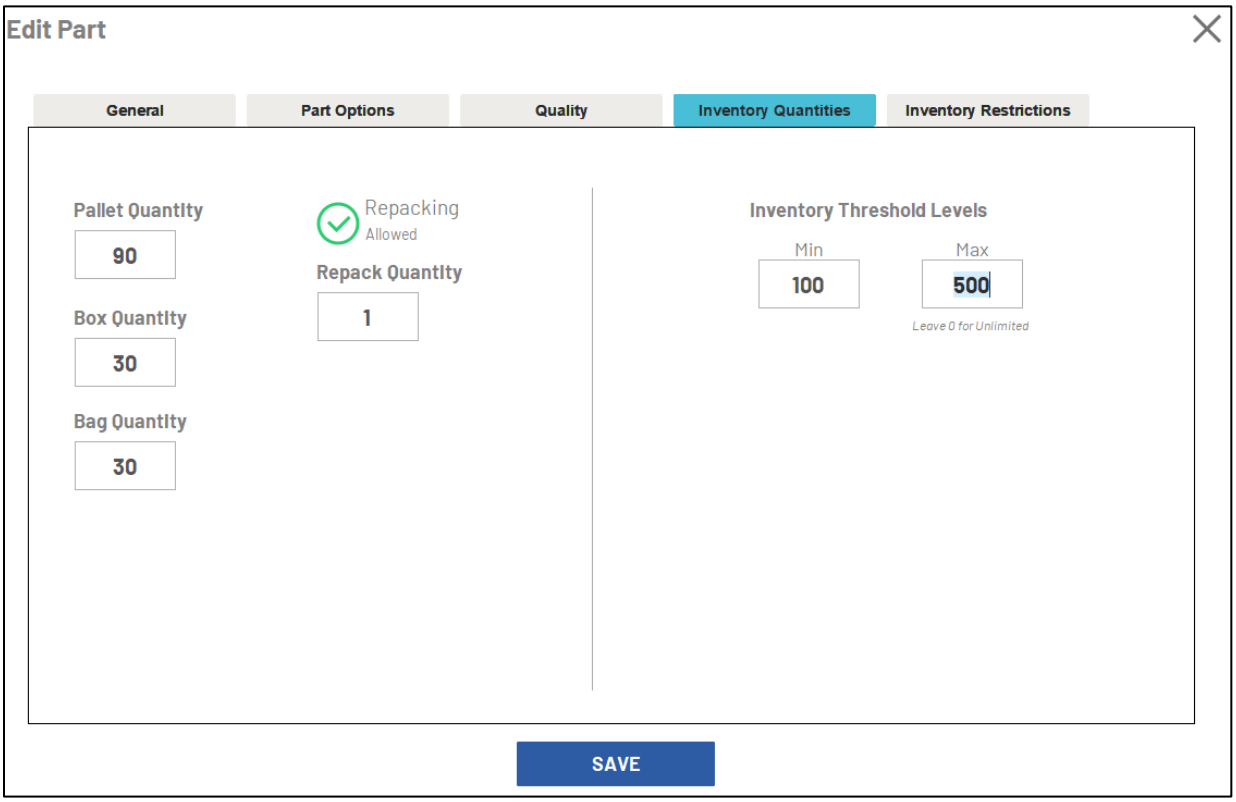


Figure 7.5 Part Configuration – Inventory Quantities

As it can be seen, the inventory configuration for both suppliers and parts provide the appropriate information to be used later in the value stream. Both suppliers are parts are essential to have and allow for the receipt of parts into the manufacturing facility.

7.2.2 Inventory Configuration – Locations

As the setup of suppliers and parts were essential, there is still an additional flow that needs to be completed before the execution of the inventory module can take place. Locations need to be setup so that when product is received and moved, the location for where those parts currently reside is known. The configuration of locations is a task for the inventory administrator. It is the inventory administrator's responsibility to setup all locations after determining what type of resolution is desired. The resolution to tracking inventory to locations can be as finite as what is setup in the system. Figure 7.6 is an example of location TA01 being setup in configuration. The

location name is TA01 which represents some physical location within the receiving warehouse and has been given a location type of inventory location so that parts can be moved to that location.

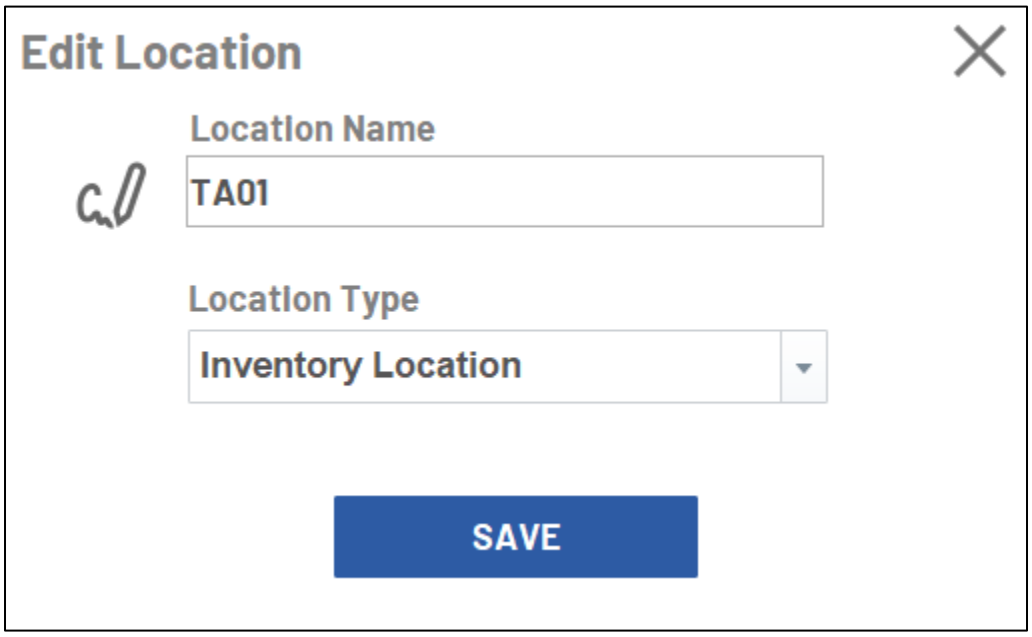


Figure 7.6 Location – TA01

Furthermore, the hierarchy was built for the receiving warehouse with additional locations to TA01. Figure 7.7 shows some of the receiving warehouse locations ranging from TA01 to TA05.

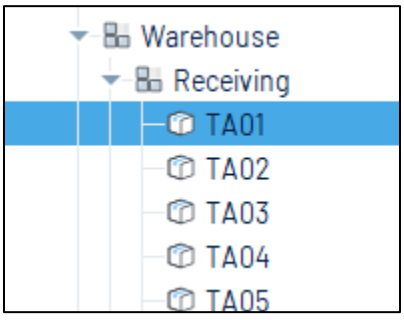


Figure 7.7 Location – Receiving Structure

For the configuration of locations, there are many steps that need completed. The steps include setting up every physical location where parts and products will be stored, including locations on the manufacturing line. This concept of setting up locations can be tedious but is required in the inventory execution and reporting.

7.3 Inventory Module - Execution

With having everything setup from the configuration side of the inventory module, the next processing the value stream is the execution. The execution portion of the inventory module does require some path dependency. For any inventory transaction to occur, the parts must first be received in the system.

7.3.1 Inventory Execution – Receiving

The first step in receiving parts includes taking a container of parts that were physically received by a supplier and then scanning the label received to place it into the system. Within the receive inventory screen of the inventory module, the user would see what is presented in Figure 7.8 and would wait for the users input of information.

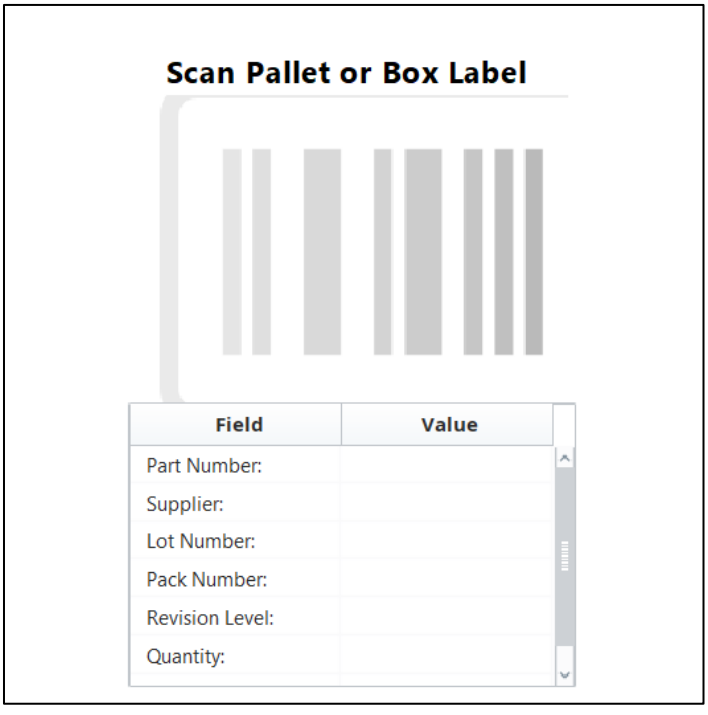


Figure 7.8 Recieve Inventory Before Scan

Once the user scans a label, there are controls in place that perform validation on the label as it was received. The three main validation steps are for the part number, supplier code and the pack number with part number combination. The part number is validated for whether it is currently active in the system as defined in the configuration portion of the inventory module. If the part number is not active or not present within the system, the label is rejected, and error presented to the user. The next control element is validation on the supplier code. This validation is matching the supplier code on the label matches the assigned supplier code for the part number in the inventory configuration. Lastly, another control element is the part number and pack number combination validation. To create a completely unique label for all instances, the part number and pack number combination need to be unique and therefore not already present in the database. If a label were to be received with a matching combination of part number and pack number, an error would be prompted to the user. This duplicate label error would also be represented of trying to receive a label that is already in the system. If the scanned label information passes all validation, the information is then parsed out into Part Number Supplier, Lot Number, Pack Number, Revision Level and Quantity. Figure 7.9 provides an example of a part being received and the information being parsed out.

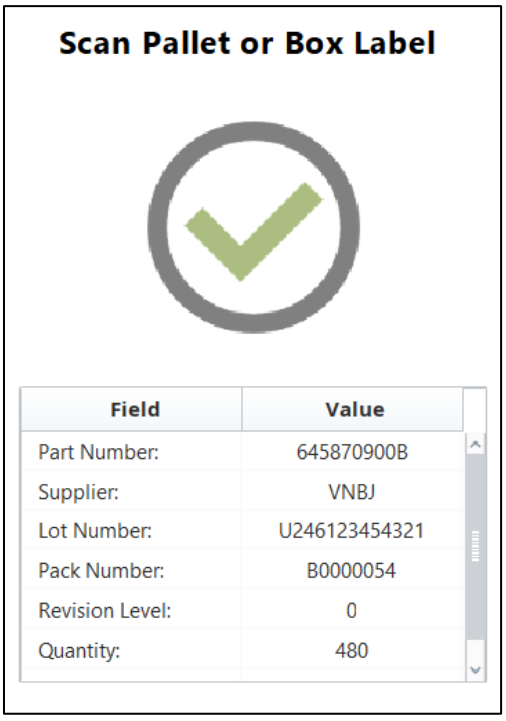


Figure 7.9 Recive Inventory After Scan

Figure 7.10 shows the entire screen after the scanning of a label where the user has the ability change the inventory type and assign the parts to a defined location. The default inventory type is standard which allows the parts to be moved into inventory. The user also has the option to change the inventory type to MRB which restricts the locations for which the parts can be received to. Once the user is set on the inventory type, they would then scan the location for where the parts are physically received to and would populate the destination location.

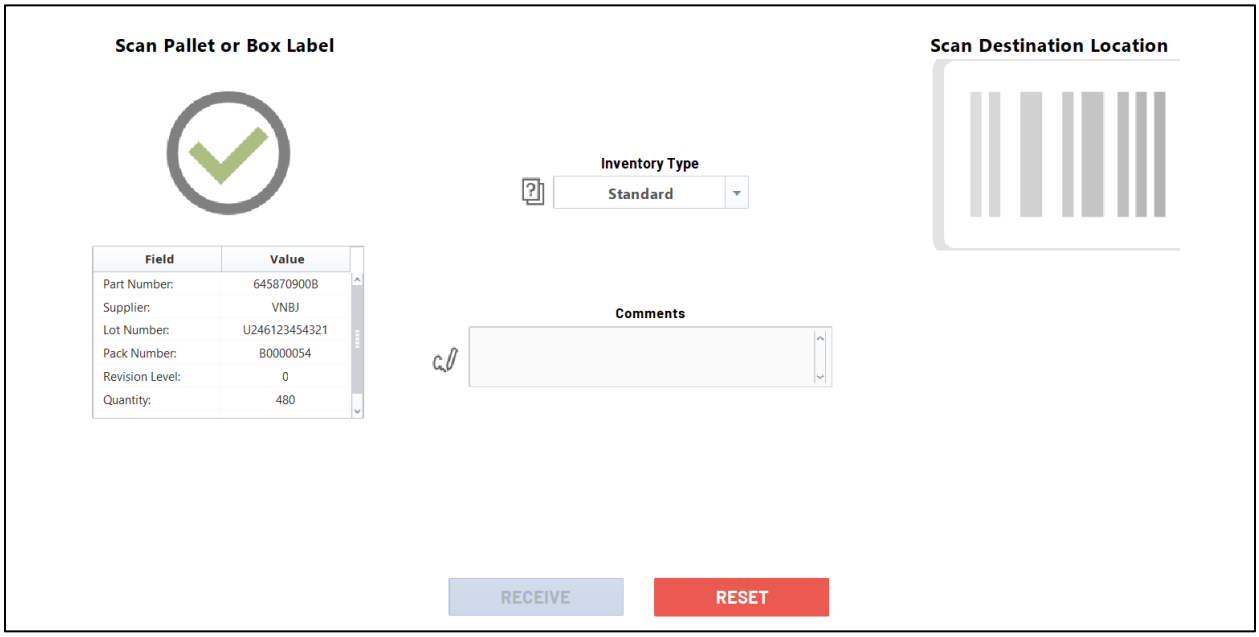


Figure 7.10 Receive Inventory

With the parts already have been received into inventory, the parts will need to be moved to their respective positions. Figure 7.11 shows the move inventory screen where the user scans the source label, defines the inventory type and then scans their destination location. The source label is any part that has already been received into inventory. The inventory type defaults to the current inventory type as assigned to that part as scanned in the source label. The user then has the ability of changing the inventory type to MRB which requires comments and a reason for why the inventory type was changed. Then when the user scans the designation location, validation occurs in the background to ensure if the parts can move or not. The biggest validation is checking the inventory type to see if the destination location allows that inventory type. A part with MRB inventory type will not be allowed to move to a standard only inventory type and vice versa. In

addition, the move inventory will not allow an inventory user to move apart from MRB to standard and is required from someone with the super inventory user. All this validation places additional control on the system and prevents unwanted actions to be performed.

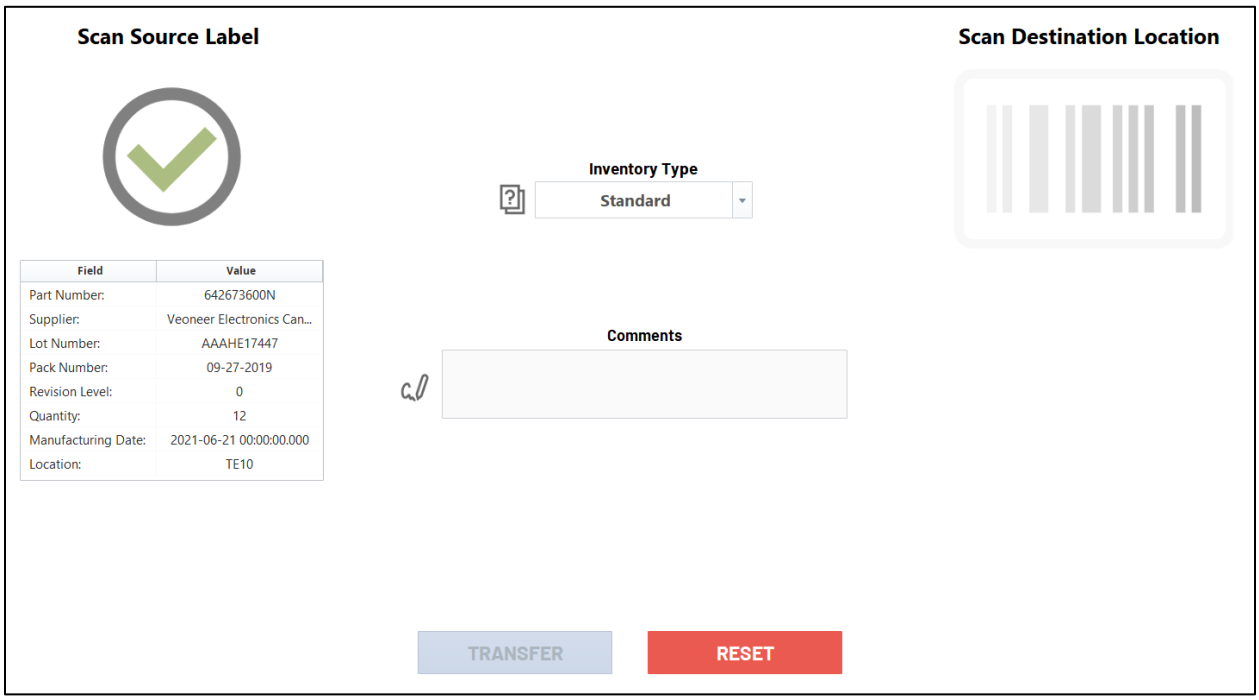


Figure 7.11 Move Inventory

With the talk of inventory and the controls that are in place, the inventory module helps to provide structure for control as it relates to the receiving of component parts and the transfer of component parts, work in process (WIP) and even finished goods. The controls that are established within the inventory module were established around the various functions to ensure that all information received is accurate and to the desired level of resolution. Accurate information is truly the goal of the inventory module, if not all MES, and is essential in providing control over the manufacturing facility. As it was examined before, the physical cost of not providing control over inventory can be massive and lead to long lasting effects. Therefore, the inventory module within the system of MES is aimed to control inventory throughout the manufacturing facility.

7.4 Implementation of Traceability Module

Outside the scope of the inventory, the next area that this thesis will explore is that of traceability. Traceability is one item that is essential to have but is not something that will be used regularly. Traceability provides the most effect when something occurs, and the range of that effect needs to be determined at a finite resolution. These occurrences are primarily experienced when a part is shipped to a customer with something that doesn't meet the intended design specifications. However, traceability can also be used to fine tune a process by isolated change points resulting in less scrap and greater operating efficiencies. Whatever the use of traceability, there are steps that need to be taken to ensure that correct data is collected.

Before stating the traceability module, it is beneficial to look at the overall process through a value stream map. Figure 7.12 shows the traceability value stream map that includes the first step of configuration before the execution process can be performed. The configuration process includes providing the product definition with sub steps while the execution process includes the steps of triggering off of a serial number, creating a route, collecting process data and then collecting product data. All steps are essential for the overall operation of traceability.

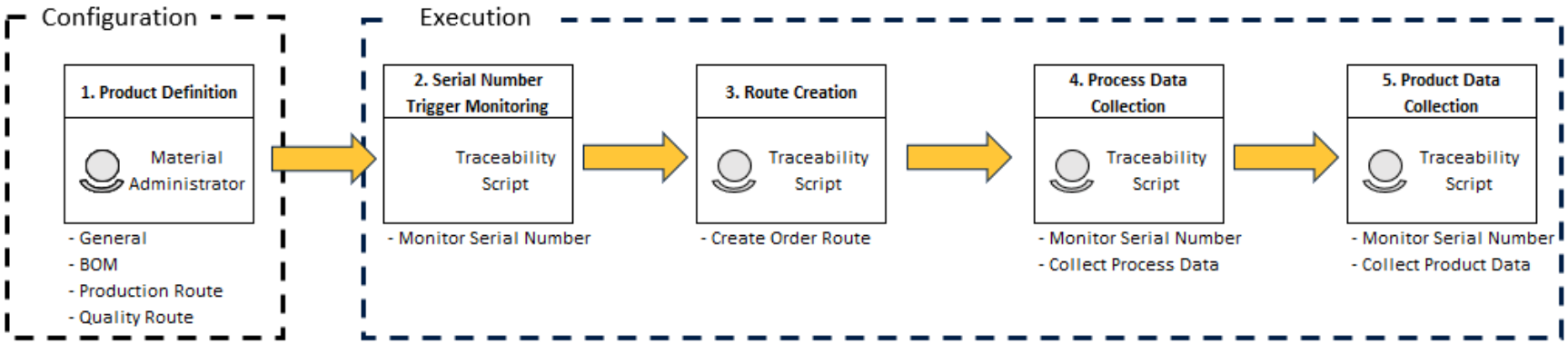


Figure 7.12 Value Stream Map – Traceability

7.4.1 Traceability Module – Configuration

Like the inventory module, the traceability module provides a configuration and execution role. The first step in traceability and in which is required in the execution of traceability is the configuration. The configuration of the traceability module provides the information required to perform al traceability functions within the execution side. As it relates to this thesis, the configuration of traceability is housed under the product definition portion of configuration. Figure 7.13 shows an example of the product definition screen where there is a unique element as product number and additional information such as active revision and configuration user information. The product number is a unique number that matches the companies design records and therefore creates a link from design to manufacturing. Then the active revision provides information to what revision the production definition is currently on. This active revision is separate of the product number and provides revision control solely to MES. In example, a change of a single element such as a process control would require a new revision. This revision control of each product provides control to what was produced and at what level.

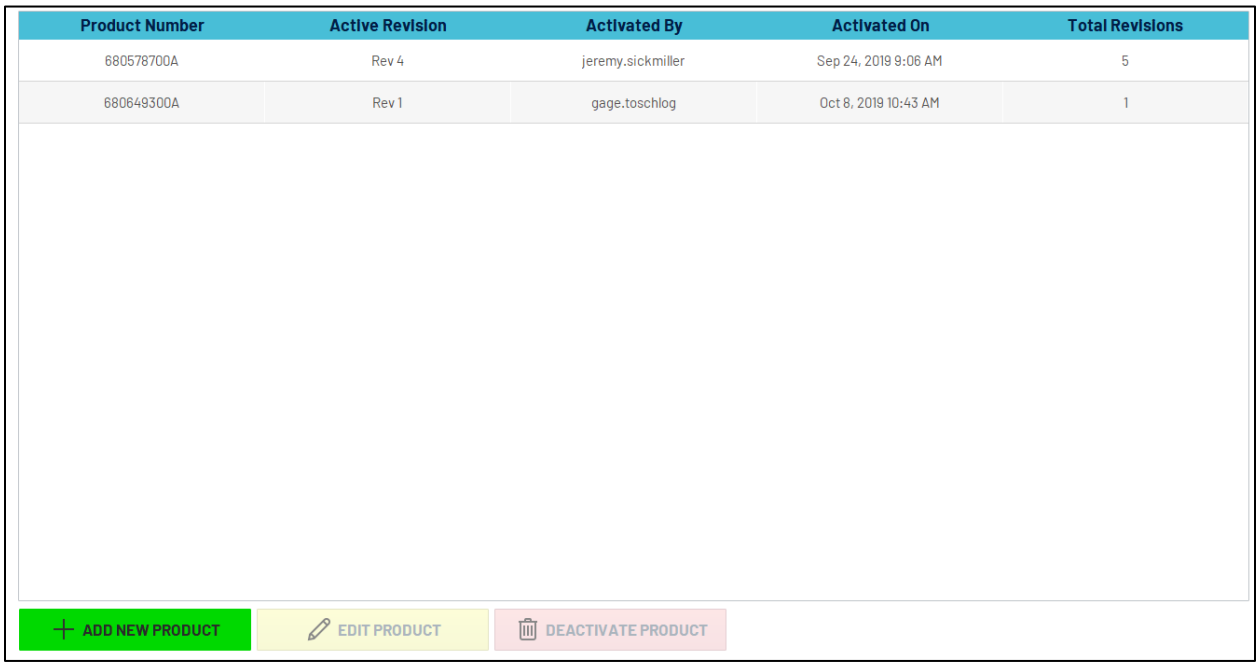


Figure 7.13 Product Definition

Divining into the product definition, Figure 7.14 shows the general information that is required for each product. This general information requires the configuration user to insert the unique product number, a description for the product, customer information and additional information about the part that will be used later within the process. There are also options to save the current revision, make selected revision active, delete a revision or even create a new revision. These actions as it relates the revisions provide control as to change points to the product definitions.

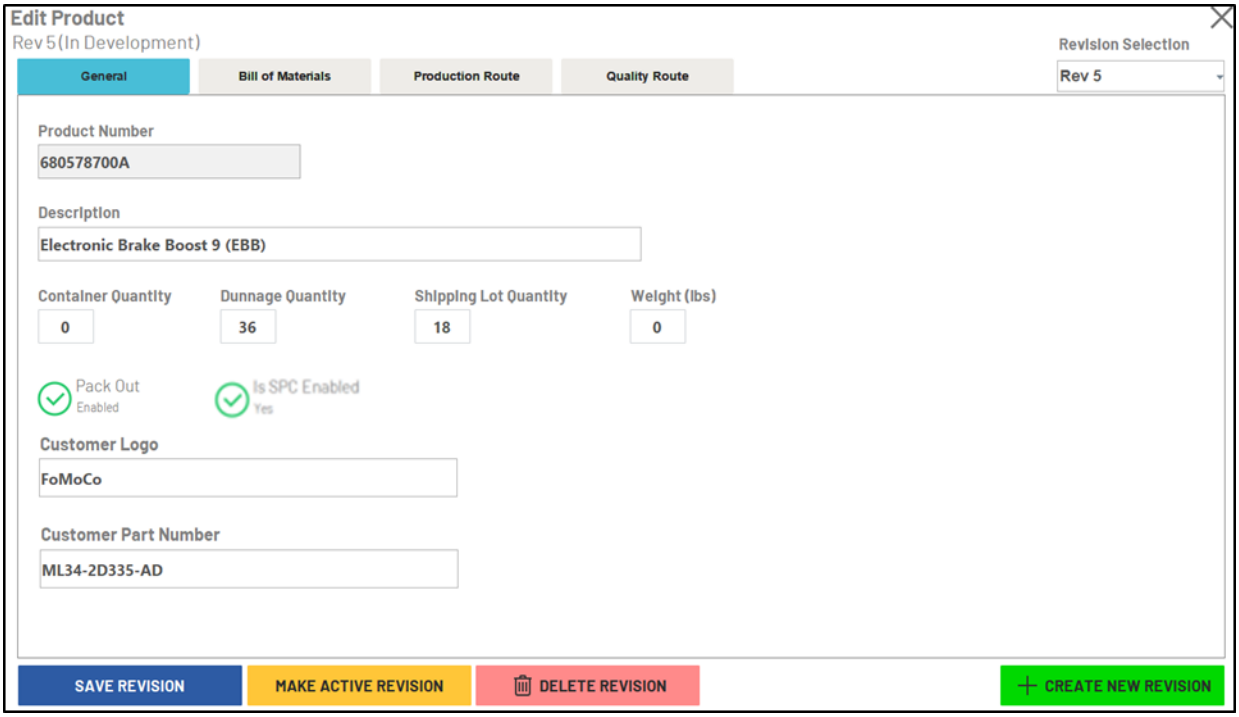


Figure 7.14 Product Definition – General

With the general tab of the product definition completed, the next step is to go to the Bill of Materials (BOM) for that product. The BOM includes all component part information that goes into the finished product. Figure 7.15 shows the BOM as it relates to a product with groupings for sub-assemblies that are created.

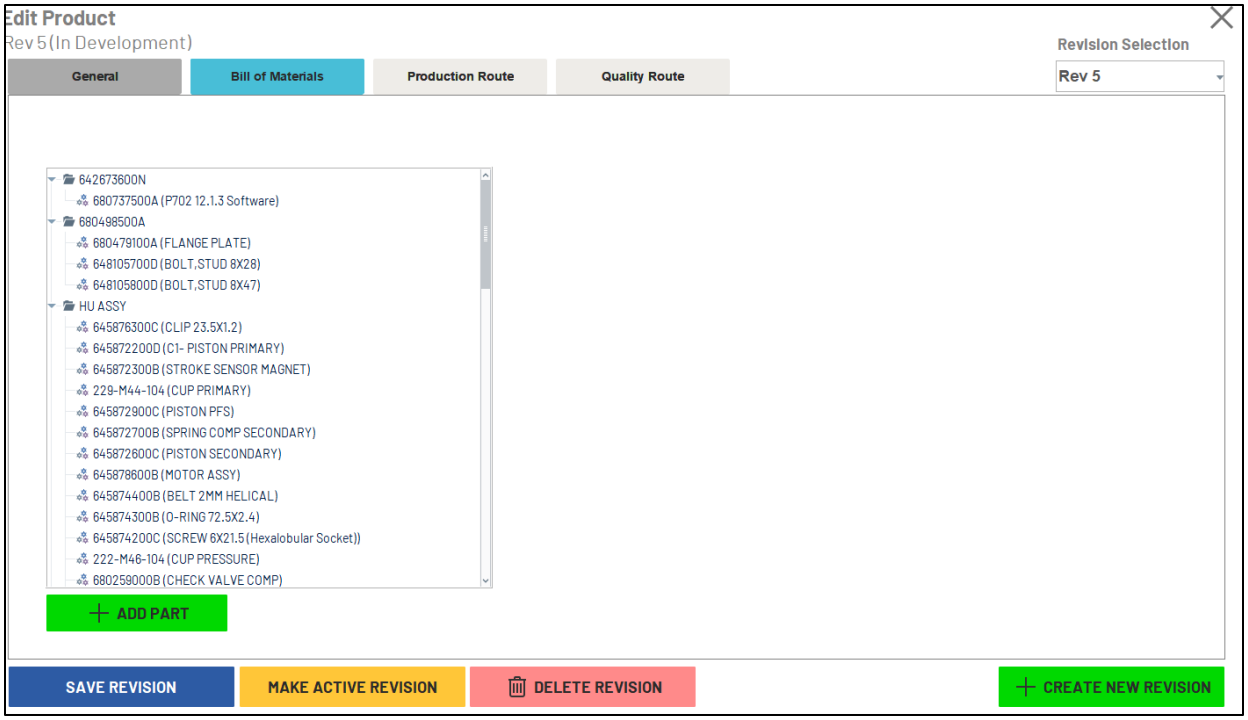


Figure 7.15 Product Definition - BOM

After the completion of the BOM, the production route needs to be defined and is illustrated in Figure 7.16. The production route defines all operations and steps that will need completed before the part can be successful and be shipped from the manufacturing facility. The production route requires the definition of operations which is where both process and production information will be collected. Additional information that is outside the realms of traceability that are required include the dunnage locations and part testing.

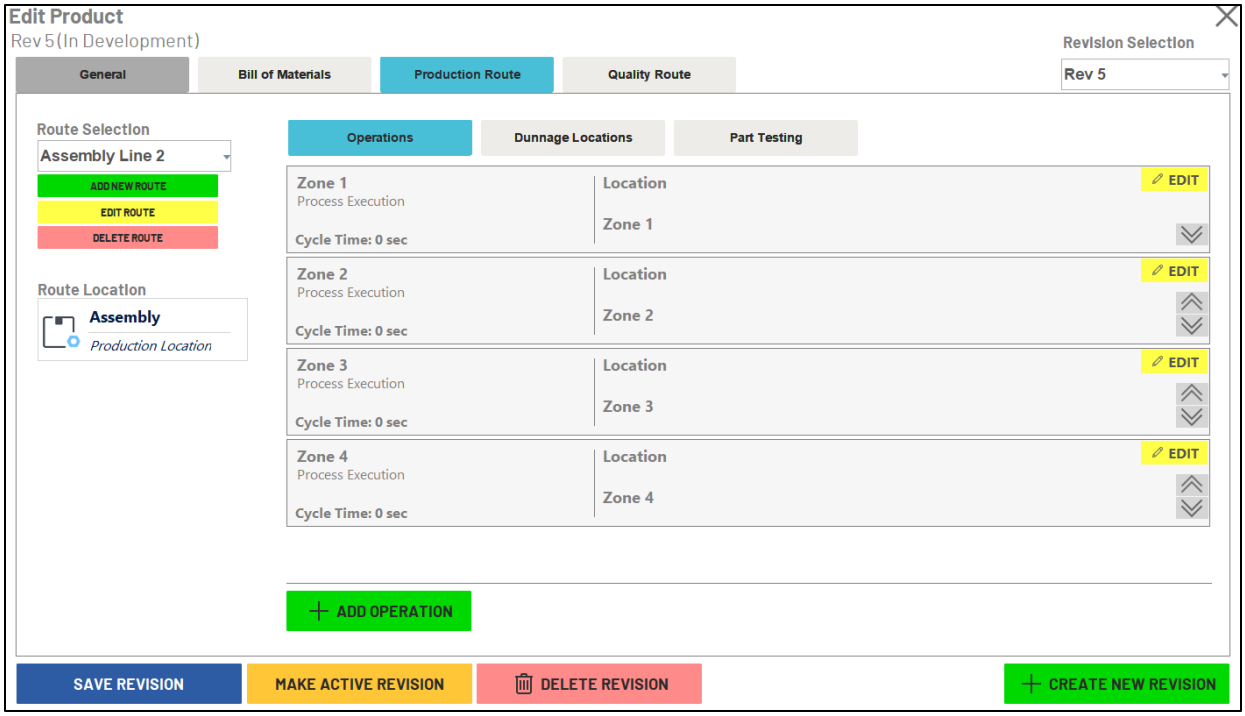


Figure 7.16 Product Definition – Production Route

Each operation within a production route needs defined and the general information for an operation is shown in Figure 7.17. This general information for an operation includes the operation name, a description of the operation and a target cycle time. This information will be used to provide better definition around each operation and provide the individual receiving the information a better understanding of that operation.

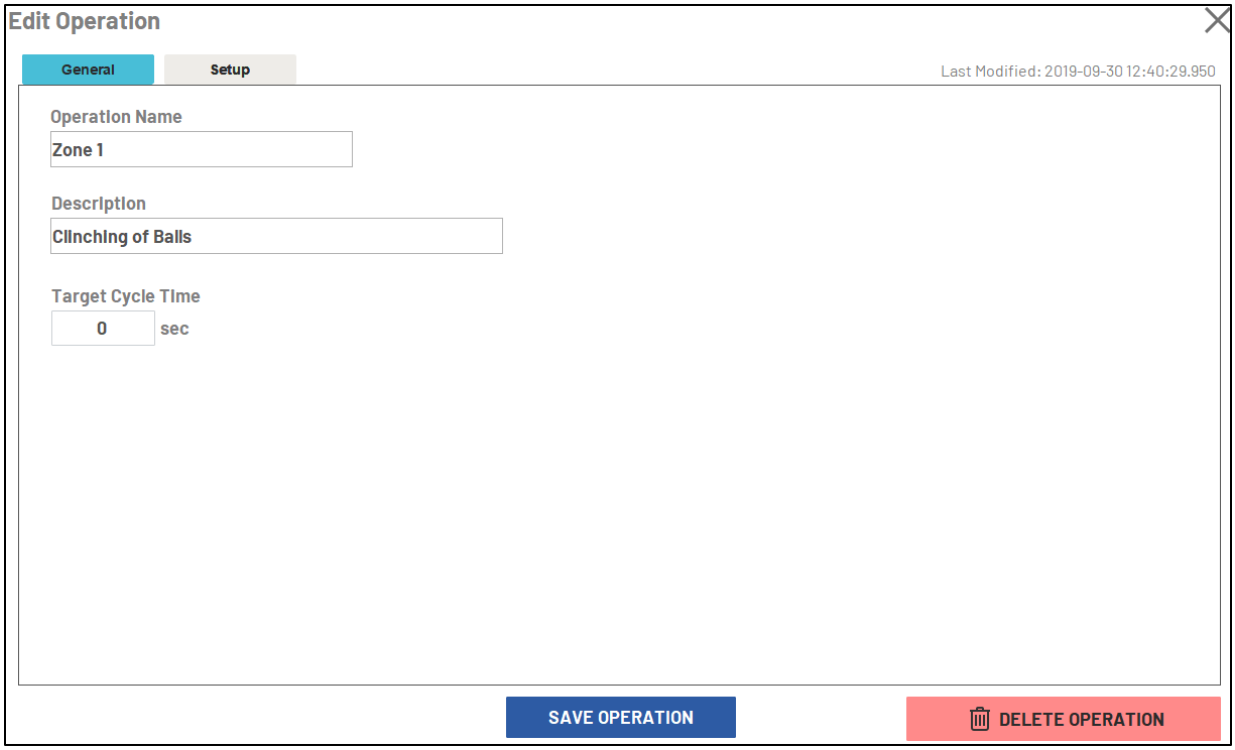


Figure 7.17 Product Definition – Operation General

After populating the general information for an operation, additional information is needed and is found under the setup tab. Figure 7.18 shows the setup information for an operation as it relates to trigger tags. A trigger tag is the manufacturing line tag in which a tag event change occurs and kicks off the start of that operation. As seen in the figure, a tag has been selected (right) from the tag list (left). The tag that is selected is the current serial number. As this setup stands, once the serial number of that operation as defined under the trigger tags changes, the operation is started, and data will now be collected including both process and product data.

Figure 7.18 Product Definition – Operation Setup – Trigger Tags

For the collection of data, process data will be considered first and is shown in Figure 7.19. Like the setup of a trigger tag, a tag list is provided in a tree format (left) in which the configuration user selects (right). The process data is a little different than the trigger tag in that the trigger tag was a single tag where the process data is a folder of tags. A folder will likely have multiple tags that will be collected when the trigger is found. As it relates to this specific example in Figure 7.19, there are 373 unique process data tags and therefore results in 373 different data points per part through this one operation. Of course, there are additional process data points that will be collected. The additional process data would need defined for each operation that the part is required to go through.

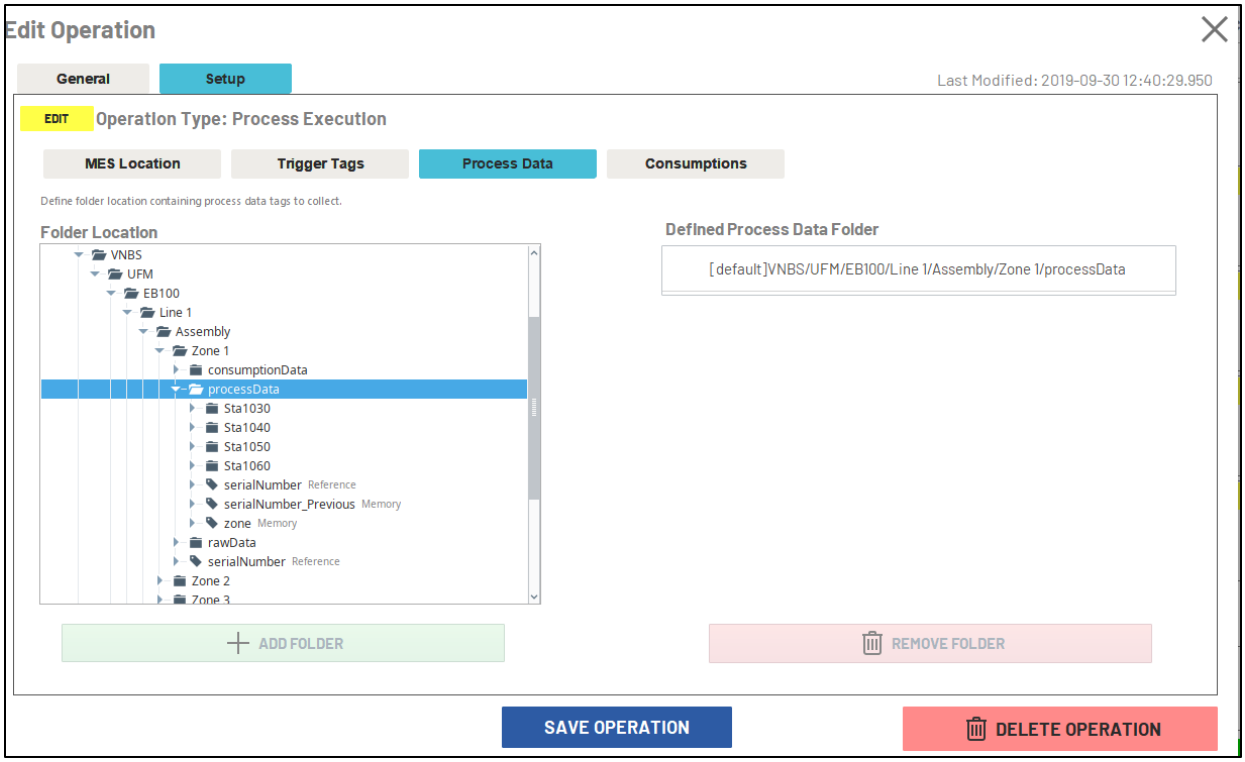


Figure 7.19 Product Definition – Operation Setup – Process Data

Once the process data has been defined for the part, the next step is to configure the consumptions. A screenshot of the consumptions tab can be found in Figure 7.20. The configuration of consumptions serves two purposes. The first purpose is, as the name states, to provide definition around how to consume component parts from inventory after the part has completed an operation. As you will remember, the BOM section of the part definition listed all the component parts that were required to build the part. Each component part from the BOM is required to be selected at each operation level for which parts are consumed. The BOM part as shown in the figure is then linked to a location. When the operation is completed, the consumption occurs and rolls into the second purpose of consumptions, traceability. As it can be defined, the part consumption can happen at a serial level (Serial Number Tag) or at a batch level. With the serial number tag defined, the system will consume a component part from the lot in the defined location and store the serial number associated. If the BOM parts includes an inventory location only, the system will consume a component part from the lot in the defined location and store the batch level information, including the pack number and batch number.

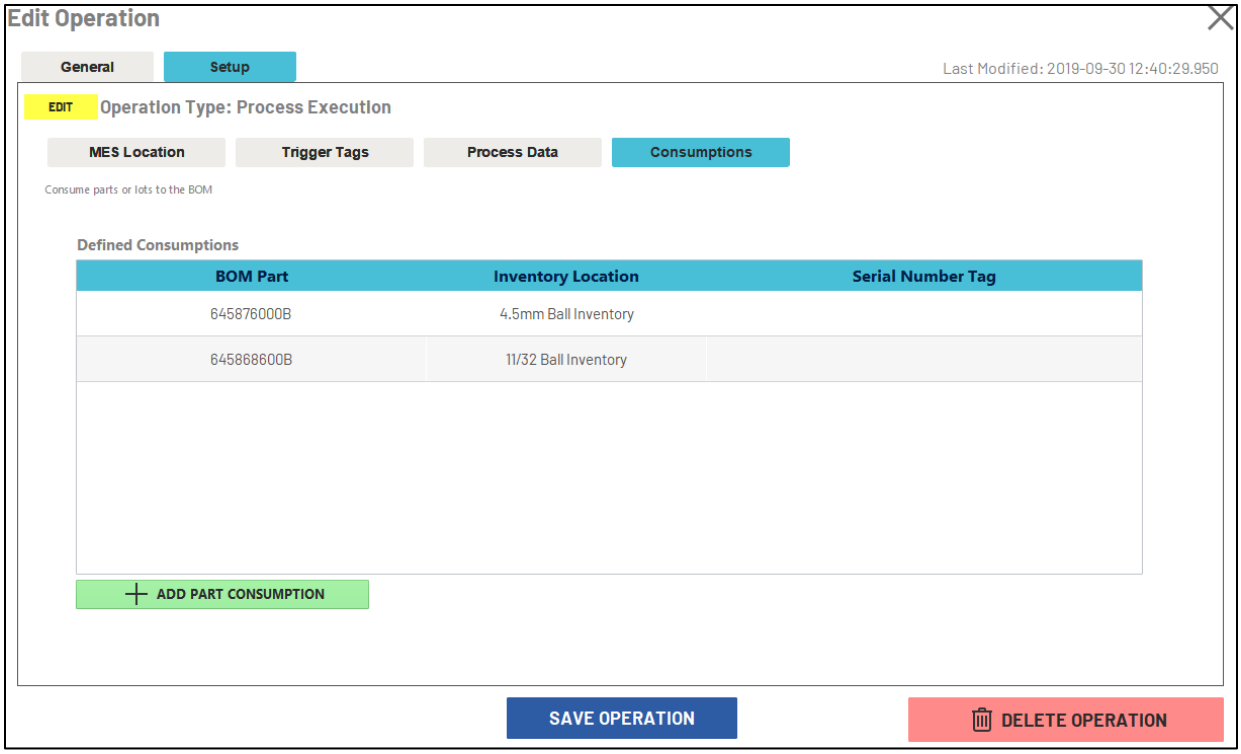


Figure 7.20 Product Definition – Operation Setup – Consumptions

7.4.2 Conclusion

In conclusion, the material presented in this chapter describes the process that was followed in the implementation of the system design decomposition map. This implementation process was shown for both the inventory and traceability modules and started with a value stream map. The value stream map really set the stage for what was to happen at each step and gave an image to the individuals involved so they knew what to expect and so that they could see the big picture. The next most important thing after the kicking of the implementation process, was to be available. With the core components present, there needed some tweaks to make the system more user friendly. Therefore, when someone gave feedback for how to make the system more user friendly, that advice was heeded and was determined how to feed it into the system. Not only did this make the individuals happy, it also created more trust which allowed MES to be better accepted. If the individuals using a system such as MES are not comfortable with it and can trust it, then it will not be utilized therefore negating all work that went into its development. During the implementation of MES, the goal was to gain user buy off so that they would own it and utilize it for the future.

8. MES CONFIGURATION TO ACHEIEVE THE 7 FRS OF MANUFACTURING SYSTEM DESING

8.1 Introduction

A key element to understand is that, MES is a tool in to assist in meeting the objectives of a manufacturing system design. MES will serve as a method to collect information, report the collected information and keep track of the information over time. When looking at a manufacturing system, there are 7 core Functional Requirements that need to be achieved before the consideration of additional Functional Requirements. The 7 Functional Requirements [Cochran et al, 2019] are:

- FR0: Continually improve
- FR1: Provide a safe and healthy work environment
- FR2: Produce the customer consumed quantity every shift
- FR3: Produce the customer consumed mix every shift
- FR4: Do not advance a defect to the customer of your work
- FR5: Immediately identify disruptions and resolve them for the long term
- FR6: Achieve FR1 through FR5 in spite of variation

After a thorough consideration of the 7 FRs, it was determined that only a couple of the 7 FRs would be included within the scope of this thesis. The limited focus of the 7 FRs in this thesis was derived from two factors:

- Some of the FRs were found to be applicable to the overall system design and not specifically the inventory or traceability modules
- Some of the FRs were not found to be applicable to the inventory or traceability modules

For the first factor, some of the FRs were found to be applicable to the overall system and not specifically targeted towards the inventory or traceability modules. An example of this is FR1 and to provide a safe and healthy work environment. Providing a safe and healthy work environment should be the goal of the overall system and therefore is not specifically applicable

to either inventory or traceability. It is essential to note that the scope of the overall MES system design is much larger than what is being presented within this thesis. This thesis aims to stay within the confines of the inventory and traceability modules while the overall MES system design includes additional scope such as: tooling module, shipping module and others. Therefore, an item such as FR1 and providing a safe and healthy work environment would be applicable to the overall system design and not allocated to specific modules as outlined in this thesis.

The second factor then results in isolating that some of the FRs were found not to be applicable to either the inventory or traceability modules. An example of this would be FR3 which has the Functional Requirement to produce the customer consumed mix every shift. This Functional Requirement is not applicable to either the inventory or traceability modules and would be applicable to the Production Tracking module within MES. Additionally, FR 6 for instance would be applicable to another module within MES, the quality module. Typically FR 6 would also be applicable to the inventory module but is not the case in this situation. Physical Solutions for FR 6 include standardized WIP and part order points but is held outside of MES. Physical Solutions to FR 6 lie in the Enterprise Resource Planning (ERP) and therefore it was determined that MES would not provide re-design. However, the future may hold the potential to move Physical Solutions of FR 6 from ERP to MES. To gain a better understanding to the 7 FRs, Table 8.1 shows the 7 FRs and how there relate to the MES core design, the inventory and traceability modules along with the other modules within MES.

Table 8.1 The 7 FRs Mapped to MES

7 FRs of Manufacturing	MES Core Design	Inventory	Traceability	Other MES Modules
FR 0: Continually Improve	1	1	1	0
FR 1: Provide a safe and healthy work environment	1	0	0	0
FR 2: Produce the customer consumed quantity every shift	0	0	0	1
FR 3: Produce the customer quantity mix every shift	0	0	0	1
FR 4: Do not advance a defect to the customer of your work	0	0	1	0
FR 5: Immediately identify disruptions and resolve them for the long term	0	1	1	1
FR 6: Achieve FR1 through FR5 in spite of variation	0	0	0	1

Therefore, the following FRs were focused on during this thesis:

- FR0: Continually improve
- FR4: Do not advance a defect to the customer of your work
- FR5: Immediately identify disruptions and resolve them for the long term

FR0 and the act of continually improving will be utilized throughout both the inventory and traceability modules. It is evident that as time continues, there may be changes that need to be addressed. Therefore, the inventory module and traceability module will be alive and continually changing to match external to MES factors. Within the process of developing the decomposition map for both inventory and traceability, there have already been changes made. Looking forward, the structure of MES should remain constant and the only foreseeable changes would be the adding more information and making changes on the front end to make a more user-friendly interface.

When looking at FR4 and not advancing a defect to the customer of your work, this would fall solely inside the traceability realm. At an even finite level, traceability within MES is to prevent a defect from continuing at the next process which could very well likely be several processes before shipping a product out the door. This prevention of products advancing to the customer, and even advancing to the next process is indicative of a phase gate process. Each process would be considered a phase of the phase gate process. Before a product can enter a phase, it would need to go through a gate where all previous phases and gates need to be completed and acceptable. Then when a product is ready to exit its current phase, the product would need to pass all criteria within that phase to exit the gate successfully. Therefore, there are many points within the manufacturing process of a product that would be certified before it ever makes it to be shipping. Then shipping also includes a phase gate process where a product needs to pass all previous phases and gates in order to ship to the customer. All these phases and gates allow the product to be examined along the way and evaluated as to whether it can continue or not and therefore fulfilling the functional requirement of not advancing a defect to the customer.

The last FR that will be incorporated within the confines of inventory and traceably under MES is to immediately identify disruptions and resolve them for the long term. As the following chapter will show, there are stages for each module within MES and ever more evident in the inventory and traceability modules. The stages include configuration, execution and then reporting.

Therefore, this chapter will look at how each FR as selected from the 7 FRs will be accomplished through decomposition mapping.

8.2 The 7 FRs and the Inventory Module

When it comes to the 7 functional requirements, not all functional requirements are applicable to the inventory module within MES. The applicable function requirements for the inventory module are:

- FR0: Continually improve
- FR5: Immediately identify disruptions and resolve them for the long term

These functional requirements will be analyzed in the following pages in how it relates to the inventory module. Real life examples will also be provided for the sub-functional requirements. The order for which the functional requirements will be broken down will be FR0 and then FR5.

8.2.1 The Inventory Module and FR0

FR0 and to continually improve is very important no matter what the scope is. Continual improvement allows a process to learn from the past and make changes to make the process more effective. When it comes to MES and the inventory module, continual improvement will be achieved through two physical solutions. Figure 8.1 shows the decomposition map for FR0 and how it relates to the inventory module. The inventory will provide a solution to achieve the functional requirement to continually improve. Then under PS 0, additional requirements were established. The first functional requirement under PS 0 is FR 0.1 and to monitor inventory be part number. If the inventory levels are not monitored by part number, then the manufacturing facility runs into concerns with not having component parts to build into a product and could then short ship customers. Therefore, PS 0.1 was established to achieve FR 0.1 with a physical solution of a low inventory by part number live dashboard. The live dashboard allows for a real-time analysis of where low-level component parts are of concern. Then moving to the second functional requirement, FR 0.2 is to monitor inventory levels by location. This functional requirement was established to ensure that the manufacturing lines had enough quantity to build products. If there are enough components inside the manufacturing facility yet they fail to arrive at the manufacturing lines, the would still be a risk of shutting the line and potentially customer down.

Therefore, PS 0.2 and a low inventory by location live dashboard was established to achieve FR 0.2. A low inventory by location live dashboard will allow for a real-time analysis of where product needs to be moved internal to the manufacturing facility to escape the potential of shutting down a line.

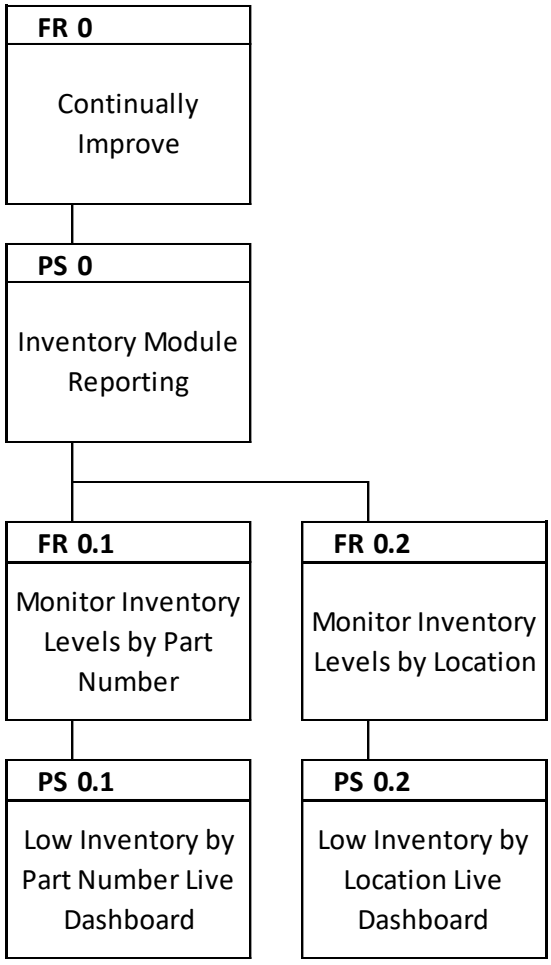
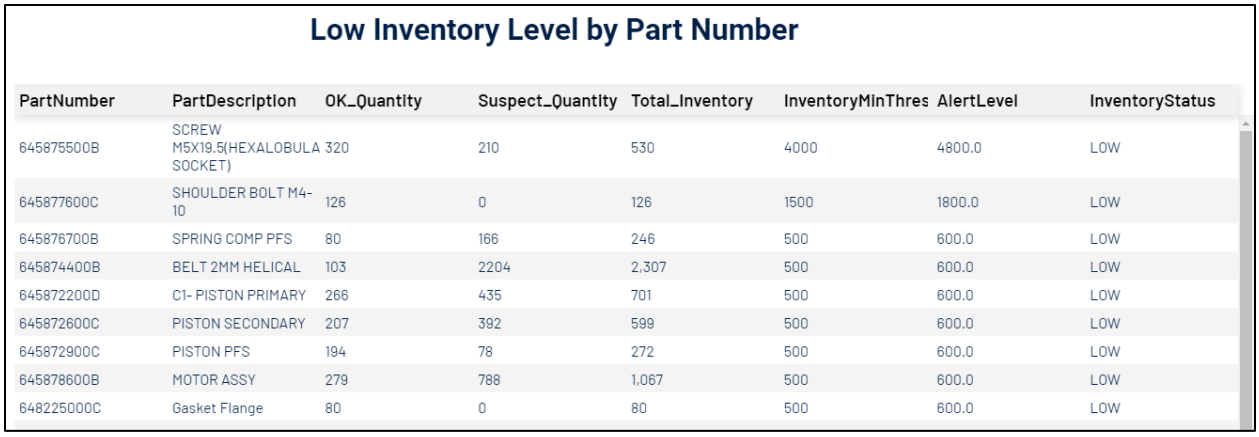


Figure 8.1 Inventory Module FR0

8.2.2 Low Inventory by Part Number

When looking at low inventory by part number, a live dashboard allows users at any point to have resolution to what part number concerns there may be. Figure 8.2 provides a snapshot of a live dashboard that allows any individual within the manufacturing facility to understand where current concerns are in relationship to component parts.



Low Inventory Level by Part Number

PartNumber	PartDescription	OK_Quantity	Suspect_Quantity	Total_Inventory	InventoryMinThres	AlertLevel	InventoryStatus
645875500B	SCREW M5X19.5(HEXALOBULA SOCKET)	320	210	530	4000	4800.0	LOW
645877600C	SHOULDER BOLT M4-10	126	0	126	1500	1800.0	LOW
645876700B	SPRING COMP PFS	80	166	246	500	600.0	LOW
645874400B	BELT 2MM HELICAL	103	2204	2,307	500	600.0	LOW
645872200D	C1- PISTON PRIMARY	266	435	701	500	600.0	LOW
645872600C	PISTON SECONDARY	207	392	599	500	600.0	LOW
645872900C	PISTON PFS	194	78	272	500	600.0	LOW
645878600B	MOTOR ASSY	279	788	1,067	500	600.0	LOW
648225000C	Gasket Flange	80	0	80	500	600.0	LOW

Figure 8.2 Low Inventory By Part Number Live Dashboard

Additionally, Figure 8.2 shows only the part numbers where the OK_Quantity is below a certain threshold. It is applicable to say that the InventoryStatus will show either “LOW” or “ALERT” depending on criteria. If the OK_Quantity is below the InventoryMinThreshold, then the inventory status will show “LOW” meaning that there is an immediate concern to either expedite more parts from the supplier or to determine the state of the Suspect_Quantity for potential use in production. The other option for inventory status is “ALERT” meaning that the current OK_Quantity is within the range of the InventoryMinThreshold and InventoryMinThreshold plus 20%. At the point that inventory reaches the “ALERT” status, action should be taken to prevent inventory from reaching “LOW.”

In having a live dashboard for the inventory levels of component parts by their part number, real-time action can be completed to prevent the shortage of parts. At the point of a part receiving the low status, analysis needs to be completed to determine the root cause so that that failure point can be corrected so it doesn’t happen in the future. This live dashboard is a good tool is only the trigger to prevent low parts, it is truly the analysis and diving into the root cause and then correcting the root cause that will gain the most benefit and therefore aid in continually improving inventory as it relates to part numbers.

8.2.3 Low Inventory by Location

Low inventory by location is very similar to low inventory by part number. However, low inventory by location looks at inventory levels throughout the manufacturing facility with respect to defined locations. In looking at inventory levels by location, gaps will become evident for how parts are flowing throughout the manufacturing facility. This information can become very critical when the manufacturing lines are becoming low and thus could very easily result in shutting a line down. Figure 8.3 shows a live dashboard for inventory levels as it relates to locations.

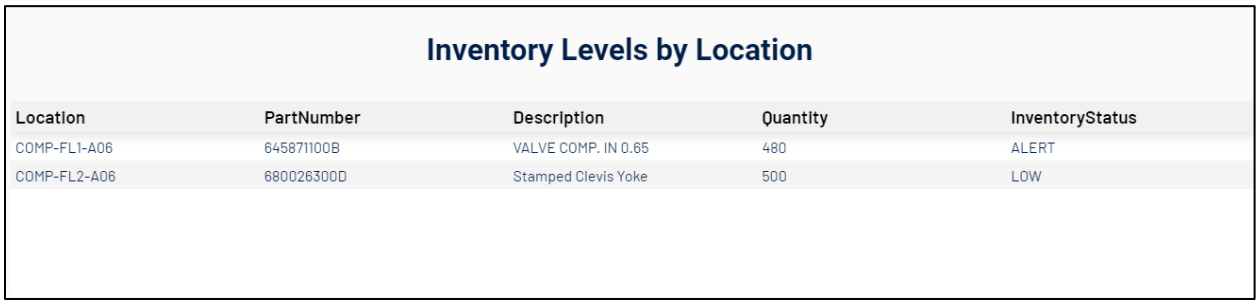


Figure 8.3 Low Inventory By Part Number Live Dashboard

Figure 8.3 shows multiple columns including location, part number, description, quantity and inventory status. The location column shows the location for which there is an inventory level concern. The locations are specifically named so that they are easily distinguished within the manufacturing facility and the appropriate individuals know exactly where that location is. The next two columns show the part number and description so that the individual reviewing this information knows exactly what is of concern. Following is the quantity in which gives a sense of concern where the inventory status explicitly states that concern. The inventory status has two distinct codes of “ALERT” and “LOW.” The “ALERT” status takes the minimum inventory level plus an additional 20%. This additional 20% of inventory allows for enough time to correct the issue before the inventory reaches the minimum quantity. However, if the “ALERT” level is ignored, the inventory status will go to “LOW” in which the inventory level is at or below the minimum quantity. In having this live dashboard for inventory levels by locations, inventory can be moved to fulfill the inventory requirements at every location and thus preventing a lack of inventory which could shut down a manufacturing line.

8.2.4 The Inventory Module and FR5

FR5 is one of the 7 FRs and states to immediately identify disruptions and resolve them for the long term. Figure 8.4 shows the decomposition map for FR5 and how it relates to the inventory module. For achieving FR 5, PS 5 has the physical solution of inventory module restrictions. Future decomposition shows that PS 5 requires three functional requirements. FR 5.1 talks about restriction inventory types to locations which is then achieved through PS 5.1 and inventory type restrictions. For all parts and product within the manufacturing facility, standard, MRB, quality hold and scrap inventory types are given. Then based upon the inventory type of the source material and destination location, will depend if the material can move. An example would be some parts with the inventory type of MRB will not be allowed to move to a standard inventory type location and thus will error out immediately. The next functional requirement for PS 5 is to restrict part numbers to locations. This functional requirement is like inventory type restrictions but looks are part numbers instead of inventory types. The main benefit for part number restrictions is for the manufacturing line and not being allowed to introduce the incorrect parts to the incorrect locations. If the part numbers do not match and the material is scanned, the inventory module will error out immediately. Moving on, FR 5.3 holds path dependency from PS 5.1 and PS 5.2 as it looks to determine the root cause of an issue so that a fix can be implemented and thus resolving the issue for the long term. In order to determine the root cause in FR 5.3, PS 5.3 has the solution of inventory history records. The inventory records will show the full history of each container of parts throughout the manufacturing facility including the individual and time stamp. From these inventory history records, there is much information that can be found out and therefore providing information to determine a root cause for any inventory concerns.

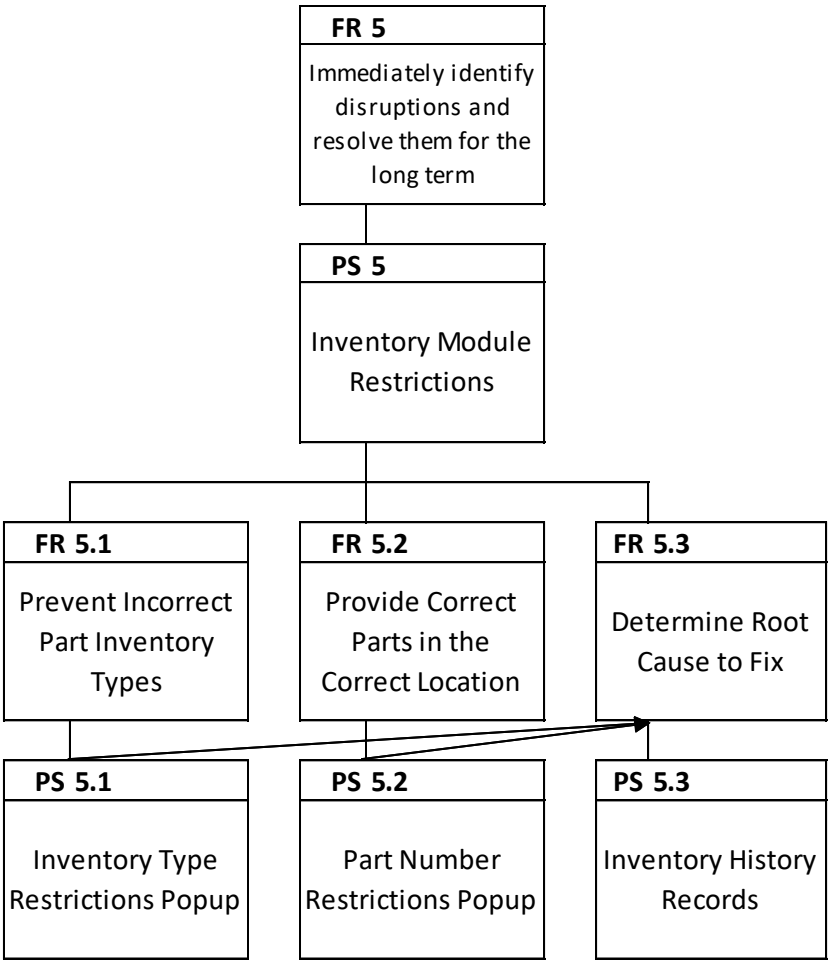


Figure 8.4 Inventory Module FR5

8.2.5 Inventory Type Restriction

The movement of inventory from one location to another happens many times throughout a given day. With each transaction of inventory and the associated movement holds probability that something may happen to cause a disruption. There are many types of disruptions that could occur just from the moving of inventory that could affect the manufacturing facility in many various manners. However, the main disruption for focus will be when a disruption occurs to the manufacturing line causing an issue for shipping parts to a customer. The main disruption would be the inability to build to takt time. Of course there are many more type of disruptions, but every other disruption feeds into the inability to build to takt time. The cause of a disruption could be as simple as having the incorrect type of inventory or incorrect parts at the manufacturing line. Inventory types following along with every container of parts and is descriptive for the status of

parts allowing on certain inventory types to be utilized for manufacturing. Furthermore, the incorrect part numbers at the manufacturing line will also cause a disruption as the prescribed products would not be able to be built and causing a disruption. In attempts to eliminate disruptions from the manufacturing line, restrictions are utilized. Restrictions provide the user with an immediate feedback when isolated causes for disruptions are encountered. This immediate feedback allows the inventory user to correct the issue and continue on with their responsibilities and prevent the disruption to go any further.

A restriction for the inventory module looks at inventory types. Inventory types are codes given to parts to signify their status. Some example statuses include standard, material review board (MRB) and scrap. Standard inventory is good inventory that can be utilized on the manufacturing line and then shipped to a customer. Another inventory type is MRB where the inventory is suspect for some reason. After additional analysis, the parts could be considered good and changed to standard or considered not good and therefore be scrapped. In looking at scrap, this inventory type considers part not usable by the manufacturing line and cannot be built into a product to be sent to a customer. With the various inventory types, mitigation can be made so that there is an immediate identification of disruptions. If a part is being moved from one inventory type, the inventory module will not allow that part to be sent to a location where that inventory type is not accepted. When trying to move parts, a popup is presented to the user to notify them that the action they are attempting is incorrect. Figure 8.5 shows the popup which states the "destination location does not allow the selected inventory type." This error was presented when an inventory type MRB was attempted to move to a location where only the standard inventory type is allowed. This type of mitigation prevents invalid parts to be moved throughout the manufacturing facility and therefore eliminates the potential of shipping suspect product to customers.

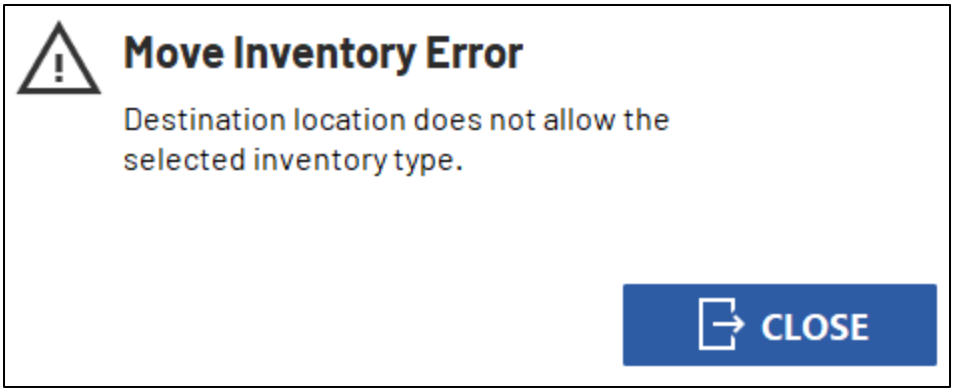


Figure 8.5 Inventory Type Restriction

8.2.6 Part Number Restrictions

Like inventory type restrictions, another restriction looks at part number restrictions. Part number restrictions look at moving a part number to a location and its associated part number. With a single manufacturing facility having potentially hundreds of different part numbers and even similar looking parts, part number restriction helps to alert users of an abnormal situation. The alert of an abnormal situation is immediate and allows for user interaction before it gets too late. This type of restriction is very essential when it comes to moving parts to a manufacturing line. The manufacturing line depends on maintaining certain parts numbers in defined locations to help with ease of manufacturing products. Figure 8.6 shows the popup error for moving a part number to an incorrect location. The popup error for the user says, “scanned location does not allow this part number.” This immediate presentation of the error allows the user to correct the issue and move the part number to the correct location.

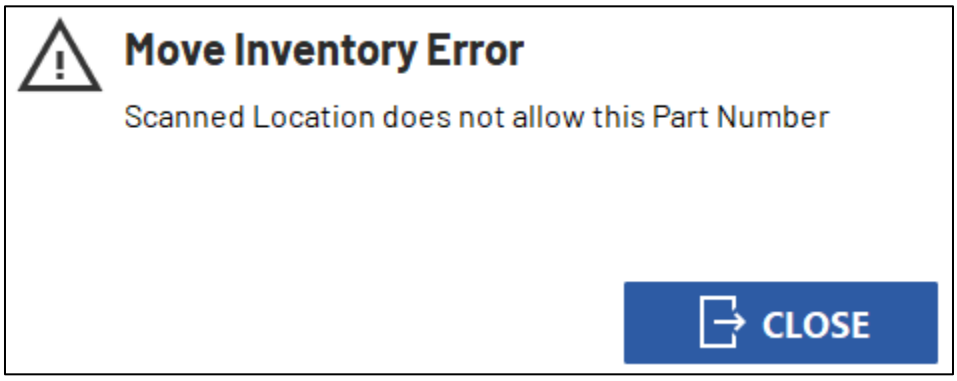
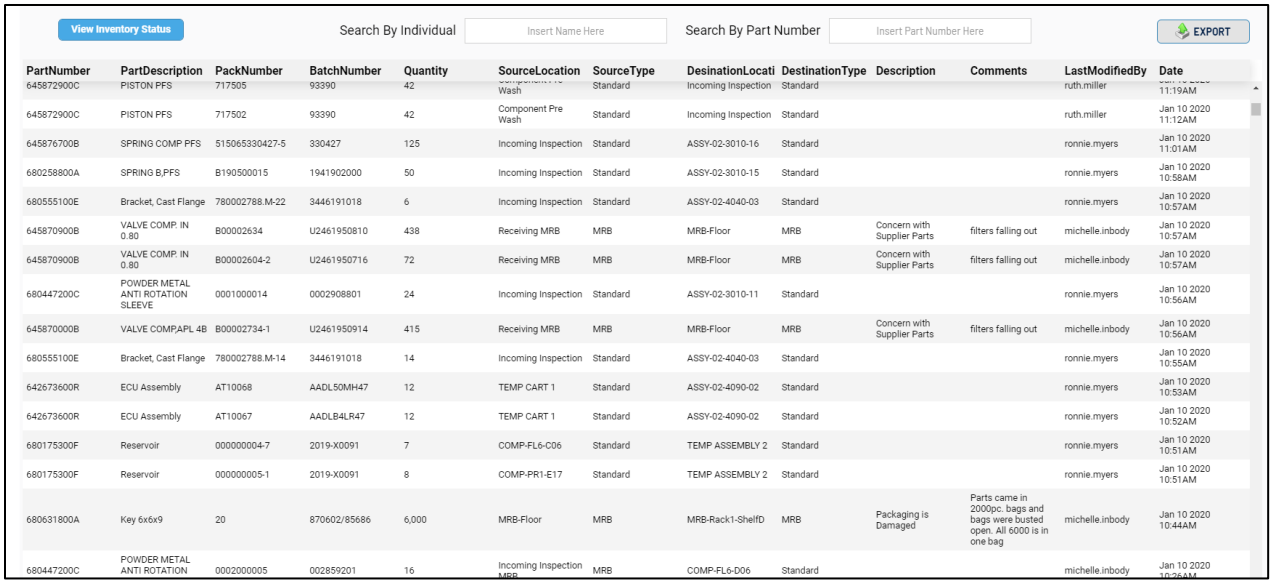


Figure 8.6 Part Number Restriction

8.2.7 Inventory History

With restrictions in place for part numbers and inventory types for achieving FR 5.1 and 5.2 respectively, the next point is to isolate any other disruptions that may occur through the determination of root cause so that an appropriate corrective action can be put into place. To facilitate the root cause analysis, information needs to be provided and is where the inventory history within the inventory module comes into play. FR 5.3 states to determine root cause and fix and is achieved through PS 5.3 and inventory history records. Inventory history records include key elements of part numbers, quantities and the tracing of part movement by individual and timestamp. Figure 8.7 shows a snapshot of a live feed for inventory history. The top of the dashboard allows filtering for individual and/or part number. Then the filtered data can be used to see the full trace of a part container's movement throughout the entire manufacturing facility and if the ending quantity was reduced throughout the process. This type of information can become very useful if there were an issue were parts did not make it to a manufacturing line on time, parts were lost or even to look at trends of how many individuals touch a given part number over a given period. It is also key to note that the filtered data can be exported into text format via the "Export" button so that additional analysis can be performed. Then once a conclusion has been arrived at, the appropriate correction action can be put into place so that the original symptom is not experienced in the future. It can be said that the information gathered from the inventory history records provide users with the items needed to determine root cause as it relates to the inventory module and therefore correct the issue, so it doesn't happen again.



PartNumber	PartDescription	PackNumber	BatchNumber	Quantity	SourceLocation	SourceType	DesinationLocati	DestinationType	Description	Comments	LastModifiedBy	Date
645872900C	PISTON PFS	717505	93390	42	Component Pre Wash	Standard	Incoming Inspection	Standard			ruth.miller	11:19AM
645872900C	PISTON PFS	717502	93390	42	Component Pre Wash	Standard	Incoming Inspection	Standard			ruth.miller	Jan 10 2020 11:12AM
645876700B	SPRING COMP PFS	515065330427-5	330427	125	Incoming Inspection	Standard	ASSY-02-3010-16	Standard			ronnie.myers	Jan 10 2020 11:01AM
680258800A	SPRING B,PFS	B190500015	1941902000	50	Incoming Inspection	Standard	ASSY-02-3010-15	Standard			ronnie.myers	Jan 10 2020 10:58AM
680555100E	Bracket, Cast Flange	780002788.M-22	3446191018	6	Incoming Inspection	Standard	ASSY-02-4040-03	Standard			ronnie.myers	Jan 10 2020 10:57AM
645870900B	VALVE COMP. IN 0.80	B00002634	U2461950810	438	Receiving MRB	MRB	MRB-Floor	MRB	Concern with Supplier Parts	filters falling out	michelle.inbody	Jan 10 2020 10:57AM
645870900B	VALVE COMP. IN 0.80	B00002604-2	U2461950716	72	Receiving MRB	MRB	MRB-Floor	MRB	Concern with Supplier Parts	filters falling out	michelle.inbody	Jan 10 2020 10:57AM
680447200C	POWDER METAL ANTI ROTATION SLEEVE	0001000014	0002908801	24	Incoming Inspection	Standard	ASSY-02-3010-11	Standard			ronnie.myers	Jan 10 2020 10:56AM
645870000B	VALVE COMP,APL 4B	B00002734-1	U2461950914	415	Receiving MRB	MRB	MRB-Floor	MRB	Concern with Supplier Parts	filters falling out	michelle.inbody	Jan 10 2020 10:56AM
680555100E	Bracket, Cast Flange	780002788.M-14	3446191018	14	Incoming Inspection	Standard	ASSY-02-4040-03	Standard			ronnie.myers	Jan 10 2020 10:55AM
642673600R	ECU Assembly	AT10068	AADL50MH47	12	TEMP CART 1	Standard	ASSY-02-4090-02	Standard			ronnie.myers	Jan 10 2020 10:53AM
642673600R	ECU Assembly	AT10067	AADLB4LR47	12	TEMP CART 1	Standard	ASSY-02-4090-02	Standard			ronnie.myers	Jan 10 2020 10:52AM
680175300F	Reservoir	000000004-7	2019-X0091	7	COMP-FL6-C06	Standard	TEMP ASSEMBLY 2	Standard			ronnie.myers	Jan 10 2020 10:51AM
680175300F	Reservoir	000000005-1	2019-X0091	8	COMP-PR1-E17	Standard	TEMP ASSEMBLY 2	Standard			ronnie.myers	Jan 10 2020 10:51AM
680631800A	Key 6x6x9	20	870602/85686	6,000	MRB-Floor	MRB	MRB-Rack1-ShelfD	MRB	Packaging is Damaged	Parts came in 2000pc. bags and bags were busted open. All 6000 is in one bag	michelle.inbody	Jan 10 2020 10:44AM
680447200C	POWDER METAL ANTI ROTATION	0002000005	002859201	16	Incoming Inspection MRB	MRB	COMP-FL6-D06	Standard			michelle.inbody	Jan 10 2020 10:26AM

Figure 8.7 Inventory History

8.2.8 7 FRs of Inventory Conclusion

In conclusion, the 7 FRs were analyzed and determined for their applicability to the inventory module. The FRs that were found to be applicable were analyzed and worked out to prove how they are effective to maintaining a robust process. It was seen under FR0 that the inventory module will provide live dashboards for inventory levels by part number and inventory levels by location. These live dashboards will allow the manufacturing facility continually to improve with their inventory levels so that there is not a shortage. Additionally, the inventory module was review with FR5 and to immediately identify disruptions and resolve them for the long term. This functional requirement looked at inventory type restrictions and part number restrictions to immediately identify disruptions. Then inventory history information was looked at for how to determine root cause so that correction could be achieved so that the issue would not occur again. For both FR0 and FR5, the inventory module was analyzed to how it would efficiently and effectively achieve each functional requirement. By looking at these core functional requirements of a manufacturing system, the inventory module within MES will work with manufacturing and create a more robust manifesting facility.

8.3 The 7 FRs and the Traceability Module

Traceability has been looked at as it relates to requirements which we pushed into physical solutions. The process was looked at for defining the traceability levels which were included in the definition process for both batch and serialized levels. Additionally, traceability was considered as it related to top down and bottom up traceability. All this information was collected when running a product on a manufacturing line but is no good to just have data sitting around. Additional steps need to be taken to look at the data in a way that will benefit the company. Therefore, traceability will now be looked at in reference to the 7 Firs' As it has already been mentioned, several FRs have been deemed to be applicable to traceability and are as follows:

- FR0: Continually improve
- FR4: Do not advance a defect to the customer of your work
- FR5: Immediately identify disruptions and resolve them for the long term

FR0, FR4 and FR5 will be analyzed for how they relate to the traceability module. Real life examples will be shown for the physical solutions as it relates to traceability. The order for which the functional requirements will be broken down will be FR0, then FR4 and finally FR5.

8.3.1 The Traceability Module and FR0

The first functional requirement that will looked at is FR 0 and the requirement to continually improve. There are many ways to improve in manufacturing, but the following will only be related towards the traceability module within MES. The decomposition map for FR 0 can be seen in Figure 8.8 for how FR 0 is achieved with respect to traceability.

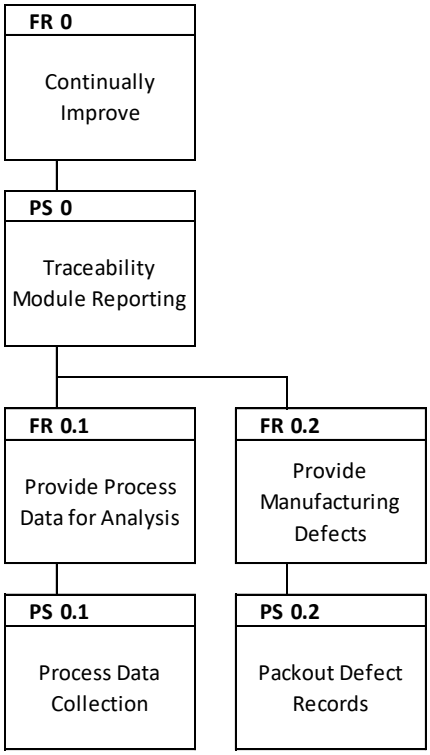


Figure 8.8 Traceability Module FR 0

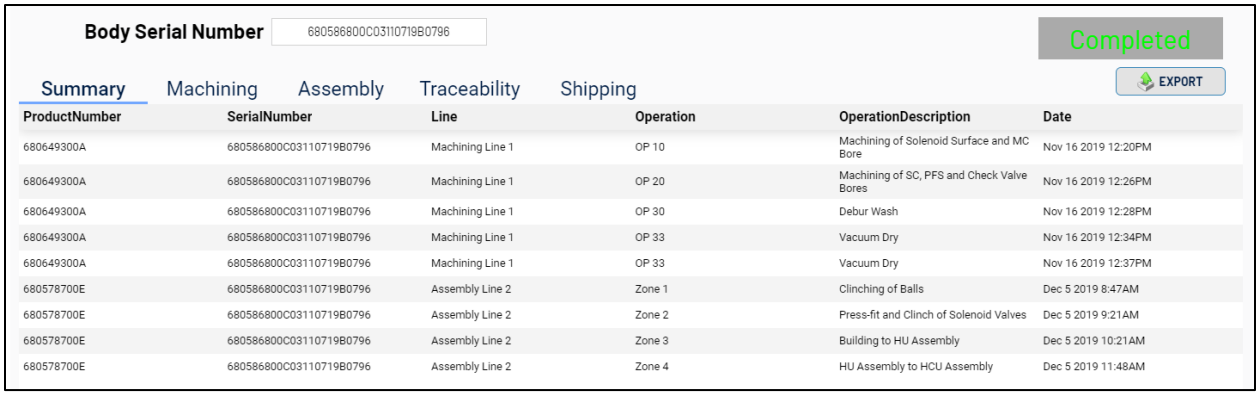
To achieve FR 0 and to continually improve, PS 0 was established and is traceability module reporting. This physical solution alone will not provide continual improvement, so it is necessary to go a level deeper where FR 0.1 and FR 0.2 are found. FR 0.1 states to provide process data for analysis in which PS 0.1 and process data collection will do so. Process data collection will allow for the appropriate data to be collected from the manufacturing process that analysis can be performed to see how the line is performing and where additional measures can be taken. A main area to look at would be the capability of the manufacturing line. Process data would be the data needed to analyze the line's capability level and then the manufacturing line's engineer could take the appropriate steps to fix items that would increase their capabilities. The next functional requirement to achieve PS 0 is held in FR 0.2 which states to provide manufacturing defects. Manufacturing defects are the reasons why parts coming off the manufacturing line can not be used to ship to the customer. This functional requirement is achieved through PS 0.2 and pack out defect records. The pack out defect records are categorized from defect location and defect type along with a timestamp so that further analysis can be performed as to why the defects are

continuing to occur. Once the defects are known, either manufacturing process or parts can be addressed to remedy the concern. Therefore, both FR 0.1 and FR 0.2 are valid functional requirements with their corresponding physical solutions to provide the proper information so that continual improvement can occur.

8.3.2 Process Data Collection

When it comes to process data collection, there are many data points that can be collected. Process data collection is very helpful for a couple of reasons. The first reason is to confirm that the product was manufactured in a manner where all features are compliant to the print and their associated specifications. If a product is produced with a feature that has a dimension outside of the specification limits, the product has a very high likelihood that it will fail for the customer. Therefore, it is essential to ensure that all features hold true to their specification limits so that defects are not found in the future. The second reason process data is helpful is to understand the capability of the manufacturing process. Process data can be analyzed to determine how a manufacturing process is performing with respect to every feature as it relates to the specification limits. If a manufacturing line has a feature with a low capability level with respect to a specification limit, then products will be produced at some rate outside of the specification limits. The lower the capability level, the higher the percentage of parts that will come off the manufacturing line outside of the specification limits. With parts outside of the specifications limits, they might be sent to the customer which could result in failures or be contained within the manufacturing facility and therefore causing additional scrap which introduces additional cost and could potentially cause delivery issues.

For looking at process data, each manufacturing line produces it own data and is split up by the unique processes. The examples given in this thesis will include machining and assembly. The starting point is an overall summary which places together all manufacturing processes so that the larger history can be provided. For the example below, serial number 680586800C03110719B0796 will be used. Figure 8.9 shows the overall summary of where the part was processed with additional information.

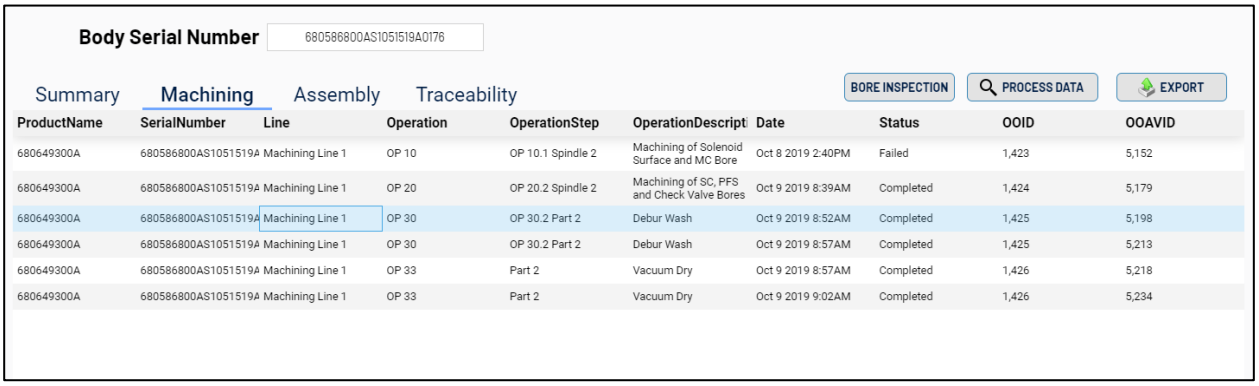


ProductNumber	SerialNumber	Line	Operation	OperationDescription	Date
680649300A	680586800C03110719B0796	Machining Line 1	OP 10	Machining of Solenoid Surface and MC Bore	Nov 16 2019 12:20PM
680649300A	680586800C03110719B0796	Machining Line 1	OP 20	Machining of SC, PFS and Check Valve Bores	Nov 16 2019 12:26PM
680649300A	680586800C03110719B0796	Machining Line 1	OP 30	Debur Wash	Nov 16 2019 12:28PM
680649300A	680586800C03110719B0796	Machining Line 1	OP 33	Vacuum Dry	Nov 16 2019 12:34PM
680649300A	680586800C03110719B0796	Machining Line 1	OP 33	Vacuum Dry	Nov 16 2019 12:37PM
680578700E	680586800C03110719B0796	Assembly Line 2	Zone 1	Clinching of Balls	Dec 5 2019 8:47AM
680578700E	680586800C03110719B0796	Assembly Line 2	Zone 2	Press-fit and Clinch of Solenoid Valves	Dec 5 2019 9:21AM
680578700E	680586800C03110719B0796	Assembly Line 2	Zone 3	Building to HU Assembly	Dec 5 2019 10:21AM
680578700E	680586800C03110719B0796	Assembly Line 2	Zone 4	HU Assembly to HCU Assembly	Dec 5 2019 11:48AM

Figure 8.9 Traceability – Process Summary

The table also shows the line and all the operations with a date in which the part was manufactured. The first column lists the product that was manufactured while additional information includes the line, operation and an operation description. The last column includes the date and time for when the specified serial number went through the process. Additionally, there is an export button that allows for the table data to be exported in a .CSV file for the user

With the summary of the finished part understood, the individual processes within the manufacturing facility allow the user to dive a little deeper. Figure 8.10 shows additional data as it relates to the machining process. This additional information includes the specific operation equipment along with which spindle or fixture the part went through.

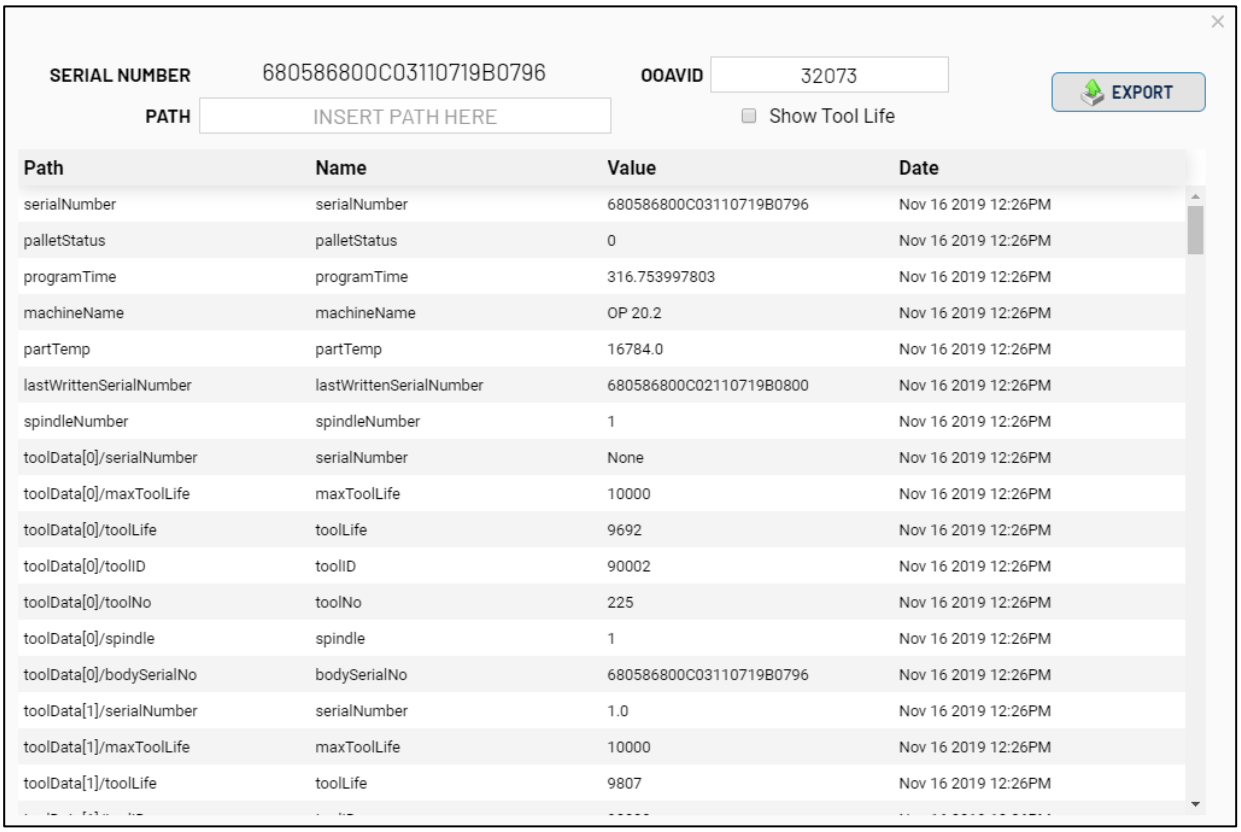


ProductName	SerialNumber	Line	Operation	OperationStep	OperationDescript	Date	Status	OOID	OOAVID
680649300A	680586800AS1051519A	Machining Line 1	OP 10	OP 10.1 Spindle 2	Machining of Solenoid Surface and MC Bore	Oct 8 2019 2:40PM	Failed	1,423	5,152
680649300A	680586800AS1051519A	Machining Line 1	OP 20	OP 20.2 Spindle 2	Machining of SC, PFS and Check Valve Bores	Oct 9 2019 8:39AM	Completed	1,424	5,179
680649300A	680586800AS1051519A	Machining Line 1	OP 30	OP 30.2 Part 2	Debur Wash	Oct 9 2019 8:52AM	Completed	1,425	5,198
680649300A	680586800AS1051519A	Machining Line 1	OP 30	OP 30.2 Part 2	Debur Wash	Oct 9 2019 8:57AM	Completed	1,425	5,213
680649300A	680586800AS1051519A	Machining Line 1	OP 33	Part 2	Vacuum Dry	Oct 9 2019 8:57AM	Completed	1,426	5,218
680649300A	680586800AS1051519A	Machining Line 1	OP 33	Part 2	Vacuum Dry	Oct 9 2019 9:02AM	Completed	1,426	5,234

Figure 8.10 Traceability – Machining Process Summary

Additional buttons allow for a deeper dive into the serialized part's process data. When the user selects a row in the table according to the operation that they are looking for, the "process

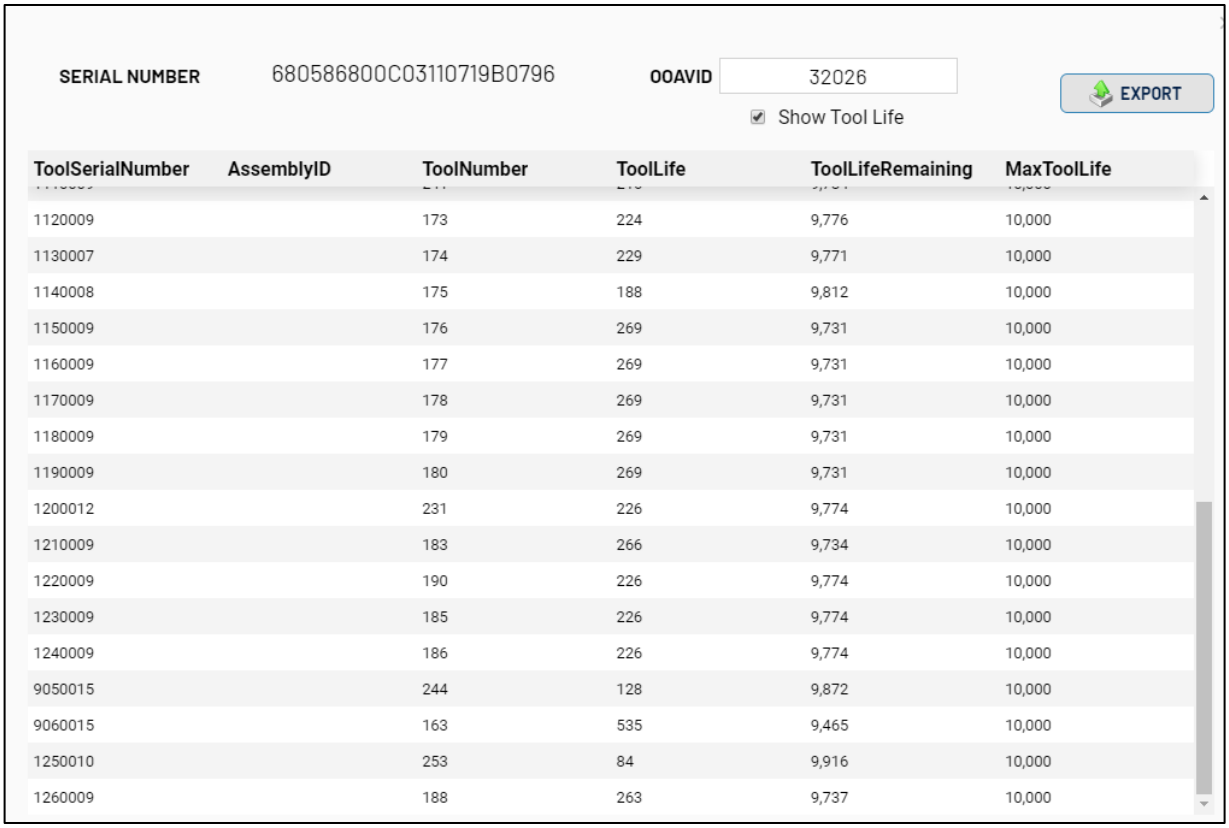
data” button allows additional information to be displayed for that serialized part and the selected operation. Figure 8.11 shows the process data as it relates to the serialized part.



Path	Name	Value	Date
serialNumber	serialNumber	680586800C03110719B0796	Nov 16 2019 12:26PM
palletStatus	palletStatus	0	Nov 16 2019 12:26PM
programTime	programTime	316.753997803	Nov 16 2019 12:26PM
machineName	machineName	OP 20.2	Nov 16 2019 12:26PM
partTemp	partTemp	16784.0	Nov 16 2019 12:26PM
lastWrittenSerialNumber	lastWrittenSerialNumber	680586800C02110719B0800	Nov 16 2019 12:26PM
spindleNumber	spindleNumber	1	Nov 16 2019 12:26PM
toolData[0]/serialNumber	serialNumber	None	Nov 16 2019 12:26PM
toolData[0]/maxToolLife	maxToolLife	10000	Nov 16 2019 12:26PM
toolData[0]/toolLife	toolLife	9692	Nov 16 2019 12:26PM
toolData[0]/toolID	toolID	90002	Nov 16 2019 12:26PM
toolData[0]/toolNo	toolNo	225	Nov 16 2019 12:26PM
toolData[0]/spindle	spindle	1	Nov 16 2019 12:26PM
toolData[0]/bodySerialNo	bodySerialNo	680586800C03110719B0796	Nov 16 2019 12:26PM
toolData[1]/serialNumber	serialNumber	1.0	Nov 16 2019 12:26PM
toolData[1]/maxToolLife	maxToolLife	10000	Nov 16 2019 12:26PM
toolData[1]/toolLife	toolLife	9807	Nov 16 2019 12:26PM

Figure 8.11 Traceability – Machining Process Data

The first two columns include descriptive information for what data is shown while the value column shows the specific process data and then the date column show when the process data was collected. Then the “show tool life” box is checked, the table changes to include the specific tool life that was generated during the processing of the part. Figure 8.12 show the tool life information associated with the specified serial number.



ToolSerialNumber	AssemblyID	ToolNumber	ToolLife	ToolLifeRemaining	MaxToolLife
1120009		173	224	9,776	10,000
1130007		174	229	9,771	10,000
1140008		175	188	9,812	10,000
1150009		176	269	9,731	10,000
1160009		177	269	9,731	10,000
1170009		178	269	9,731	10,000
1180009		179	269	9,731	10,000
1190009		180	269	9,731	10,000
1200012		231	226	9,774	10,000
1210009		183	266	9,734	10,000
1220009		190	226	9,774	10,000
1230009		185	226	9,774	10,000
1240009		186	226	9,774	10,000
9050015		244	128	9,872	10,000
9060015		163	535	9,465	10,000
1250010		253	84	9,916	10,000
1260009		188	263	9,737	10,000

Figure 8.12 Traceability – Machining Tool Life

Within the tool life table, the first column includes the serial number of the tool for tooling traceability while the tool number is a distinct number that relates to the machining features. Additional information includes the tool life which shows the number of parts that serialized tool has machined while the tool life remaining shows the number of parts remaining with the max tool life showing the maximum number of tools that can be machined. When it comes to machining, the tool life information is important to ensure quality of the parts in addition to determining suspect ranges if something would to happen and out of specification parts were to be produced.

All of the information that has been provided for traceabilty as it relates to conitnually improving is good, however at some point the data needs to be actively used in a manner that support continual improvement or else the data is usless. Within the automotive industry, standards exist as base line indicators to determine how a manufacturing line is performing. Figure 8.13 shows a continuously updating graph to show the capabiltiy of a manufacturing process. The reporting tool used to show this information allows for the selection of differnet elements, however only one element should be viewed at a time and is thus what is presented.

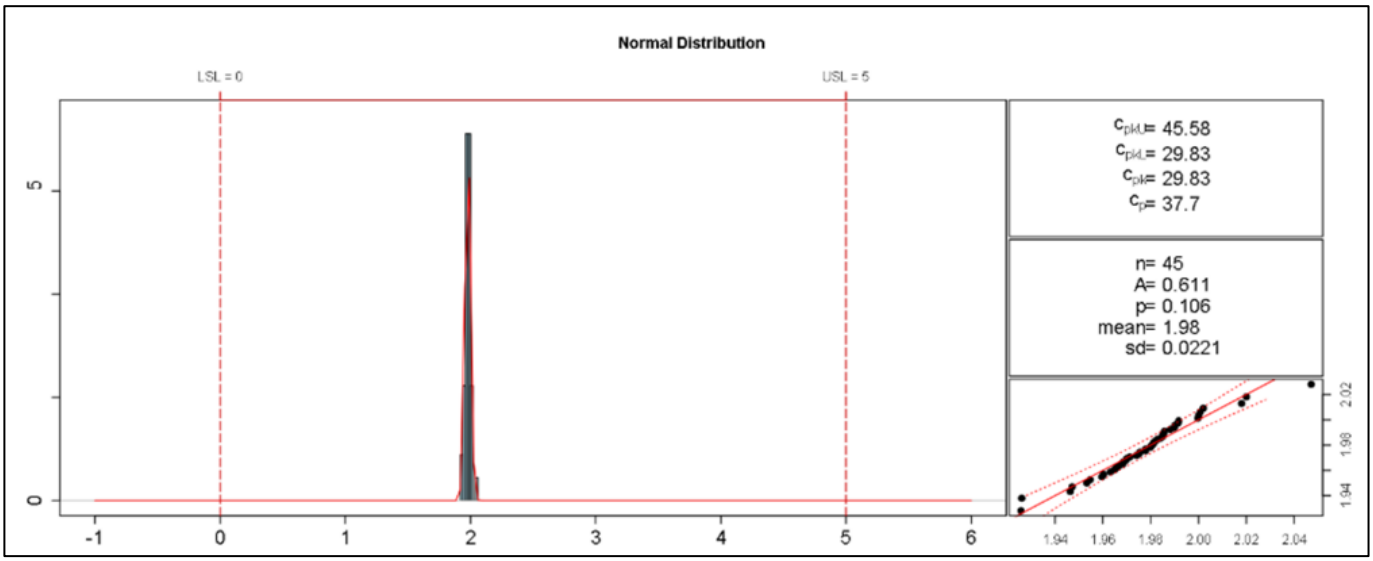


Figure 8.13 Traceability – Machining Tool Life

Figure 8.13 have a couple of things going on to determine the capability of a manfuacturing process under the confinds of the user selected element. The first chart and the larger chart shows a normal distribution for that selected element. The red dotted lines at the 0 and 5 on the x-axis show the specification limits and are labeled as LSL and USL while the distribution lays on the 2 on the x-axis. If at any point the distribution exceeds the bounds of the LSL or USL, there is a call for improving the process. To continue on, the lower right chart shows a probability plot and helps to show if the data follows a normal distrbution or not. The above has all dots within the red limits and would be considered a normal distribution curve. Since the data follows a normal distribution, the Cp and Cpk can be evaluated. The Cp and Cpk values are in the top right box and show values of 37.7 and 29.83 respectively. For both Cp and Cpk, the industrial standard for the automotive indsutry is to be greater than a value of 1.33 in which this easily exceeds. From the given data, this process and associated element are acceptable and therefore do not require additional work. However, there will be other processes and elements within the process that will not be acceptable and work will need to be completed to make the process acceptable. The data provided from the collection of process data will help to drive the continual improvement process and at first give the direction for a corrective action. Then once a corrective action is implemented, additional parts can be ran and the data analyzed again to see if the corrective action was beneficial or not. This type of iteration should occur until the process and associated element become acceptable.

8.3.3 Pack Out Defect Records

A heavy focus was given towards the collection and then analysis of process data to drive continual improvement actions. Another way that the traceability module within MES will drive continual improvement is through the pack out information. The pack out process is the last process on the manufacturing line and involves a manual inspection of the finished product. At the pack out station, the serial number is scanned and passed if it is acceptable or failed if there is a defect. Figure 8.14 shows example data for what was collected during the pack out process.

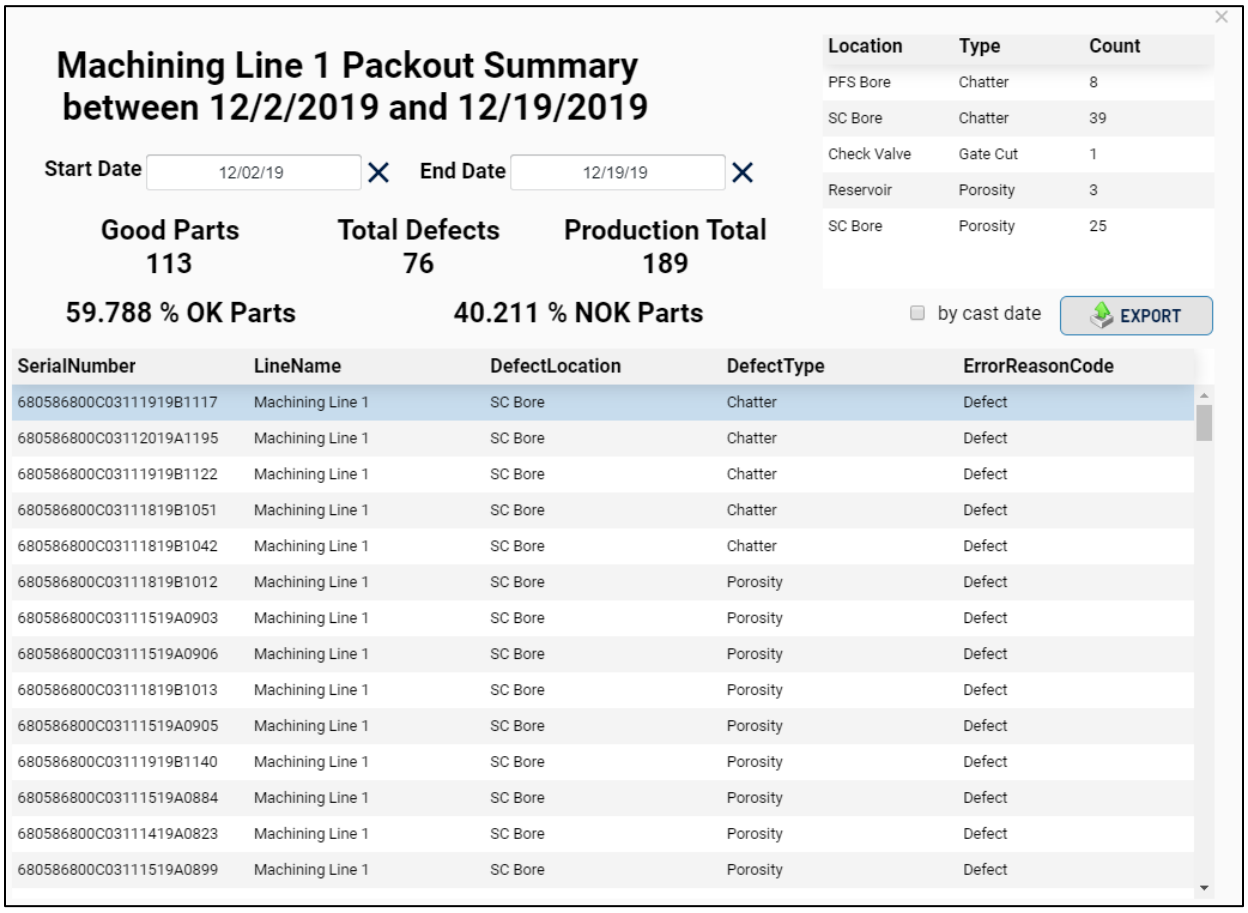


Figure 8.14 Pack Out Report

The above figure shows pack out information from a specific time frame and is adjustable to meet the users need. Once a time frame is selected, general information is provided such as the count of good parts, total defects and the production total. This information is then utilized to determine the percentage of OK and NOK parts. The information is then listed in the bottom table

with the unique serial number and the reason for why it was rejected. The defect location and defect type show the reason for the defective part so that the user can fully understand. This information is then summarized in the table on the top right and groups the unique defect location and defect type failures.

In using the information provided from the pack out station, improvements can be performed to reduce these defects in the future. Continual improvement should start with a focus in which the pack out information provides; a corrective action is implemented and then parts should be ran again to see the impact of the corrective action. As with any corrective action, the first implemented corrective action may not be adequate and will require additional attempts to reduce if not eliminate the defects.

8.3.4 The Traceability Module and FR4

The second functional requirement that is achieved through the traceability module with respect to the 7 FRs is FR 4 and do not advance a defect to the customer of your work. FR 4 is really the intent of the traceability module as it provides validation points within the overall manufacturing value stream. These validation points support PS 4 and the physical solution of traceability gates. Each validation point is considered a gate where the part must meet all requirements to pass through the gate and arrive at the next process. Figure 8.15 shows the decomposition map for FR 4 and the additional functional requirements and physical solutions.

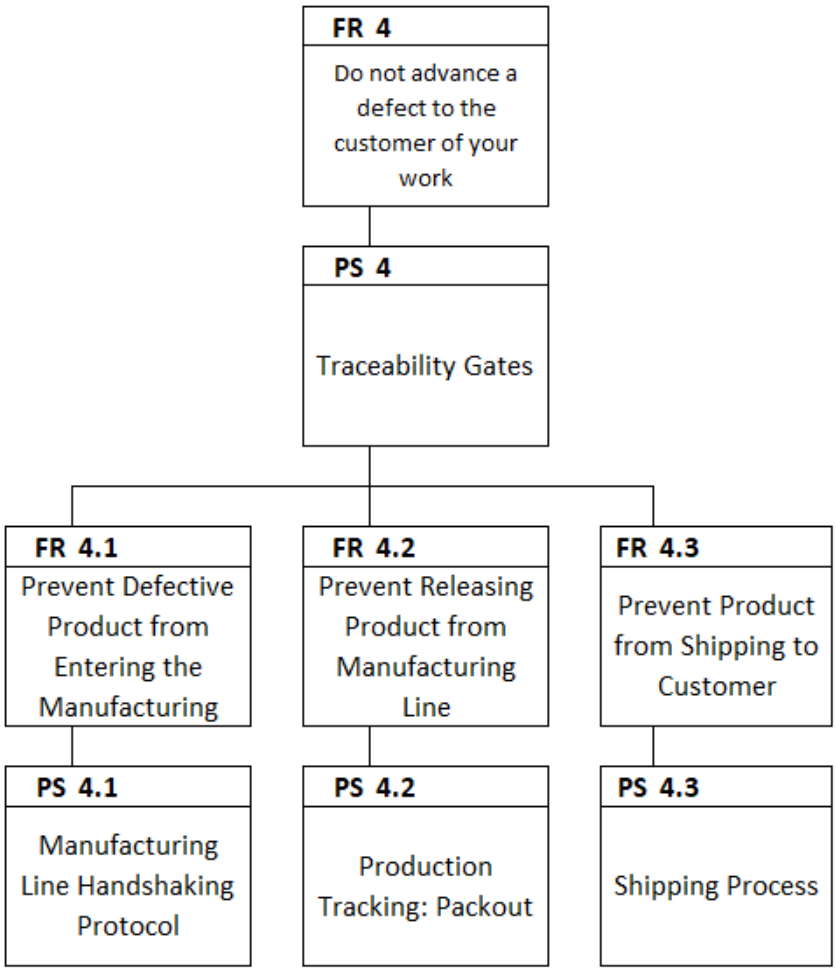


Figure 8.15 Traceability Module FR 4

As the traceability gates have already been mentioned, these traceability gates require the additional functional requirements of FR 4.1, FR 4.2 and FR 4.3. FR 4.1 is to prevent a defective product from entering a manufacturing line that do not meet the specified requirements. To prevent a defective product from entering a manufacturing line, PS 4.1 provides a physical solution for manufacturing line handshaking protocol. Manufacturing line handshaking involves the line scanning the serial number and then allowing the traceability module to validation that the part is ok and has passed all required processes to be accepted into the line. The traceability module then alerts the line about the status of the serialized part and then deals according with that part. The next functional requirement is FR 4.2 and is the requirement of preventing the release of a product from a manufacturing line. To achieve this functional requirement, PS 4.2 was established with a physical solution of the pack out process. The pack out process not only allows for an inspector to

manual reject a part for inspection, but also validates that the part successfully completed all processes within the current manufacturing process. If a part did not successfully go through all specified manufacturing processes, the serialized part is rejected and marked as material review board (MRB). Then the last function requirement for traceability gates if FR 4.3 which is to prevent product from shipping to the customer. FR 4.3 is achieved through PS 4.3 and the physical solution of the shipping process. During the shipping of the product, every part's serial number is scanned and is then validated to be shipped. The product will either be accepted or rejected based upon the products status.

8.3.5 Manufacturing Line Handshaking

Manufacturing line handshaking is used within MES and specifically the traceability module and was established as a physical solution to achieve the function requirement to prevent product from entering a manufacturing line. Handshaking is used for two purposes, confirming a part has passed all required process steps to continue processing at the entry of a manufacturing process and to confirm that all data has been received from the manufacturing process at the end. Figure 8.16 further shows the handshaking diagram between MES and the manufacturing process.

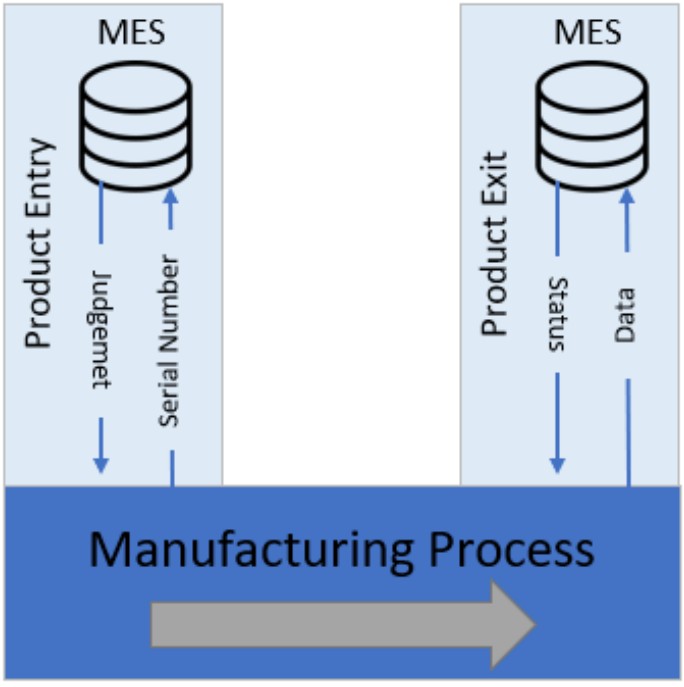


Figure 8.16 Manufacturing Line Handshaking

For the handshaking to work, there is a required interaction between the manufacturing line and MES. The manufacturing line will utilize the Programmable Logic Controller (PLC) since it is the brains of the operation. The PLC will keep a live status of its current handshaking status which is also known as a bit and will continually be monitored by MES. When the PLC bit's status changes, then MES will go in and perform its task. Figure 8.17 shows the process flow for handshaking between MES and the manufacturing line. It is key to note the process flow is the same for both entering the manufacturing line and exiting. The only difference is the PLC bit's location. There is a PLC bit for line entry and a PLC bit for line exit.

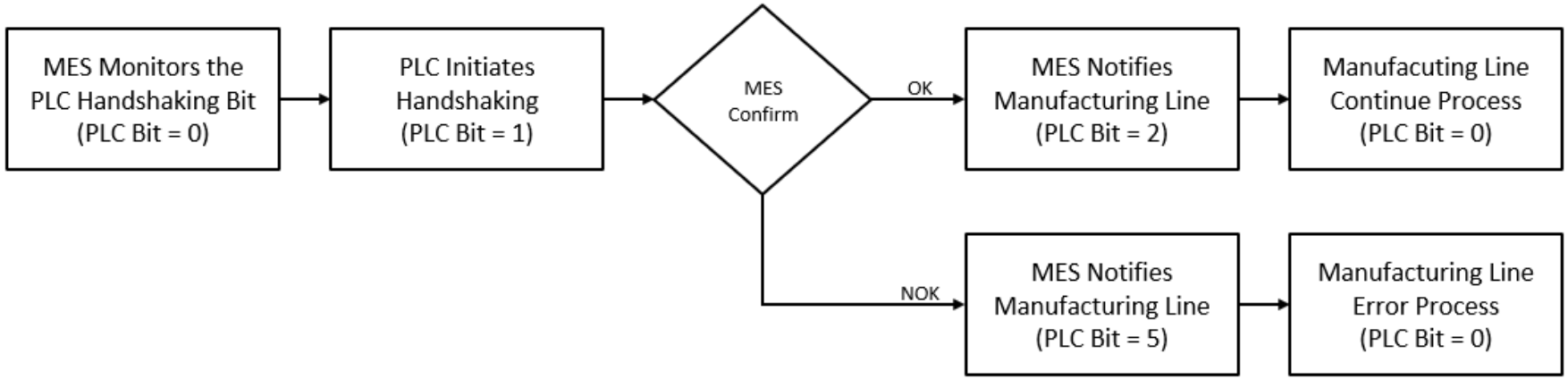


Figure 8.17 Manufacturing Line Handshaking Process Flow

The initial state of handshaking involves the PLC's handshaking bit set at 0. When either a part enters the line or exits, the PLC bit changes from a 0 to a 1 and signals MES to come in to either confirm the previous process steps for successful completion or to collect process data depending on what the address is of the PLC handshaking bit. If MES confirms the part to be ok, MES will then write a value of 2 to the PLC bit in which the manufacturing process continues and the PLC bit is taken back to a value of 0 by the manufacturing line's PLC. If MES confirms the part to be NOK, then MES will write a value of 5 to the PLC bit and the manufacturing line will error and alarm out. At the point of alarming out, the manufacturing line has an error recovery process that needs to be performed to remove the part from additional processing and then the manufacturing line's PLC will write the PLC bit back to a value of 0. This process of handshaking between MES and the manufacturing line allows the prevention of a defective part from entering along with ensuring all traceability data is properly accepted and store before the part can continue in procession. If the handshaking were not to occur, defective parts can either enter a manufacturing line or even have parts exit the manufacturing line without the required level of traceability. Therefore, it is essential to have constant communication between MES and the manufacturing processes so that defect parts are not advanced.

8.3.6 Pack Out Process Validation

As the decomposition map continues with respect to FR 4 and not advancing a defect to the customer, there is a need to contain defective products and a way to do just that is to prevent releasing a product from the manufacturing line. FR 4.2 has a functional requirement of preventing the release of a defect product from the manufacturing line and is achieved through PS 4.2 and the production tracking workstation in the traceability module of MES, and furthermore, the pack out process. The pack out process is the very last process for each manufacturing line and acts as gate system to prevent the release of a defective part. The pack out process includes the scanning of a serialized code to confirm if the part can be advanced to the next process. Figure 8.18 shows a sample of what the pack out user would see for a defective part. The yellow background was designed to give the user an immediate and visual recognition of the parts status. Even if a serialized part was scanned and found to be ok, the user has the ability of marking the part as defective simply by assigned the part with the defect as defined in the dropdowns. This type of manual rejection allows the user to mark a part as suspect and provides data collection for rejected

parts. It is then when the appropriate individuals can look at the data collected from the pack out process and make the appropriate changes to correct the defects.

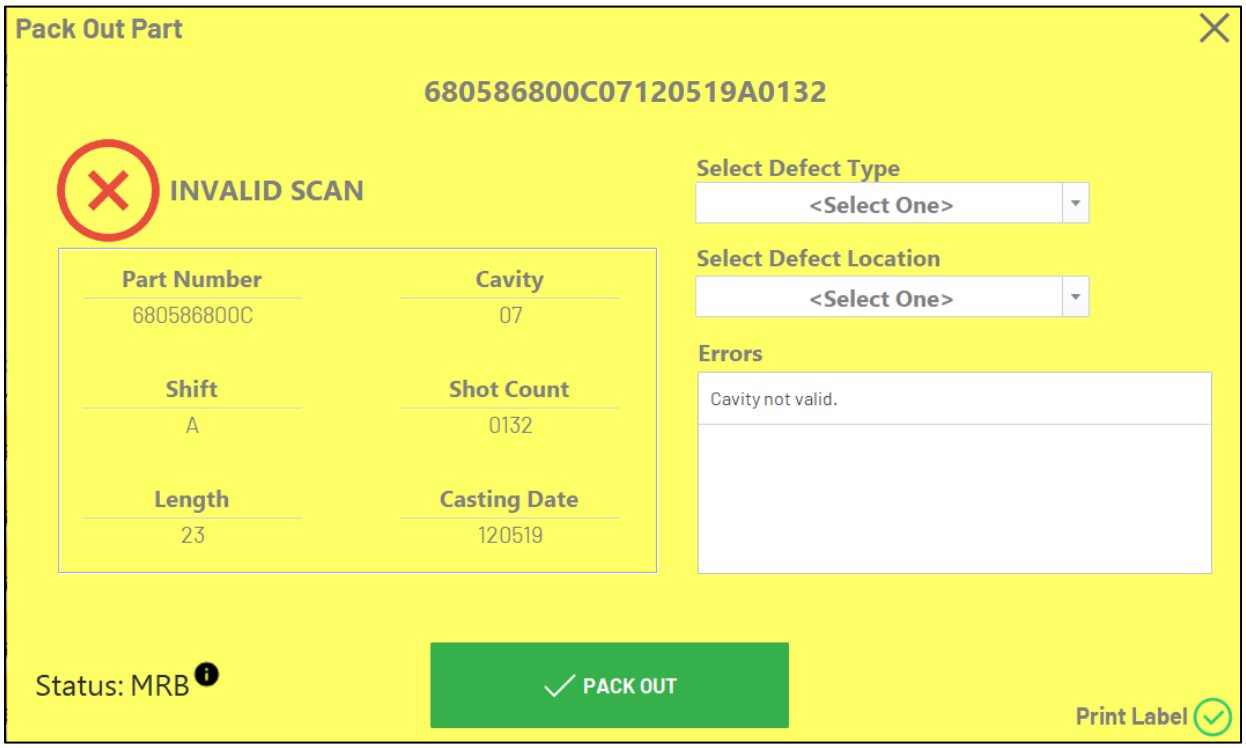


Figure 8.18 Pack Out Defect Screen

8.3.7 The Traceability Module and FR5

As it has already been seen for FR 0 and FR 4; FR 5 will also be shown via a decomposition map. The functional requirement of FR 5 is to immediately identify disruptions and resolve them for the long term. To truly meet this requirement, the first step is to identify disruptions so that individuals are aware of an abnormality and they can respond. The next step is to correct the abnormal event and ensure that the correct actions were taken so that the concern does not occur in the future. Figure 8.19 shows the decomposition map for FR 5 and the additional physical solutions and functional requirements that are needed.

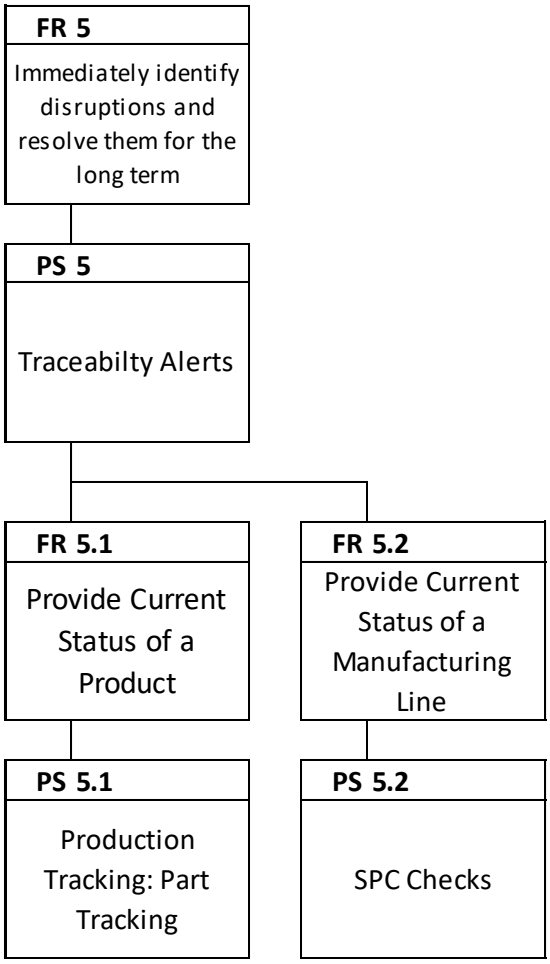


Figure 8.19 Traceability Module FR 5

To achieve FR 5, PS 5 was established and has a physical solution of traceability alerts. The traceability alerts provide not just an alert or status of an abnormal situation but is the starting point for identifying the abnormal events so that corrective actions can be applied. Under PS 5, two additional functional requirements were established and can be seen in FR 5.1 and FR 5.2 respectively. FR 5.1 has a functional requirement to provide the current status of a product. This functional requirement really looks at the product individually and is achieved through PS 5.1 and the physical solution of part tracking under production tracking which is a part of the traceability module. The next functional requirements under traceability alerts lies in FR 5.2 and is to provide the current status of a manufacturing line. To achieve FR 5.2, PS 5.2 has the physical solution of SPC checks as embodies the core tools needed to ensure that the manufacturing line is performing

in a capable and predictive manner. Therefore, any noticeable shift in a SPC check and more specifically control charts, provides evidence that some abnormal event has just occurred with the manufacturing line. In conclusion, both the part tracking an SPC checks look at a different aspect that together provide transparency to abnormal events and therefore meeting the functional requirement of immediately identifying disruptions and then providing additional tools so that the correct actions are put into place so there is no re-occurrence.

8.3.8 Part Tracking

In looking at immediately identifying disruptions, the first aspect is to look at the product level. FR 5.1 states the looking at the product level with a functional requirement to provide the current status of a product and is achieved through PS 5.1 and the physical solution of part tracking. A user can either pick a serial number from the latest parts running or have a search box option where they can scan their part to find what they are looking for. An example of the part tracking feature is provided in Figure 8.20 below. The part tracking screen allows the user to find the operation that the part needs to run through under the Operation column and then find where the part ran under the executed at column. Additional information is provided in the status column stating the status of the part through each operation along with the last activity column which indicates when the part ran that specific operation.

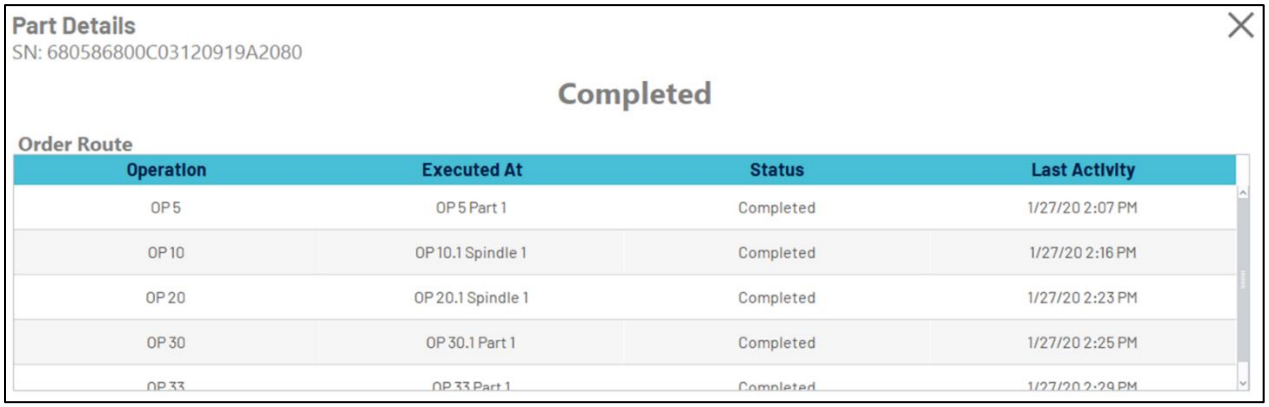


Figure 8.20 Part Tracking

With the top FR stating to immediately identify disruptions and resolve them for the long term, the first step is to identify disruptions. Only can disuptions be resolved for the long term if

they are first noticed and then the root cause is determined so the proper corrective action can be put into place. Figure 8.21 starts this process by identifying the disruptions and then additional analysis can be completed.

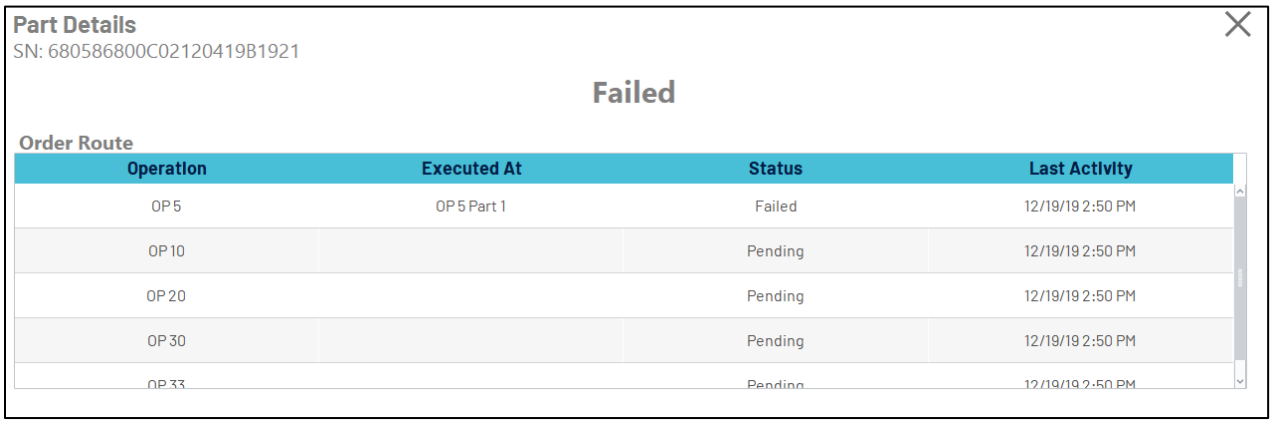


Figure 8.21 Part Tracking- Identify Disruptions

Figure 8.21shows a serialized product with the status of "Failed" and the overall product information associated with that part. It is at this point that the user would take the serial number from that serialized product and dive deeper into the reason for the failed product. The operation that the serialized product failed at can be seen in Figure 8.21and would give the user a place to start the root cause analysis. Then when the user does find the root cause of the failure then attempts of implementing a corrective action can be taken so that is does not occur in the future.

8.3.9 SPC Checks

As it was already stated about immediately identifying disruptions, the first aspect looks at the product level. It is now time to talk about the second aspect which includes look at the manufacturing line level. FR 5.2 has a functional requirement to provide the current status of a manufacturing as of a way fulfilling the traceability alerts as has a physical solution in PS 5.2 of SPC checks. SPC checks were established to give a general overview of the manufacturing process and was designed to act as a health check from varying angles. These varying angles can be found in Table 8.2 where multiple tests are to be utilized.

Table 8.2 Containment Results

Test	Test Description
1a	Measurement is outside of the defined control limits using the ± 3σ method
1b	Measurement is outside of the defined control limits using the capability method
2	9 points in a row are on the same side of the center line
5	2 out of 3 points > 2σ from the center line
6	4 out of 5 points > 1σ from the center line

Test 1a in SPC checks has the description to determine if the measurement is outside of the defined control limits using the ± 3σ method. This test looks at an individual serialized product and compares the measurement(s) as defined from the print and compares it with control limits. The control limits are set to be $\bar{x} - 3\sigma \leq \bar{x} \leq \bar{x} + 3\sigma$ which according to a normal distribution would account for 95% of products. Test 1b then takes a similar approach to 1a but confines the control limits to a tighter tolerance. Test 1a uses the lower and upper specification limits as the outer bounds while test 1b takes and pre-calculates the σ level as it relates to the desired capability of the process element. Therefore, test 1b would be a tighter range than 1a and would therefore provide a different alert. Test 1a would provide the alert that the process has a modified distribution where test 1b would state that the process has a modified capability level with respect to the original distribution. Moving into test 2, the description has 9 points in a row being on the same side of the center line. This test looks at the past 9 points of a given element to determine if the process is trending, either up or down and give an indication that something abnormal is starting to occur. Test 5 then looks at the last 3 points and determines if 2 point are greater than 2σ from the center line. Test 5 looks at larger shifts in the mean that happen suddenly. The last test is test 6 and is like test 5 but looks at the last 5 points to see if 4 of those 5 are greater than 1σ from the center line and looks at smaller shifts in the mean that are maintained over a longer period. It can

therefore be said that each test under SPC checks have their own reasoning and helps to identify different types of variation or abnormality as it relates to the manufacturing process.

8.3.10 Conclusion

In conclusion, the 7 FRs hold specific meaning to different aspects of manufacturing and were analyzed for their applicability to MES as it relates to inventory and traceability. It was found that out of the 7 FRs that two were applicable to the inventory module:

- FR0: Continually improve
- FR5: Immediately identify disruptions and resolve them for the long term

And three were applicable to the traceability module:

- FR0: Continually improve
- FR4: Do not advance a defect to the customer of your work
- FR5: Immediately identify disruptions and resolve them for the long term

Each one of the 7 FRs had their own value with respect to the inventory and traceability modules and therefore required additional functional requirements and corresponding physical solutions which was illustrated by decomposition maps. It was then that additional information was provided for how the lower level functional requirements and corresponding physical solutions were established to achieve the top-level FR. In addition to the information, real-life examples were given as evidence to show how each physical solution was being utilized. It is through this decomposition process and real-life examples help to illustrate the controls that MES can have in the manufacturing facility and on the manufacturing processes. And without control in the manufacturing facility and on the manufacturing processes, the company could severely suffer and result in unfavorable results.

9. CONCLUSIONS AND FUTURE WORK

9.1 Lessons Learned

There were many lessons learned found out through the development of MES. The top two lessons learned are as follows:

- System users do not know what they really want until they see it
- Need to better define or not change system boundaries to minimize requirements creep

The first lesson learned deals with understanding what other individuals want. This task of determining what others want can be a very daunting task when many times, the individuals you are asking, does not know what they want until they see it. There were many times throughout the development of the thesis that the content the individual wanted remained the same, they just wanted to see it in a different manner. This lesson learned was not too great of an undertaking but is something to watch out for in the future.

The second lesson learned is a little more cumbersome as it deals with the system and more specifically the system boundary. Requirements creep was encountered during the system design and resulted in expanding the system boundary. Expansion of the system boundaries itself is not a concern if it is truly necessary and beneficial for meeting customer needs. An instance of the system boundary expansion was in the inventory module and a feature set addition for physical inventory. It was deemed necessary to include physical inventory to validate that all inventory functions were being executed properly.

In conclusion, the main point underlying the lessons learned came down to data collection and reporting. In the beginning of development, the stakeholders had a very small idea of what MES could place control on. Then when MES started controlling various processes, the stakeholders continued coming back with additional requirements. In some cases additional requirements expanded system boundaries while others did not. Therefore, for any future projects, this type of resolution for what can be done needs to be spelled out in more detail to have a better matching scope from the beginning to the end of a project.

9.2 Future Work

9.2.1 Future Work Introduction

There will be future work to MES which includes adding additional feature sets that provide more overall control along with using the data through data analytics to provide data driven decisions for the manufacturing processes. Additional requests have already been made to provide the desired control that will expand the current system boundary. As more and more individuals within the manufacturing facility see the control that MES can have on various operations, additional requests will come to provide the desired control.

In addition, a vast array of data is being collected from the manufacturing facility that currently is being stored at the database level. By storing the data alone, there is no value and something needs to be done. Data analytics provide a method to utilizing the stored data in a way that brings benefit that is explained in section 9.2.3. Therefore, data analytics may be used to provide future insight into processes to provide continual improvement activities and thus reducing costs and increase profits. With these future actions, we will now look at some of the initial ideas that can be explored for both additional features of MES and providing data analytics.

9.2.2 Additional Features of MES

As MES continued to gain acceptance and individuals within the manufacturing facility started to realize the control that MES could provide, additional request were made in the form of customer needs. The customer needs that would formed from these additional requests include:

- Require specific part numbers to go through a cleaning process before going to the manufacturing line
- Allow software reflash while maintaining traceability

These customer needs were then analyzed for better understanding and contributed to defined functional requirements. The functional requirements are as follows and can be linked to their respective customer need:

- Provide cleaning process for specific parts.
- Provide the ability to reflash products

The functional requirements determined for how they could be achieved thus establishing a physical solution for each functional requirement. The following physical solutions aim to achieve the functional requirements above:

- Part specific cleaning route
- Software reflash process

The first request is to create a process where specified part numbers need to go through a special cleaning process before they are be moved to the manufacturing line. This additional feature will allow for parts to come in the door and be auto assigned an indicator that they need to be cleaned. The parts would be flagged when received to indicate that they need to go through the cleaning process. Then when the parts successfully pass the cleaning process, the "needs to be cleaned" flag would be removed allowing parts to move to the manufacturing line. If the parts were not to go through the cleaning process, then the MES software would restrict parts from being moved and provide a trigger that those parts are not allowed to be used on the manufacturing line.

Then the second additional feature is to develop a method for software flashing while maintaining traceability. For example, one of the parts that is in-house requires some board level software to operate a higher-level software that runs the operations of the final product. There is a request that this part, no matter whether assembled or not, has the capability of flashing the required software. Therefore, future work will include the ability to flash the part and to maintain traceability. If the unit is built into a finished product, then care will need to be taken to ensure the product has the correct part number to ship to the customer.

It is through the CSD methodology that these additional requests will be added to the system. MES is more than likely going to expand and it is key to stick with the same methodology so that unwanted design types are not encountered. Thus, the future work currently understood is a next phase of the system design process but will look a little different in having a core framework to append future work on.

9.2.3 Data Analytics

Data analytics can be very cumbersome when there is a large amount of data. MES has the ability of collecting and storing massive amounts of data. As this thesis has shown, there is a lot of data being collected with MES and is then stored in a database. To overcome this difficulty as

a starting point, the approach is to select a number of items will be evaluate using data analytics. The need is to evaluate the following two areas within the realm of inventory through data analytics and include the following:

- Drive down excessive inventory levels by lowering trigger points and order quantities
- Drive down excessive inventory movement by ensuring the desired flow is followed while striving for an optimal route

The first item for data analytics in the area of inventory is to drive down excessive inventory as it is the main contributor to waste within any manufacturing facility. If the excessive inventory were to exceed shelf life or become out of date, then all that inventory when end up becoming scrap. This excessive inventory can be tracked to determine what the optimal level of inventory is required and then the ordering of material could gradually change by lowering the point for when inventory is ordered along with a potential to order a smaller quantity at a given time. The second item for the area of inventory is to drive down the excessive movement within the manufacturing facility. Every time inventory is moved, there is a cost associated and the goal is to eliminate as much cost as possible. Upon the design of the process, the most optimal route would have been set up. However, variables can change over time which would lead to a recalculation of the optimal route. Data analytics can support the flow of material in two ways. First, the movement of inventory can continually be monitored to ensure that the material is always going through the same route. If there are instances where material does not go through the standard route, root cause analysis can then be performed and a corrective action can be put into place. Second, the standard route will be challenged to determine if it is still optimal when a trigger point occurs. For instance, a trigger point could be a change in layout whether in the warehouse or in the manufacturing area. It is only through the analysis and challenging of the current route that a better route could be isolated and then standardized.

Then moving outside of the area of inventory, the next area will focus on traceability. The area of traceability provides a great deal of data and will therefore be broken down to machining and assembly. When it comes to machining, data analytics will look at the following:

- Better isolate tooling abnormalities through tool wear tracking
- Extend tool life through measurement data analysis and variable tool life

The first item under machining is to better isolate tooling abnormalities such as underutilized tool life, a chipped tool or even a broken tool which will be achieved through tool wear tracking. The traceability data collected provided all tool life data along with other information that can be tracked to help determine if an abnormality will occur. The main dataset that will be looked at is processing data such as cycle time and tool temperatures. The second item is similar and will look to extend tool life to the point that the next part machined would produce a defect. To accomplish maximum tool utilization, the tool life will be analyzed according to sample measurement data to provide the maximum tool life value on a serialized tool level. For both items in the area of machining traceability, the intent is to extend tool life to its maximum without producing a defect.

Moving outside of machining, assembly will also use the traceability data to help drive improvements through data analytics. Assembly will look to perform the following items:

- Determine process failures of press stations through continuous data analysis
- Drive process performance through using previous process results to drive down stream processing

The first item for assembly will help determine process failures of press stations. For the operation of pressing, there is a lot of data coming from each press station that can be analyzed to help determine the optimal parameters so that tooling and other equipment are utilized to their full potential. Some of these parameters that can affect the integrity of an assembly product include the servo speed, peak load and initial load start point. The second item is a little different than the first and will look to drive process performance by using data from a subsequent process to drive the process down-stream. This would entail using variable processing parameters throughout a

manufacturing line so that the amount of defect parts made can be reduced if not limited through the improvement of process capability.

9.3 Conclusions

In conclusion, there are many avenues to pursue for the future with respect to additional features of MES and data analytics. As there are many potential paths that could be executed in the future, the manufacturing facility's management needs to define the priority so that a plan can be developed and implemented. If the items are not isolated and an action plan created, priorities from outside individuals may restrict already started tasks from being completed. It is also a good learning point to see one item to completion, acquire lessons learned and then apply those lessons learned to the next items It is only through this process that the best method can arise and will performed throughout the additional features added to MES.

As there have been many different requirements from many different individuals, the design process helped to provide collaboration and drive efforts to link all aspects of MES together. The initiation of connections across the various module of MES was due to the CSD process. If it were not for the structured approach as provided through CSD, the requirements creep that was experienced would have been much harder to deal with and could have potentially halted the project. Looking a little farther in CSD, the design types were found to be tremendously helpful. As requirements creep was experienced, the task of placing that requirement into the overall design would have been difficult if it were not for the decomposition mapping process. There were many times then going through the process of adding the additional requirement that the Functional Requirement was either coupled or path dependent at another level. Additional research was then conducted and exposed a better solution that originally experienced and found to be either uncoupled or path dependent at the correct level.

When it comes to the design of any system, there are many lessons learned that will drive changes in the development of designing another system. Even with the systematic design of MES, there were lessons learned that will provide context for what will be done differently in the future. The lessons learned as explained in section 9.1, deal directly with better understanding the customer requirements and providing better definition to the system boundaries to minimize requirements creep. It was from these lessons learned the following items will be done differently in the future:

- Provide stakeholders with the initial system boundary to ensure the customer requirements are correct.
- Make visible the system boundary during the system design for all stakeholders.
- Communicate with the stakeholders when additional requirements come in. Review the requirement with respect to the system boundary and explain the implications of the additional requirements with the team.

The first item to do differently is to provide stakeholders with the system boundary at the start of the project to ensure that all stakeholders can see how their requirements have been interrupted and so that they can see the overall concept of design. Without sharing the system boundary, the stakeholders may not fully understand the scope of the project and then continually thinking of additional requirements that might be nice to have. This leads us to the second item which is to make visible the system boundary during the design process. As it was mentioned in the first item of sharing the system boundary at the beginning, the second item expounds on making the system boundary visible throughout the entire design process so the stakeholders can have a continual reminder of what the overall system when encompass. Then for the third item, when additional requirements come, it is essential to make the stakeholder fully aware of the changes that will need to be made along with the implications that may come with it. An example of an implication for adding a requirement is timing. If additional requirements are given, there is time associated with the additional along with the effect of the overall timing. Therefore, it is essential to notify the stakeholder so there is common understanding throughout the entire design and implementation process.

Even though there were lessons learned and items to be done differently in the future, the systematic approach for designing MES was found to be beneficial. The use of CSD and Decomposition Mapping aided in streamlining the entire process and ensuring the best design would be implemented. If it weren't for the CSD process and Decomposition Mapping, the overall design would have been plagued with confusion, leading to a poor design. The following were the main conclusion points from the entire process of system design.

- CSD provided a core methodology to help stay on track during the development process and not gravitate towards the nice to haves.
- CSD provided a common language to communicate requirements and solutions with the working group.

Through this structured approach, MES was designed to provide control for the manufacturing facility and the subsequent manufacturing processes. It is through the CSD methodology that MES will continue to provide control for the future.

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