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Internal Logistics Process Improvement through AGV Integration at TMMI

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ABSTRACT

The purpose of this project was to improve and optimize the internal logistics activities associated with the Under Rear process at Toyota Motor Manufacturing Indiana (TMMI) to alleviate the ongoing labor shortage challenges in the manufacturing industry. This general objective is achieved through the integration of an Automated Guided Vehicle (AGV) system and the application of lean manufacturing principles. The Under Rear AGV system is designed, simulated, and analyzed with the use of FlexSim, a discrete-event simulation software. To design this system, it was necessary to determine the required number of AGVs, picking and delivery locations, as well as the flow path and layout configuration. Activities such as unnecessary motion and waiting were eliminated, thus contributing to better ergonomics and an increase in safety. Additionally, the repurposing of team members from non-value-added activities that include the transportation of parts around the manufacturing can be achieved through the integration of this AGV system and leads to a substantial overall cost reduction. Additionally, facility layout improvements were implemented, leading to a reduction in distance traveled of 30.45 meters. Furthermore, a projected increase in operational availability of 10% is accomplished, while far exceeding TMMI's operational requirements. The AGV system design also provides various benefits in the context of environmental CO_2 emissions, opportunities for global scalability, and maintainability.

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1. INTRODUCTION

Toyota Motor Manufacturing Indiana (TMMI) located in Princeton, Indiana, is one of the fourteen manufacturing plants in North America. TMMI, as a competitive manufacturing plant in the automotive industry, is committed to the integration of innovative technology to achieve its ambitious automation targets and reduce the need for human work in its manufacturing processes. This leads organizations to enter into a series of continuous improvement activities to guarantee sustained customer satisfaction and to level up competitiveness with other competitors (Correia 241). TMMI uses a lean manufacturing philosophy acting in accordance with the Toyota Production System (TPS) principles. Thus, it is critical to reduce wasteful activities is critical.

Due to the COVID-19 pandemic, labor shortages, and logistical challenges, TMMI intends to find processes that are currently labor-intensive and automate them. This way, team members can be repurposed to complete value-added activities, alleviating the labor shortage challenges. The scope of this project covers the reduction of waste in an internal logistics process through automation and labor repurposing. An internal logistics process that has several wasteful activities such as waiting, excess motion, and manual transportation is the Under Rear (UR) process. One way of improving the internal material handling of Under Rear parts is through Automated Guided Vehicle (AGV) Systems integration (Kumbhar 4). This paper describes the process improvement activities that were carried out to reduce waste and labor costs as well as increase productivity in a TMMI internal logistics process through the integration of an AGV System.

To accomplish the overall project objective several aspects were studied. First, the initial state was analyzed through the investigation of the existing layout configuration, the sequence of operations, and the identification of the requirements specifications. Secondly, to implement the AGV system, it was essential to determine an optimal travel path, select an AGV based on customer requirements, identify the number of vehicles needed based on speed capabilities, and establish an improved sequence of operations. Thirdly, FlexSim, a simulation modeling software, is used to validate the AGV system conceptual design through the confirmation of performance indicators such as utilization rate and cycle time. Finally, a cost and economic evaluation is performed to justify this AGV system implementation project as an economically feasible endeavor. The project timeline defined for this process improvement activity can be found in Appendix A.

2. BACKGROUND

2.1. Labor Shortage Challenges

The COVID-19 pandemic has drastically affected the world's economy since its beginning in January 2020 with the intensive implementation of large-scale containment measures by governments to contain the spread of the COVID-19 virus (Verschuur, et al. 1). Moreover, retaining a skilled workforce in the manufacturing sector has been one of the most prominent challenges even before the pandemic, which worsened the ongoing issue ("Addressing the Manufacturing Skilled Worker Shortage" 13). Many manufacturing companies such as TMMI intend to tackle the labor shortage challenges through technology implementation and the repurposing of the current workforce to value-added activities.

2.2. Lean Manufacturing Framework

2.2.1. Seven Wastes

The seven wastes identified by Shigeo Shingo include overproduction, inventory, transportation, defects, waiting, motion, and non-utilized talent (Santos, et al. 27). These are activities that do not add any value to the actual product and must be eliminated when possible. The continuous effort to reduce and eliminate waste from processes is critical in the manufacturing environment to achieve optimal performance. Moreover, TMMI follows the global Toyota Production System (TPS) protocols, which focuses on the elimination of waste in value streams through lean production (Lander and Liker 3681)

2.2.2. Material Handling

Material handling includes all the flow, movement, and storage of materials within a manufacturing plant. Material handling can be costly and is regarded as non-value adding function that can account for more than one-half of the total cost of manufacturing (Green, et al. 2975). The cost associated with material handling and transportation systems can be reduced significantly if lean manufacturing principles are used to continuously improve these systems. Additionally, the incidence rate of injuries associated with transportation can be improved through the optimization of material handling systems.

There are 10 material handling principles recognized by the College-Industry Council on Material Handling Education (Ten Principles of Material Handling). Some of these will be considered throughout the project and are as follows:

1. Planning Principle. A plan is a prescribed course of action that is defined in advance of implementation. In its simplest form, a material handling plan defines the material (what) and the moves (when and where); together they define the method (how and who).

2. Standardization Principle. Standardization means less variety and customization in the methods and equipment employed.

3. Work Principle. The measure of work is material flow (volume, weight, or count per unit of time) multiplied by the distance moved.

4. Ergonomic Principle. Ergonomics is the science that seeks to adapt work or working conditions to suit the abilities of the worker.

5. Unit Load Principle. A unit load is one that can be stored or moved as a single entity at one time, such as a pallet, container, or tote, regardless of the number of individual items that make up the load.

6. Space Utilization. Space in material handling is three-dimensional and therefore is counted as cubic space.

7. System Principle. A system is a collection of interacting and/or interdependent entities that form a unified whole.

8. Automation Principle. Automation is a technology concerned with the application of electromechanical devices, electronics, and computer-based systems to operate and control production and service activities. It suggests the linking of multiple mechanical operations to create a system that can be controlled by programmed instructions.

9. Environmental Principle. Environmental consciousness stems from a desire not to waste natural resources and to predict and eliminate the possible negative effects of our daily actions on the environment.

10. Life-Cycle Cost Principle. Life-cycle costs include all cash flows that will occur from the time the first dollar is spent to plan or procure a new piece of equipment, or to put in

place a new method, until that method and/or equipment is totally replaced. (Ten Principles of Material Handling)

2.3. Automated Guided Vehicles

An automated guided vehicle (AGV) is a driverless industrial truck. It is a steerable, wheeled vehicle, driven by electric motors using storage batteries, and it follows a predefined path along an aisle (Tompkins, James A., et al 240). The path followed by an AGV varies and it can be a simple loop or a complex network, which is accomplished with a path-following system integrated into the AGV. There are three main types of AGVs that are typically considered in internal logistics operations (Dass and Rakesh 1-2):

1. Forklifts: Used when the system requires automatic pickup and drop-off loads from floor or stand level and where the heights of load transfer vary at stop locations. An example of a forklift AGV type can be seen in Figure 1.

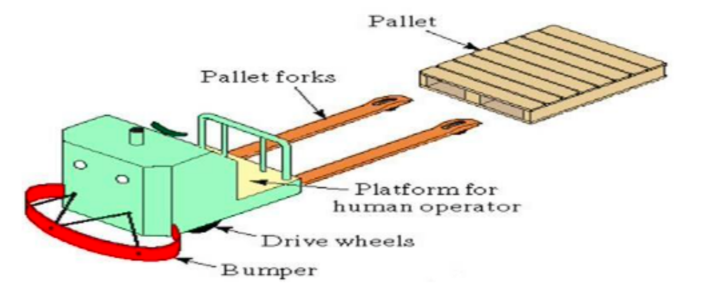


Figure 1: Forklift AGV

2. Tow/Tugger: Towing applications involved the bulk movement of product into and out of warehouse areas or direct service to a manufacturing/assembly operation. Usually, side path spurs are placed in receiving or shipping areas so that the trains can be loaded or unloaded off the main lune without hindering the movement of other trains on the main path. This system is also used when the distances are long, and its use can be justified through the elimination of fork trucks or manual trains and operators. An example of a tugger AGV type can be seen in Figure 2.

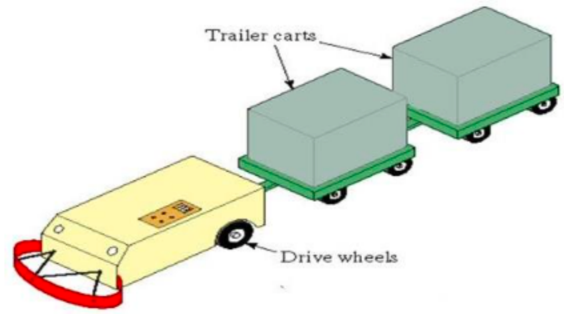


Figure 2: Tow/Tugger AGV

3. Unit Load: Applications involve specific mission assignments for individual load movement. These are utilized quite often within storage retrieval systems. An example of a unit load AGV type can be seen in Figure 3.

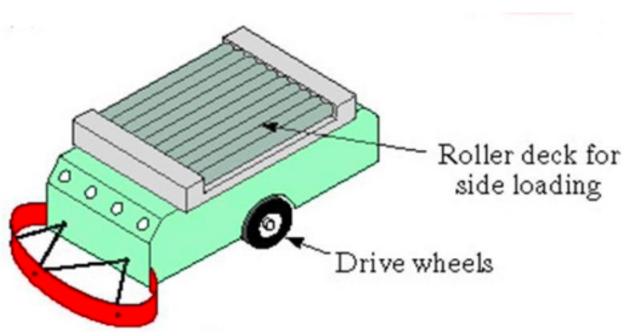


Figure 3: Unit Load AGV

For the purposes of this project, the two/tugger AGV type was found to be the most suitable for this application because the transportation occurs over a long distance within the manufacturing plant at ground level and the mission assignments involve the movement of multiple parts simultaneously. Both conditions regarding the expected working environment of the system suggest that the tow/tugger AGV type is the most fitting for this specific application

2.4. SIMULATION MODELING

Simulation models can be used to facilitate the design process and support the decision-making process. A model is a simplified representation of the dynamics of a real-world application that provides realistic results and can highlight factors that are relevant to the problem (Blanchard and Fabrycky 121). The simulation-based technologies constitute a focal point of digital manufacturing solutions since they allow the experimentation and validation of different product, process, and manufacturing system configurations (Mourtzis 1942).

FlexSim is an effective simulation software that has allowed researchers to accurately analyze production logistic systems, assess outcomes of multiple scenarios, and improve production efficiency, throughput, and resource utilization (Tellis, Ranjith, et al 83). The basic steps of simulation can be divided into six steps: Formulate the problem statement, build a conceptual design for the proposed solution, define the sequence of operations for the system, construct the simulation model, validate the conceptual design through the required operational parameters, and analyze the simulation results. Ultimately, FlexSim can be used to model an AGV system in the context of material handling in a manufacturing environment and validate decisions during the system design. FlexSim is the software utilized by TMMI engineers.

2.5. System Development Life Cycle

The System Development Life Cycle (SDLC) is a phased approach to the analysis and design of engineering systems. The SDLC includes the following phases according to Daniel Dasig Jr (2):

1. **Preliminary study**

This is the first phase in the systems development process. It identifies whether there is a need for a new system to achieve a business's strategic objectives or not. The purpose of this step is to find out the scope of the problem and determine solutions.

2. **Systems Analysis and Requirements**

The second phase is where the root cause of the problem or the need for a change is identified. In the event of a problem, possible solutions are analyzed to identify the best fit for the goals of the project. This is where the functional requirements of the project or solution are considered. It is also where system analysis takes place or analyzing the needs of the end-users to ensure the new system can meet their expectations.

3. **Systems Design**

The third phase describes, in detail, the necessary specifications, features, and operations that will satisfy the functional requirements of the proposed system which will be in place. This is the step for end-users to discuss and determine their specific business information needs for the proposed system. It is during this phase that they will consider the essential components (hardware and/or software) structure (networking capabilities), processing, and procedures for the system to accomplish its objectives.

4. **System Development**

The fourth phase is when the system is developed — in particular, when programmers, engineers, and other system developers are brought on to do the major work on the project. This work includes using a flow chart to ensure that the process of the system is properly organized. The development phase marks the end of the initial section of the process. Additionally, this phase signifies the start of production.

5. **Integration and Testing**

The fifth phase involves systems integration and system testing of programs and procedures. During this phase, it will be determined if the proposed design meets the initial set of business goals. Testing may be repeated, specifically to check for errors and interoperability. This testing will be performed until the end-user finds it acceptable.

6. **Implementation**

This phase involves the actual installation of the newly developed system. This step puts the project into production by moving the data and components from the old system and placing them in the new system. Both system analysts and end-users should now see the realization of the project that has implemented changes.

7. **Operations and Maintenance**

The seventh and final phase involves maintenance and regular required updates. This step is when end users can fine-tune the system, boost performance, add new capabilities or meet additional user requirements.

For the purposes of this project, the focus on the initial phases (Preliminary Study, System Analysis and Requirements, System Design) will be highlighted throughout the paper. The system development, testing, implementation, and maintenance operations are not within the scope of this report. Nonetheless, the entirety of the project will be completed to meet TMMI's deadline of Winter Shutdown 2022 in December. The seven phases of the SDLC described above are also displayed in Figure 4, highlighting in green the phases that are within the scope of this report, and in orange the phases that are not.

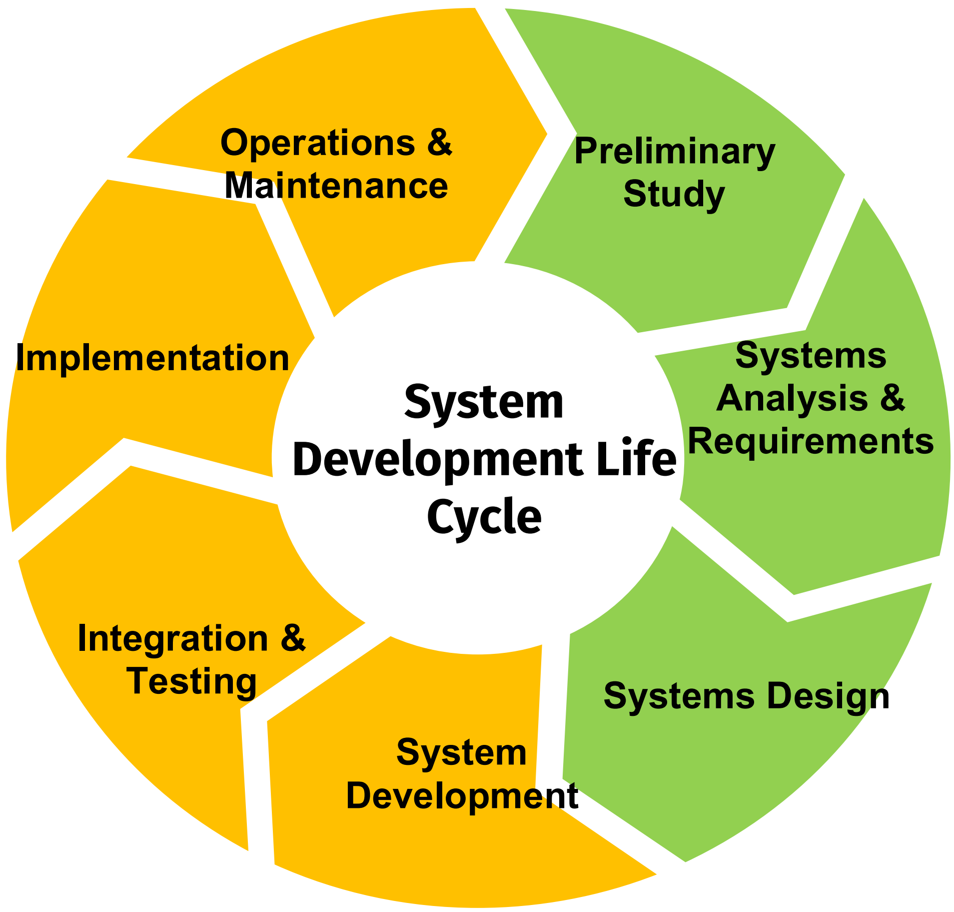


Figure 4: System Development Cycle Life

3. OVERALL SYSTEM DESCRIPTION

This section summarizes the project rationale and objective, describes the proposed system solution with its appropriate justification, supportability considerations, and the stakeholders who have an interest in this AGV system

3.1. Problem Statement

The existing system that transports parts from the Loading dock area to the UR lineside location is a labor-intensive process that requires tugger drivers, assembly workers, and other team members to effectively load, unload, and assemble parts. This process is associated with many of the wasteful activities associated with lean manufacturing including waiting, non-utilized talent, transportation, and extra motion. Along with this, TMMI plans to move from two eight-hour shifts to three 8 hour-shifts by 2023. This will require the addition of 3 team members to deliver dedicated routes in the Under Rear process under the current sequence of operations.

3.2. Objective Statement

The overall mission of this system is to support TMMI's efforts to increase the levels of automation across the manufacturing plant. Automating the transportation aspect of some of TMMI's internal logistics processes will lead to ultimately repurposing non-utilized talent, eliminating waiting and unnecessary motion, while increasing productivity for the team members involved in the process, and achieving a labor cost reduction. This will also aid the manufacturing plant to become more flexible and address the current labor shortages that have resulted from the COVID-19 pandemic.

3.3. Description of the Proposed System

The proposed solution to address the problem statement while achieving TMMI's objectives consists of an AGV system that will automate the Under Rear internal logistic process. The AGV System will have the capability of transporting all the UR parts in a loop between the Loading dock area and the UR lineside location. The existing tugger drivers will be repurposed to assist with value-added activities where needed in the plant. Also, team members that had low productivity due to waiting and unnecessary motions will increase their utilization rate by having an increased responsibility in the process. These team members will be responsible for directing the loading and unloading activities with the AGVs, rather than waiting for the tugger driver to do so. This will eliminate waiting and unnecessary motion originating from having to move containers around constantly.

3.4. Solution Justification

The integration of automated handling equipment such as robots is proven to improve material handling operations in the manufacturing environment (Nilsson 6). Automated Guided Vehicle systems are one of the solutions that have addressed the growing cost of labor and its scarcity over several decades. AGVs provide an alternative that has successfully reduced labor costs, enhanced plant ground safety, and eliminated human errors caused to products and conveyor damage in large manufacturing industries (Kumbhar 4). Moreover, Toyota Motor Manufacturing, Indiana Inc. has had several successful AGV integration projects that have led to many of these operational benefits.

3.5. Supportability

The AGV System will be supported by the maintenance team at TMMI, and the manufacturer of the Automated Guided Vehicle chosen to deploy the project. Team members in charge of unloading and loading parts will be trained to operate the AGVs and understand the safety features associated with them. A user operator manual provided by the manufacturer will also work as a reference for all the operators involved with the AGV system. Additionally, this system will be considered economically justified if a two-year payback is achieved and the appropriate risk assessments will be completed.

3.6. Stakeholders

TMMI is the client and sponsor of this project. Therefore, this project must meet TMMI's standards and acceptance criteria. Other stakeholders involve people and organizations who are affected by this system, or whose input is needed to build the product. The stakeholders involved in this project are the following:

- Production team members
- Maintenance TEAM
- Internal Logistics Engineers
- Innovation Engineers

- Safety Team
- Accounting personnel (Budget)
- IT Department
- Human Resources (Repurposing of team members)
- Designers & developers of selected AGV
- System Engineers
- Software Engineers
- Regulators (OSHA, Government, etc.)

4. REQUIREMENT SPECIFICATIONS

In this section, the requirement specifications for the AGV system to effectively transport parts in a continuous loop between the Loading dock area and the UR lineside location safely will be highlighted. These requirements specifications were obtained from TMMI management, Engineering team, Team Member input, Maintenance Team, Safety Team, and other stakeholders. The AGV system must comply with the following requirement specifications:

4.1. Safety

- Clearance between an AGV including its load, and any external structure must be a minimum of 0.5 m (19.7 inches). This clearance must be maintained between obstructions and vehicles (including loads).
- Poka-yoke connectivity
- Object detection through scanner views
- Manual mode support with emergency stops

4.2. Reliability and Availability

- Operational availability must be 85% or above (6 hours for maintenance support between shifts for each production day).
- Battery management capability to run continuously with little opportunity charging for the duration of the entire eight-hour shift.

4.3. Capacity

- Takt time for the UR production line is 59’.
- Time of travel per cycle must meet takt time requirements.
- Demand consists of the production of 442 vehicles per shift.
- Capability of carrying weight of up to 10,000 pounds.

4.4. Maintenance

- Self-diagnostic fault isolation capability
- Operation Manual availability with clear countermeasures to potential technical problems.

4.5. *SOFTWARE*

- Mapping function for automatic traveling guidance.
- Andon support with alarm alert system.

4.6. *AFFORDABILITY*

- System implementation must achieve a two-year payback.

4.7. *SCALABILITY AND EXTENSIBILITY*

As TMMI increases the level of automation at the manufacturing plant, the AGV system will have to have the capability of communicating with multiple servers that distinctively operate different AGV systems so they can operate harmoniously. Also, as the layout configuration changes due to updated operational requirements, the AGV route must be easily adjustable.

4.8. *EASE OF USE REQUIREMENTS*

- **Efficiency of use:** Team members trained to drive forklifts or similar vehicles at the manufacturing plant should be able to take AGV technical training and quickly learn how to accurately operate the AGV.
- **Ease of remembering:** Indicator lights and the self-diagnostic system must be easy to remember using colors, labels, and intuition.
- **Error rates:** It is crucial for team members interacting with the AGV system to know when the vehicle is going, when it has stopped, or when it needs to be manually operated. The AGV should also stop when objects are identified in its path.
- **Feedback:** Safety team must feel confident that the product is operating accurately and keeping everyone interacting with the system safe while meeting OSHA and TMMI's standards.

4.9. *SUPPORTABILITY REQUIREMENTS*

- The maintenance burden with existing AGV systems must be analyzed so correct levels of maintenance support are acquired by TMMI.
- IT department must be able to handle all problems regarding TMMI servers, software, and AGV network.

5. EXISTING SYSTEM DESIGN ANALYSIS

This section will describe in detail the existing system, its shortfalls, and what actions are needed to address the gap between the current situation and the desired outcome.

5.1. System Hierarchy

The UR process is one of the many processes that are a part of East Body Weld at TMMI. Figure 5 visually displays where the UR process fits within the Toyota Motor Corporation and Toyota Motor Manufacturing, Indiana Inc.

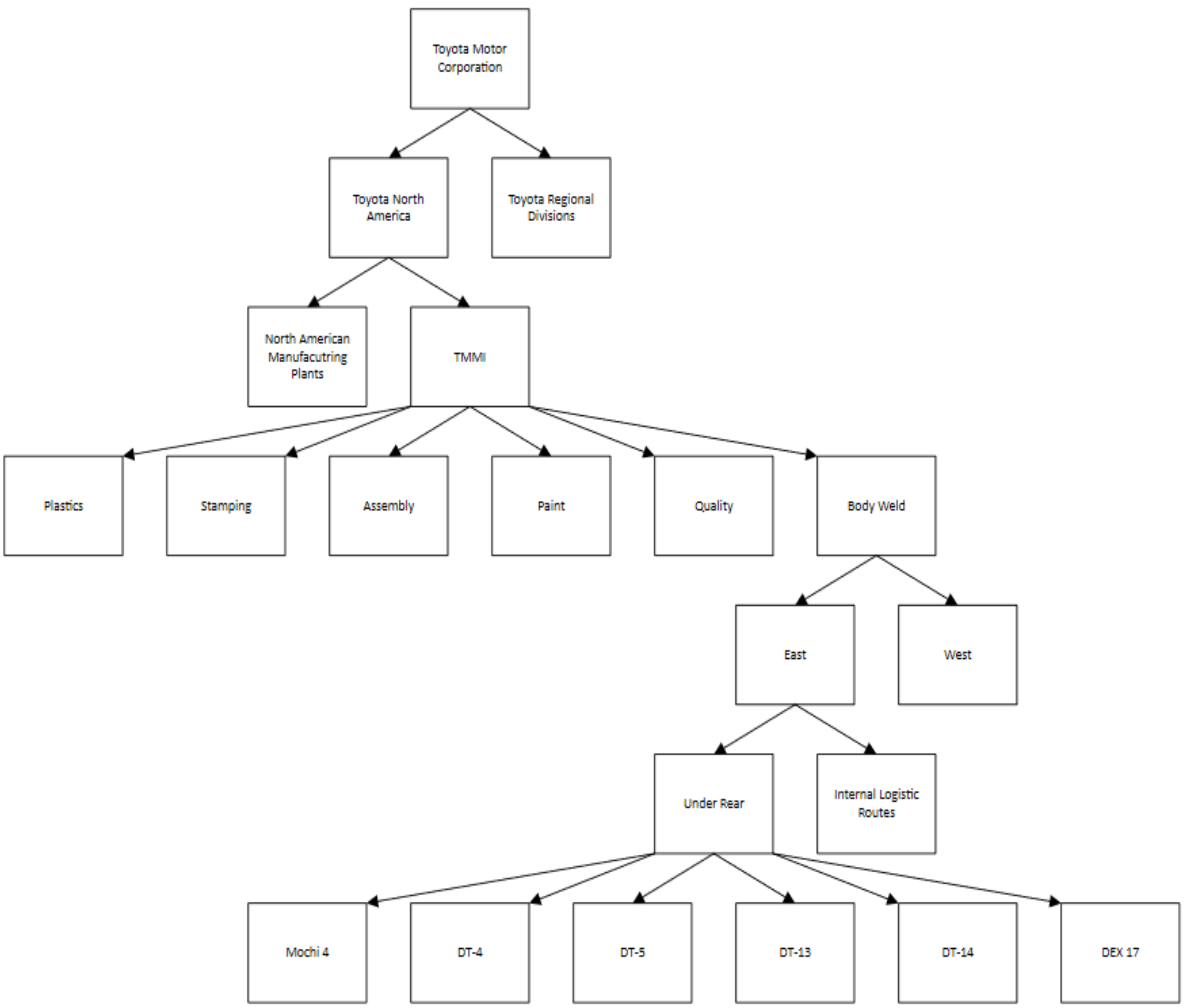


Figure 5: AGV System Hierarchy

5.2. *EXISTING LAYOUT CONFIGURATION*

The UR parts material handling process is divided into six distinct routes. Each route consists of different parts with distinct quantity per cycle (QPC) requirements. Takt time for the process is also defined for each route according to the parts that are transported within it. The UR delivery matrix that shows part numbers and QPC requirements per route is displayed in Table 1.

Table 1: Part-Delivery Matrix

Route	Part Number	QPC
Mochi 4	1, 2, 3, 4, 5	12, 22, 24, 36, 50
DT-4	6, 7	9, 9
DT-5	8, 9	6, 9
DT-13	10, 11	8, 8
DT-14	12, 13	18, 18
DEX-17	14	12

Currently, all six routes have the same general path but have distinct loading and unloading locations. Generally, the Loading dock area, the UR lineside location, and the dock location are displayed as areas 1, 2, and 3 respectively in Figure 6. Additionally, the general route for the tugger drivers in this process can be seen in this layout as well.

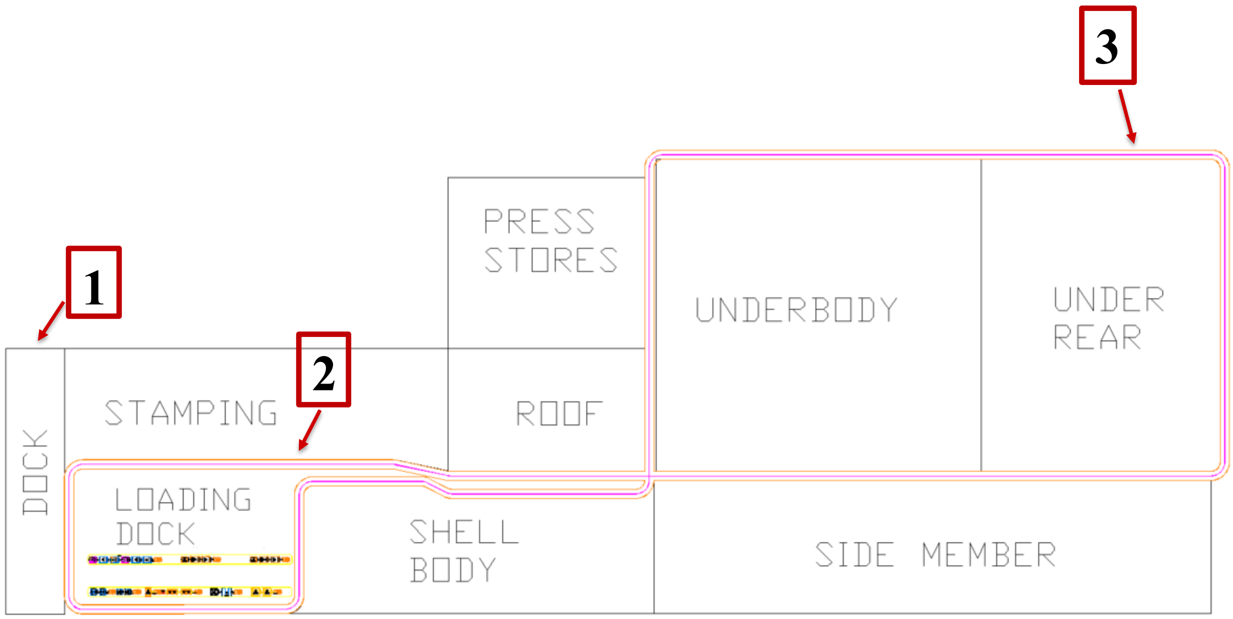


Figure 6: Existing Layout Configuration

The Loading dock area consists of several lanes where fork truck drivers can drop-off parts directly from their vehicles. Then, these parts become ready for redistribution by tugger drivers to their respective drop-off locations. Figure 7 shows a closer look of the Loading dock area, clearly highlighting the five pick-up locations of all fourteen parts that are used in the UR process.

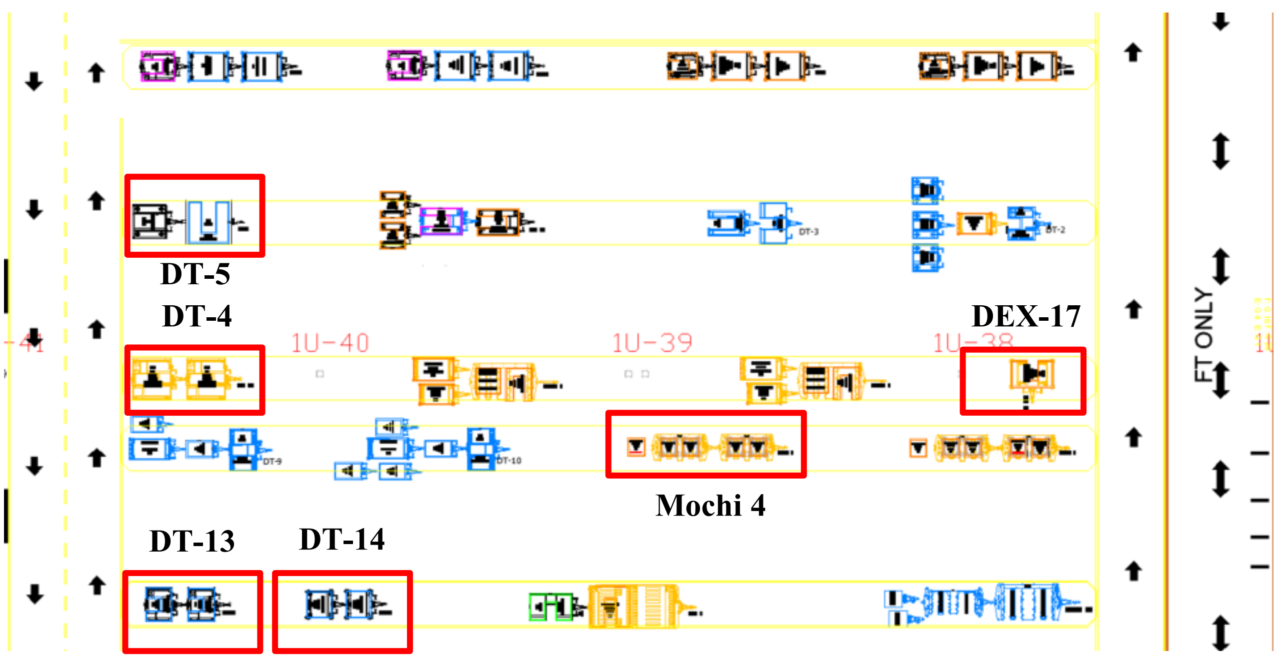


Figure 7: Loading Dock Layout Configuration

As it can be seen in Figure 7, not all the parts for the under rear process are consolidated in a single lane. These are currently located in such a way that allows easy access for fork truck drivers from the part supplier gate to the respective part location within the Loading dock. Section 5.4. will address the labor workforce required to run this system with the current layout. However, it is important to notice that these routes are executed with three tugger drivers. The routes are consolidated as follows:

1. Routes DT-4 and DT-5
2. Routes DT-13, DT-14, and Mochi 4
3. Route DEX-17

Each one of these routes has a different tugger drive distance due to their unique locations, some of them being farther away from the pickup location. Table 2 shows the tugger drive distance per route, which will be used to reduce total distance travel as a part of the AGV integration activity.

Table 2: Tugger Drive Distance per Route

Route	Tugger drive distance (meters)
Mochi 4	743
DT-4	745
DT-5	660
DT-13	697
DT-14	697.3
DEX-17	679
Average	703.55

5.3. Current Sequence of Operations

It is at the lineside location located in the Under Rear process where parts 1-14 are used to assemble under rear components of vehicles assembled at TMMI. Each product is in containers as defined by their QPC requirements at the Loading dock area. Three team members transport these containers manually with tuggers from the Loading dock area to the UR Lineside location. Then, the tugger driver must get off the vehicle, unhook the dollies, swap the full containers with empty containers located in this lineside location, and then hook the dollies to the tugger. Once this is done, they must get on the tugger and head back to the Loading dock and repeat this process continuously throughout the entire shift. In addition to the team members driving the tuggers, there are also team members whose job is to move empty and full containers around the UR lineside location in such a way that allows for both the drivers and the assembly workers to access their empty and full containers respectively. Figure 8 shows the overall process flow diagram for the different parts that are a part of the UR system.

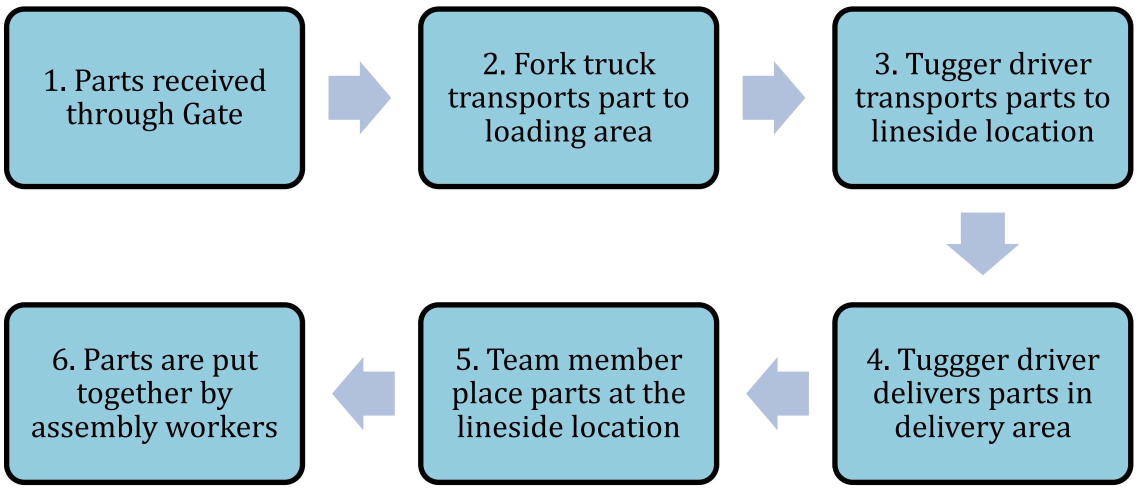


Figure 8: Process Flow Diagram

Figure 9 also shows the operational flow from the parts' perspective across TMMI's current manufacturing layout.

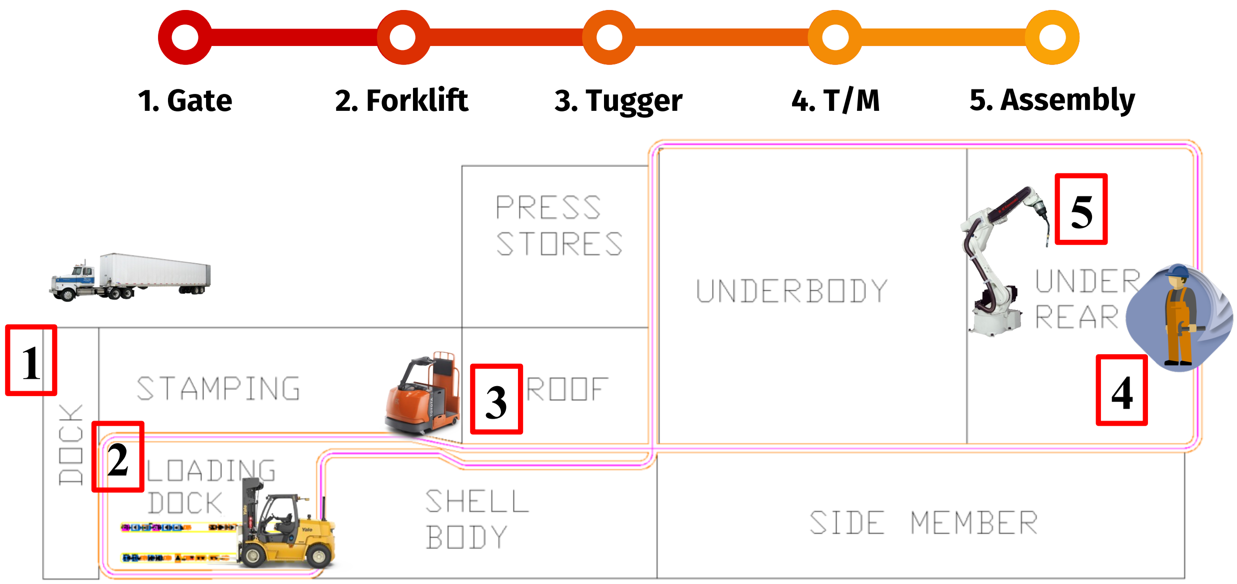


Figure 9: Operation Flow Diagram

5.4. Labor Workforce

The existing UR internal logistics system works through three eight-hour shifts each day. There are a total of three tugger drivers, two team members moving empty and full containers around the UR lineside location, and three assembly workers per shift. This section will discuss the tasks associated with each role as well as the number of team members needed to run the existing system.

The tugger drivers are currently responsible for the transportation of the parts in the continuous loop between the Loading dock area and the UR lineside location. In addition to transporting the containers, they are also responsible for loading and unloading the containers by getting off the tugger and manually hitching and unhitching the dollies at the loading and unloading locations. Nine tugger drivers are needed in the existing system between all three shifts to run the process. Each tugger driver is estimated to represent $100,000 in yearly costs corresponding to salary and benefits.

The team members moving full and empty containers around the UR lineside location do this so the assembly workers can access the parts they need, and the tugger drivers can swap their loaded containers with empty ones. Six team members doing this activity are needed in the existing system to run the process in all three shifts. Each team member is estimated to represent $100,000 in yearly costs corresponding to salary and benefits.

The assembly workers take the individuals parts carried in the loaded containers in the UR lineside location and assemble UR components that get welded together through robot cells. If the assembly workers assemble parts at a higher rate than the parts are delivered, the process can potentially have idle time. Therefore, it is important to ensure the assembly workers have the parts they need when they need them, which corresponds to the Just-in-time philosophy. Nine assembly workers are needed in the existing system to run the process in all three shifts. Each assembly worker is estimated to represent $100,000 in yearly costs corresponding to salary and benefits.

The decision of needing three tugger drivers to pick up and deliver parts 1-14 run the UR process was made through labor requirement calculations. These labor calculations consider the total drive distance, the delivery and pickup time which depend on the delivery type, number of stops, and walk distance. From these calculations, an average of 2.48 tugger drivers would be needed to run the process per shift. Therefore, TMMI decided to run said process with three tugger drivers per shift.

5.5. Improvement Opportunities

The process described in the exiting sequence of operations is labor-intensive work. It requires team members responsible for driving the tuggers and team members moving containers around to be able to organize all the parts in convenient locations for the assembly workers. The seven wastes discussed in section 2.2.1 are detrimental to any manufacturing process. As a part of this process improvement project, the reduction of the non-value-added activities will be reduced or eliminated with the implementation of an AGV system. This analysis of opportunities for improvement will be divided into two sections by functions such as tugger driver and swapping containers at the UR lineside location.

5.5.1. Tugger driver

This job in itself is considered waste since it does not directly add value to the final product. However, with the current system layout, the transportation flow between these two locations is critical and cannot be changed under the current conditions. This means that the transportation of parts in this process is a necessary non-value-added activity. Nevertheless, it is important to mention the utilization of the tugger drivers as well as the number time transporting empty containers in comparison to full containers.

The total distance of the path the tugger drivers must use is approximately 654 meters long. The tugger drivers also drive approximately 277 meters with unloaded dollies from the UR lineside location to the Loading dock area. In other words, the loaded tugger distance represents about 57.6% of the total drive distance. This means that roughly 42.4% of the drive distance occurs with empty containers. Additionally, based on the theoretical labor requirement calculations discussed in section 5.4., 2.48 people are needed, which translates into 3 tugger drivers. This does mean, however, that the utilization of these tugger drivers is not ideal. Equation 1 shows the utilization formula that can be used to determine how productive the tugger drivers are.

$$Utilization\ Rate = \frac{Theoretical\ Number\ of\ Workers\ Required}{Actual\ number\ of\ workers} * 100 \qquad \text{Equation 1}$$

The theoretical labor requirement calculations yielded 2.48 while the actual number of workers is 3. Thus, the utilization rate can be calculated as follows:

$$Utilization\ Rate = \frac{2.48}{3} * 100$$

$$Utilization\ Rate = 82.7\%$$

With an 82.7% utilization rate and 42.4% of drive time being spent with empty containers, this is an unproductive activity and must be improved. Ideally, the team members playing the role of tugger drivers can be repurposed and introduced in a different system where their utilization can be higher and the current labor shortage challenges can be alleviated.

5.5.2. Swapping empty and full containers

This position has several wasteful activities that include waiting and excessive motion. These team members need to wait on multiple components within the system. They must wait for the tugger driver to unhinge the dollies, remove the container full of parts and swap it with an empty container to even begin taking the full container and relocating it near the assembly worker. They must also wait for the assembly workers to be completely done with all the parts in their container to be able to swap it with a container full of parts. This constant waiting only worsens when there are a total of six different routes that have these same operating procedures that repeat throughout the entire shift during a total of three shifts a day.

Additionally, there is excessive unnecessary motion in the process given that the tugger driver swaps the containers once, and then the team members need to relocate them again within the UR lineside location. This excessive motion and waiting time make the tasks for these team members unproductive and wasteful. It is important to mention, however, that adding tasks to this team member in such a way that waiting time and motions are reduced, is one way to increase the utilization and productivity of these team members.

6. AGV SELECTION

The integration of an AGV system was determined to be a feasible solution to improve the materials handling process in UR due to the many benefits described in the supporting analysis in section 5 and past proven success in Toyota processes. This section will describe in detail the AGV specifications for each one of the two models proposed by distinct suppliers whose technology met the basic operational requirements needed for this system. A decision matrix that can be found in Appendix B clearly describes the criteria utilized to compare these two models and select the one that fits TMMI's needs the best.

The selection criteria used to rank both AGV models were created by working closely with co-workers in the innovation team in Body Weld Pilot at TMMI, who then visited both suppliers and evaluated the features of their products. The selection criteria were divided into four sections: functional, viability, existing presence, and professional services offered. Each item within these categories was ranked with a 0 for poor, 0.5 for fair, or 1 for excellent. Certain items were ranked corresponding to which model offered something better when compared to the alternative, and others were ranked based on whether a specific functionality was available or not. In this section, we will refer to each model as Supplier 1 and Supplier 2 for confidentiality purposes.

6.1. FUNCTIONAL

Functional capabilities in the automated guided vehicles must directly meet the operational requirements set within the scope of this project. These functional characteristics directly describe the technical capabilities of each AGV model. These were divided into five subsections: Safety, hardware, software, maintenance, and general requirements.

6.1.1. Safety

Some of the items determined through a formal risk assessment process that assist with the AGVs performance from a safety perspective include cantilever load detection, poka-yoke connectivity, a dynamic scanner with blind-spot detection, off-path detection mechanism, and object in path detection. These items assure the safety of all the team members involved in the systems that will interact with the AGV system, both internally and externally. Poka-yoke connectivity is particularly important since it is a part of TMMI's standardized procedures for error detection.

Also, object in path detection is critical to ensure team members' safety and well-being when operating at the manufacturing plant.

6.1.2. Hardware

The hardware selection criteria include items that directly satisfy operational requirements as well as items derived from improvements from past projects at the plant. Some of the hardware criteria include network access through Wi-Fi and local servers, PLC integration capability, Andon support, opportunity charging for battery management, human-machine interface (HMI) screen, status indicator lights, and manual mode support.

6.1.3. Software

The software selection criteria include a centralized traffic control system, alarm alert and history capability, dynamic insertion point, independent route update, battery display on the user interface, independent view setting for payload, and the ability to access the AGV status remotely as well mapping functionality.

6.1.4. Maintenance

The AGV system will be maintained by the maintenance and innovation teams at TMMI with the support of the chosen supplier's engineering team. TMMI maintenance and innovation teams determined items that would aid the troubleshooting process when technical problems occur. Some of the selection items include an operation manual, spare parts list, electrical and mechanical drawings, and a policy manual.

6.1.5. General Requirements

One of the operational requirements needed for this AGV system included the ability of the Automated Guided Vehicles to transport materials that weigh at least 10,000 pounds. Additionally, the speed of each vehicle is extremely important because this will determine the ability of the system to meet takt time and truly improve the existing system. Supplier 1 offered an AGV with a maximum speed is 4 mph while Supplier 2 offered an AGV with a maximum speed of 6.7 mph.

6.2. Viability

TMMI values experience as well as in-house work, which are activities completed without the assistance of third-party contractors, as critical driving factors in decision making. Thus, the number of years in the business and the presence of hardware, software research, and development team in-house are relevant items that assess the viability of the project to occur and be successful.

6.3. Existing Presence

The existing presence of a supplier in the automotive industry is also relevant information in the decision-making process to ensure that the technology that is being acquired from the suppliers is ultimately competitive and will be able to meet TMMI's needs as a strong competitor in this industry. Some of the selection items include the number of automotive industries where their AGV technology has been implemented, the number of AGVs implemented in the past, as well as the number of times that they have supported the deployment of AGV systems.

6.4. Professional Services

The innovation and maintenance teams recognize the need for support to launch and troubleshoot new technology in the manufacturing plant. Therefore, selection criteria reflect the size of their professional services groups. Furthermore, the vendor's level of interest in working with Toyota as well as their knowledge of Toyota's Business Processes are considered in the selection process.

6.5. Final Decision

The complete decision matrix with ratings can be found in Appendix B. Table 3 displays a final evaluation summary. This table displays the points achieved by each supplier in each category as well as the final decision that highlights which AGV model is suggested for this system.

Table 3: Final Evaluation Summary

System Evaluation	Functional Safety	Functional Hardware	Functional Application	Functional - Maintenance	Functional - General	Viability	Existing Presence	Professional Services (Installation)	Evaluation summary
Supplier 1	**0.80**	**0.81**	**0.83**	**1.00**	**0.75**	**1.00**	**0.83**	**0.88**	**0.77**
Supplier 2	**0.60**	**0.56**	**0.72**	**1.00**	**1.00**	**1.00**	**0.33**	**0.63**	**0.65**

The judgment rating used in this decision matrix is a TMMI standard and can be found in Table 4.

Table 4: Decision Matrix Judgement Rating

Excellent > 0.67	
Fair = 0.34 - 0.66	
Poor = 0.00 - 0.33	

As it can be found in Table 3, Supplier 1 has the highest rating with a 0.77 weighted average when compared to supplier 2 with a 0.65 weighted average. Thus, Supplier 1 is chosen as the official vendor for the Automated Guided Vehicles that will be integrated into the UR process. The complete decision matrix can be found in Appendix B.

7. AGV SYSTEM DESIGN

The ideal goal is to "totally eliminate" material handling and transportation, although in most cases reducing it is the most feasible and practical approach. In this section, a comprehensive AGV system design is proposed to automate the UR process considering the ten material handling principles introduced in Section 2.2. *Lean Manufacturing Framework.*

7.1. Flow Path Layout

To fully implement the AGV system, the flow path layout must be clearly defined. As a part of this layout improvement activity for AGV integration, all layout changes made by sibling processes within the Body Weld area had to be taken into consideration. Additionally, relocation of parts within the Loading dock area, possible layout expansion, the speed capabilities for each portion of the path, and positioning when idle had to be considered while meeting TMMI layout standards.

7.1.1. TMMI Layout Standards

- The distance between aisles where fork truck loading happens is 4.8m
- The distance between parts must be at least 3.2 m to allow exit of the vehicle

7.1.2. Parts Relocation

The ideal state for this flow path layout is one where all the parts can be consolidated in a single lane to accomplish system simplicity and address safety concerns with fork truck interaction. Figure 10 shows the first attempt at the part relocation activity, where part DT-5 does not fit in the same lane as the other Under Rear parts.

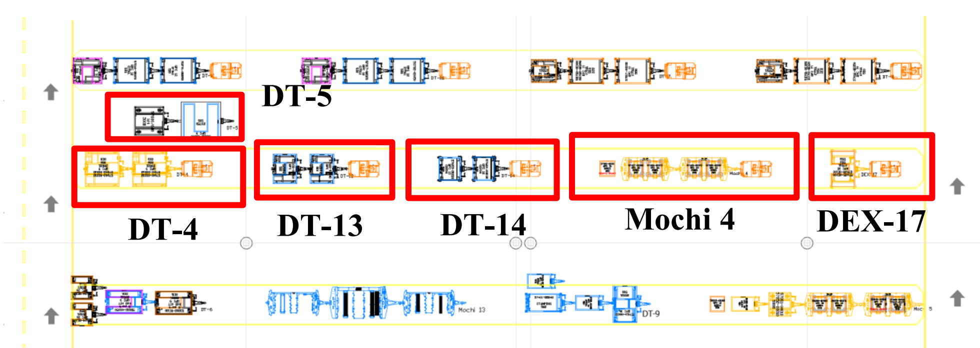


Figure 10: First Modification to the Loading Dock Layout

The lack of space for all the parts to be located in the same lane led our team to work with production and discuss opportunities for expansion. Figure 11 displays the initial dimensions of the loading dock and dock locations. The dock has an initial area of 3,242 m^2 while the loading dock has an area of 1,609 m^2.

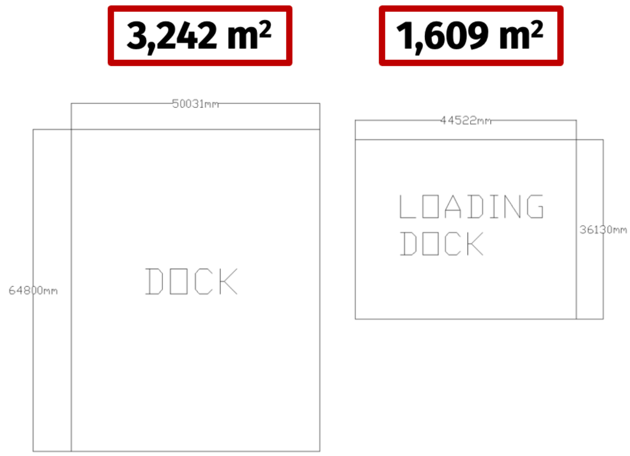


Figure 11: Loading Dock & Dock Initial Dimensions

After careful consideration, the first major layout change was achieved by expanding the Loading dock and reducing the dock's overall square footage as seen in Figure 12. The loading dock area was expanded to 2,020 m^2 while the dock location was reduced to 3086 m^2.

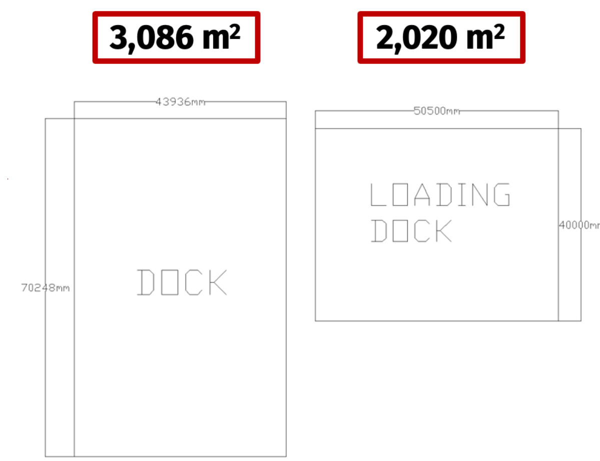


Figure 12: Loading Dock & Dock Final Dimensions

After careful discussion with other departments within the manufacturing facility, with the layout configuration shown in Figure 12 approved, it became feasible to relocate all the UR routes and consolidate all the parts in a single lane as shown in Figure 13. Notice that DT-13/DT-14 were merged due to space constraints.

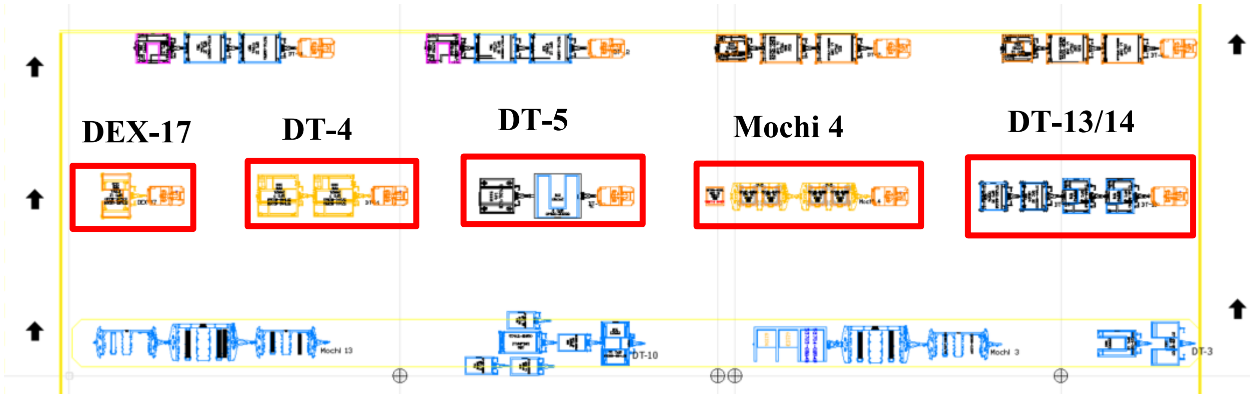


Figure 13: Second Modification to the Loading Dock Layout

7.1.3. AGV Path

After the development of the layout configuration modification as well as the parts relocation, it became feasible to propose an AGV Path. Figure 14 displays the detailed path layout that has been proposed for the UR AGV system. The total length of the proposed route is 673.1 meters, which is a distance traveled reduction of 30.45 m when compared to the previous average length for all six routes of 703.55 m as displayed in Table 2 in *Section 5.2. Existing Layout Configuration.*

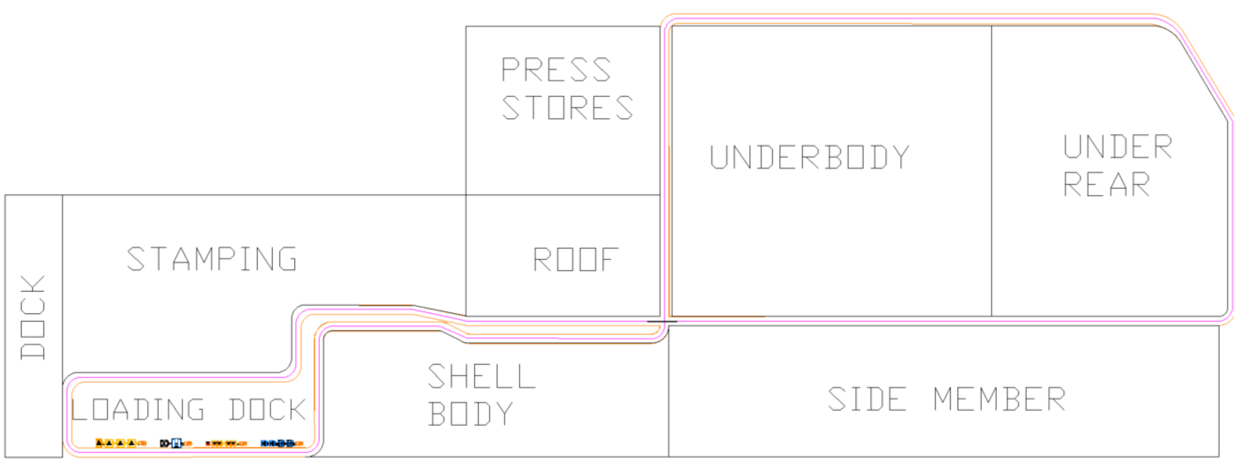


Figure 14: AGV Flow Path Layout

Additionally, the proposed layout meets all TMMI's layout standards having empty spaces of at least 3.2 m between parts that are transported by tugger-like equipment and 4.8 m spacing between aisles where fork trucks operate. These standards of compliance can be found in Figure 15 where all units are in millimeters.

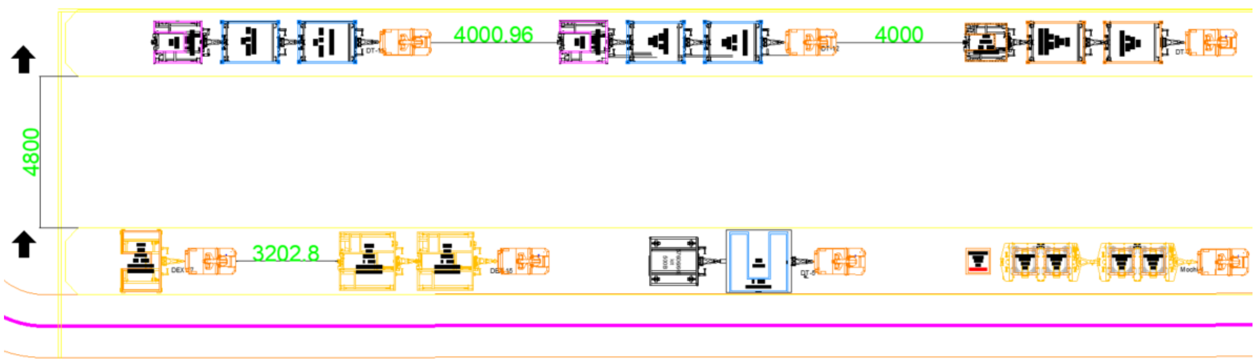


Figure 15: Distance Between AGVs Safety Compliance

Furthermore, Figure 16 displays the proposed AGV route with estimated speed requirements based on a traffic study conducted on-site as well as AGV specifications from the equipment selected in *Section 6: AGV Selection*.

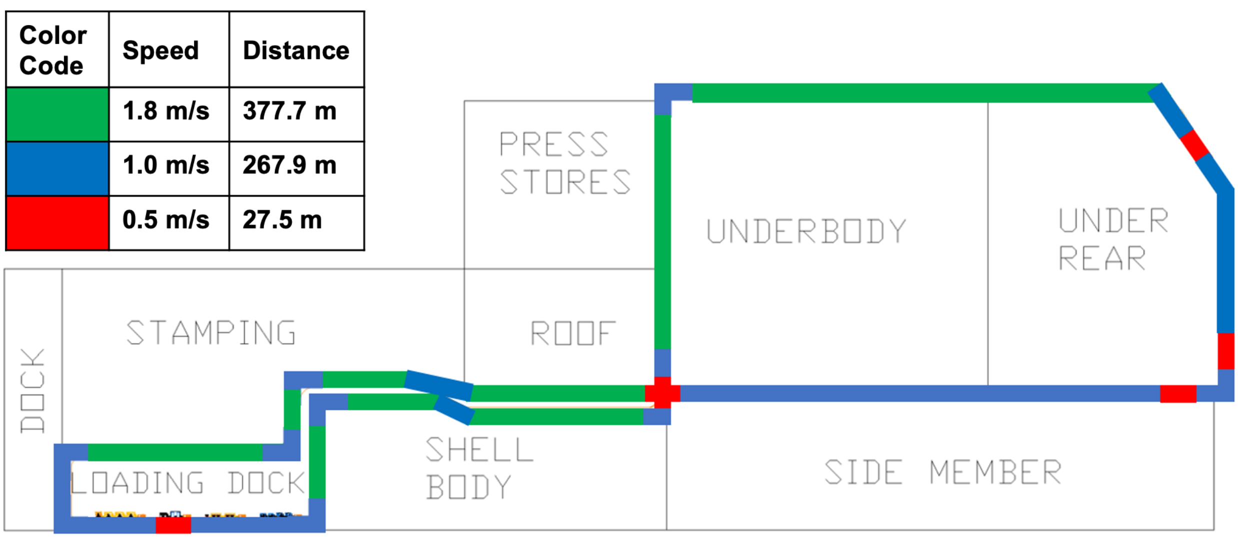


Figure 16: AGV Speed Zones

The finalized layout shown in Figure 14 was broken down into three speed zones depending on how straight and congested the zones are. The maximum speed that can be achieved by the selected AGV is 1.8 m/s, which can be reached in straight, non-congested paths. The maximum speed zone makes up 56.1% of the route with 377.7 meters falling in this category. Next, the average speed zone is 1 m/s, which can be achieved in straight but congested paths as well as curved paths. This zone makes up 39.8% of the entire route with 267.9 meters falling in this category. Finally, the low-speed zone is 0.5 m/s, and it is used near stops and on highly congested paths. This zone makes up 4.1% of the entire route with 27.5 m falling in this category. The speed zones will be critical during the AGV system design process as it sets constraints on our operational capabilities to meet takt time.

7.2. Design Considerations

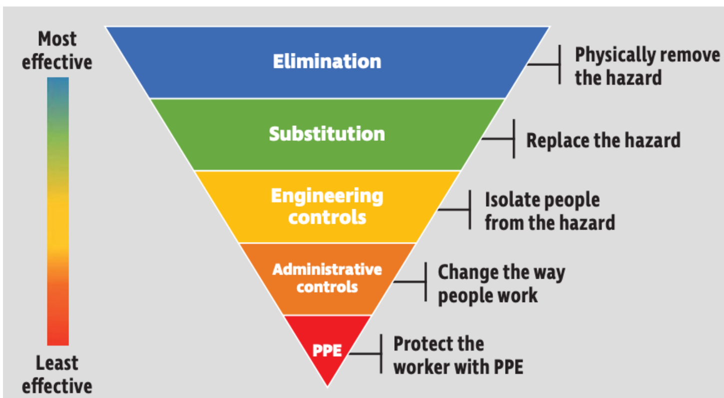
7.2.1. Safety Considerations

Engineering safety into the AGV design can reduce or avoid reliance on personal protective equipment (PPE). The safety and welfare of all the team members are a priority in design and OSHA compliance is critical to achieving this milestone. OSHA Technical Manual - Chapter 4: "Industrial Robot Systems and Industrial Robot System Safety" describes robot systems and provides safety considerations and requirements for Industrial Mobile Robots, which is the category that AGV systems would fall under. Also, RIA Technical Report (TR) R15.606-2016, *Robots and Robotic Devices – Safety Requirements for Collaborative Robots*, requires that integrators must conduct comprehensive hazard analyses and risk assessments for each application, ideally with participation from the employer and workers. This is an activity that will be enforced prior to the implementation of the AGV system at TMMI

The AGVs that were selected for the purposes of this project comply with the following industry standards and regulations in effect on the date they were manufactured:

- Safety standard that addresses design, construction, application, operation, and maintenance of Low Lift and High Lift trucks (Kelechava ANSI B56.1-2020)
- Safety requirements of elements regarding design, operation, maintenance, and test methods for Operator Controlled Industrial Tow Tractors (ANSI B56.9-2012)
- Safety standard for driverless, automated guided industrial vehicles and automated functions of manned industrial vehicles (Kelechava ANSI/ITSDF B56.5-2019)
- Safety requirements relating to fire protection, design, maintenance, and use of fork trucks, tractors, platform lift trucks, motorized hand trucks, and other specialized industrial trucks powered by electric motors or internal combustion engines (OSHA 29 C.F.R. Section 1910.178)

In addition to the rigorous safety requirements and procedures that the AGV system will endure prior to be fully integrated into TMMI's internal logistic processes, AGVs are also far safer than other manual transportation equipment such as fork trucks. Forklifts alone were the source of 78 work-related deaths and 7,290 non-fatal injuries involving days away from work in 2020 (Work Safety: Forklifts). The integration of an AGV system attempts to physically eliminate the hazard by reducing the number of manual transportations in the manufacturing plant. The standardization principle makes AGV systems a much safer system by eliminating potential route changes, speeding, and human distractions that are associated with human decision-making with the manual operation of tuggers and fork trucks. The elimination of safety hazards is also the most effective strategy and normally leads to the implementation of inherently safer systems (Hierarchy of Controls). Figure 17 shows the Hierarchy of controls supported by the National Institute for Occupational Safety and Health.



Note. Adapted from "Hierarchy of Controls," by NIOSH, 2015, www.cdc.gov/niosh/topics/hierarchy.

Figure 17: Hierarchy of Controls

Furthermore, the Failure Mode & Effects Analysis (FMEA) is an important document in the AGV system design to ensure that the system addresses safety concerns and that action plans are put in place when the identified risks are triggered. The FMEA serves as a systematic approach to address potential problems or failures of a specific system and it TMMI has a standard system in place that consists of a high-level hazard identification system, followed by a risk assessment via a formal FMEA. First, the high-level hazard identification is displayed in Appendix G, and it shows the hazards that apply to the integration of the AGV system at TMMI. Secondly, the FMEA displays the risk priority number that considers probability of occurrence, severity of occurrence, and ease of detection. This will assist the innovation team at TMMI to propose countermeasures and address these safety hazards. The probability of occurrence, severity of occurrence, and ease of detection will be ranked in a 1-10 scale. Under this scale, 1 represents low probability, low severity, and easily detectable while 10 represents high probability of occurrence, high severity (death), and hardly detectable. The FMEA for this AGV system can be found in Appendix C.

7.2.2. Environmental Considerations

The environmental impact of the AGV system can be measured through CO_2 emissions and energy consumption. Climate projections suggest that global-mean surface warming increases nearly linearly with the accumulation of CO_2 emissions (Williams et al. 9343). Thus, the reduction of CO_2 emissions, especially in the automotive industry, is critical to combat environmental challenges such as global warming. One way to accomplish this at the factory level is through the integration of AGV systems within the internal logistic activities. AGV systems have been estimated to have significantly less CO_2 emissions than alternative loading systems (Park et al. 12). Moreover, Automated Guided Vehicle systems have been used to comprehensively raise the energy efficiency of production systems and reduce energy consumption (Meißner and Massalski 481).

7.2.3. Global & Social Considerations

Toyota Motor Manufacturing Indiana is a part of a much larger corporation, which is the Toyota Motor Corporation. The global impact that the successful deployment of this AGV system along with other innovation activities to meet TMMI's ambitious automation targets relates to the scalability of this project. The opportunity for expansion of cutting-edge technology in internal logistic processes while also reducing cost and increasing productivity will represent a competitive advantage for the Toyota Motor Corporation. This also benefits the local U.S. communities as Toyota affiliates support programs through non-profit partnerships in various areas such as education, inclusive mobility, community resilience, health services, arts, and culture, as well as civic and community as defined by Toyota's Mission in North America.

7.2.4. Cultural Considerations

One of the cultural implications of the integration of an AGV System is the potential language barrier that this automatic system could have on various ethnic groups in TMMI's workforce.

Particularly, the prominent presence of Japanese administration and Hispanic workers at TMMI highlights the importance of an accessible communication system that uses colors and labels in multiple languages when necessary. To ensure cross-cultural engagement, signs on the floor highlighting the presence of an AGV route will be implemented with visuals of an AGV and warning signs in English, Spanish, and Japanese. Emergency stops and hitch points will be clearly labeled according to TMMI's standards, ensuring assertive communication with people from different backgrounds that will interact with the system.

7.3. NUMBER OF VEHICLES

The total number of vehicles required for this AGV system to run properly can be determined through the analysis of various factors such as the distance traveled, speed of the vehicles, load/transfer time, Quantity per Cycle (QPC), and takt time as defined by TMMI's vehicle model build ratio. For the purposes of these calculations, the vehicle model build ratios for both models A and B will be defined in terms of the B model. In other words, if the build ratio is 70% Model B, all parts that are used for the construction of vehicle model A would have a 30% build requirement from the overall build production target. Currently, TMMI targets the production of 442 vehicles per shift. Routes DT-5, DT-13, and DT-14 carry parts for vehicle model B, and the rest carry parts for vehicle model A. It is also important to mention that the number of vehicles will also depend on the reflection of traffic on the route. TMMI's standard to account for traffic is to target 80% of takt time, which will be introduced in the followings calculations as well.

To calculate the number of Automated Guided Vehicles required for this AGV system, there are two main variables that need to be explored:

1. Estimated Cycle Time with existing parameters: The sum of the following parameters
    a. Travel time: How long the AGV takes to run the entire route with the existing speeds zones.
    b. Dolly transfer: How long it will take for the team member swapping the containers to unhook/hook the dollies and transfer the parts. This will depend on the delivery type defined by the dolly specifications. Cycle time studies made by TMMI team members resulted in DMS (Dolly Exchange – Mother/Child small) delivery types lasting 25 seconds, PRO (Powered Roll-Off) lasting 30 seconds, DMX (Dolly

Exchange – Mother/Child extra-large) lasting 45 seconds, and DEX (Dolly Exchange-Standard) lasting 50 seconds.

   c. Dock Load Time: How long it will take for the fork truck driver to load and unload each pallet.
   d. Fork Truck Driving Time: How long it will take for the fork truck driver to exchange the empty pallet with a full one by driving from the AGV pick-up location to the dock location and back. The average speed for a fork truck in the loading dock at TMMI is assumed to be 0.47 sec/m.

2. Quantity of Parts Required for Delivery:
   a. Quantity per Cycle (QPC): Total number of parts transported at a time for each type.
   b. Vehicle Build ratio: TMMI's build ratios are set to meet demand and for the models B-A it can be 70-30, 60-40, 50-50, and 40-60. The total production target is 442 vehicles per shift.

Both variables are then used to determine how many vehicles would be needed since takt time and expected cycle time have been identified. Equation 2 will be used to calculate the travel time for the AGV to complete the defined loop.

Let x_i be the distance traveled in the i^{th} speed zone, where $i = 1, 2, 3$ for max, average, and low-speed zones respectively.

Let v_i be the speed for the i^{th} speed zone where $i = 1, 2, 3$ for max, average, and low-speed zones respectively.

$$Travel\ time = \sum_{i=1}^{3} \frac{x_i}{v_i} \qquad \text{Equation 2}$$

The detailed initial spreadsheet used to calculate the number of AGVs needed for the system can be found in Appendix D. Table 5 displays the main results from this activity with each distinct possible build ratio. The "Theoretical #AGVs" is the sum of the theoretical numbers of AGVs required for each defined route, while the "Practical #AGVs" is the sum of the numbers of AGVs required for each defined route rounded up. The practical number of AGVs is calculated per route and then summed up to finally calculate the number of AGVs required to successfully run the routes as specified in the calculations. For instance, for the 70% Model B build ratios, each route yielded 1.00, 1.35, 0.84, 0.73, 0.33, 0.80 respectively. These rounded up and summed together add up to 7, which is displayed as the practical number of AGVs in Table 5. This same methodology will be applied for the rest of the number of AGVs required calculations.

Table 5: First iteration of number of vehicles calculations

	Build Ratio	Theoretical #AGVs	Practical #AGVs
AGV total	70% Model B	5.04	7
	60% Model B	5.22	8
	50% Model B	5.40	8
	40% Model B	5.58	8

With the current set parameters and the routes that have been defined, a total of 8 AGVs would be necessary to meet TMMI's requirements. This is a large number of AGVs for a single process that would lead to further complications regarding the layout space constraints, staging locations, and economic justification. Thus, combining some of the routes that carry the same model (A/B) parts and similar QPC would be ideal to be able to reduce the distance traveled and consequently, reduce the number of AGVs required.

The second iteration of calculations is performed with some major changes:

- DT-13 and DT-14 were combined: Both routes pertain to vehicle model A and have the same delivery type (DEX). While DT-14 has a higher QPC, deliveries can be done for this route every other cycle if it meets takt time, which is feasible from a production standpoint. Additionally, each fork truck load must be double stacked, so some of the fork truck travel time can be cut in half.
- DT-4 and DEX 17 were combined: DEX 17 is responsible of a single part whose dolly can be easily attached to the back of the DT-4 dollies. This eliminates the need for an entire AGV to run the previous DEX 17 low-frequency requirements, which would have led to low utilization of as low as 46%.

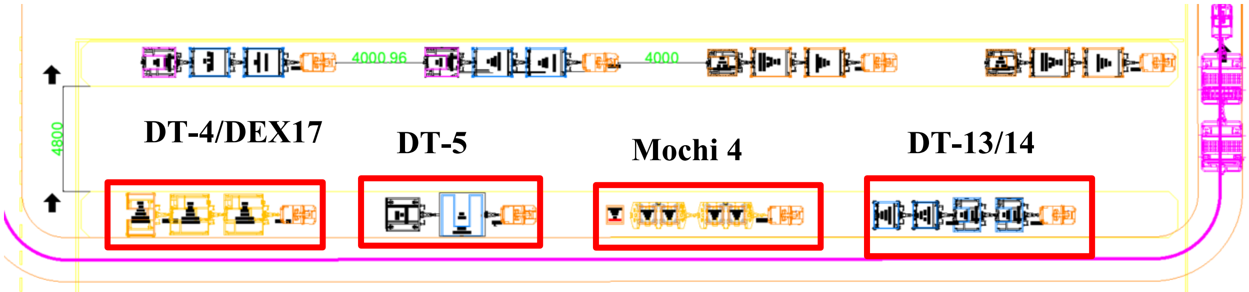


Figure 18: Final Proposed Loading Dock Layout

These improvements are reflected in the second iteration calculations that can be found in Appendix D. Table 6 displays the main results from this second iteration with the changes mentioned above. With the current set parameters and the routes that have been redefined, a total of 6 AGVs would be necessary to meet TMMI's requirements. This is a reasonable number of AGVs when compared to other functional AGV systems at TMMI and is feasible with the defined layout and economic constraints. Notice that the practical number of AGVs is calculated per route and then summed up to finally calculate the number of AGVs required to successfully run the routes as specified in the calculations

Table 6: Second iteration of number of vehicles calculations

	Build Ratio	Theoretical #AGVs	Practical #AGVs
AGV total	70% Model B	3.36	4
	60% Model B	3.67	5
	50% Model B	3.97	6
	40% Model B	4.28	6

Thus, 6 Automated Guided Vehicles are proposed for this system and will be subject to a confirmation process via simulation modeling and economic analysis.

7.4. Proposed Sequence of Operations

The impact of the sequence of activities performed on the efficiency of a manufacturing or distribution operation is very evident in material handling. Work simplification can help eliminate unnecessary operations or improve those that remain and combining steps and changing the sequence of operations can also result in more efficient material flow (Tompkins, James A., et al. 177). The proposed sequence of operations uses the new flow path layout and number of vehicles calculations to address material handling improvements, combined steps, and the role of the AGV system in the UR internal logistics process. Appendix E contains a layout that highlights the load/unload locations, charging locations, current and to be installed traffic lights to minimize the risk of traffic accidents between the manually driven routes and the AGV system, alarm zones, and the necessary interlock systems that ensure the interoperability of the AGV system as it interacts with various types of AGVs.

7.5. Simulation Model Development

The construction of a simulation model is a viable way to verify the decisions made for the AGV system and confirm its various functionalities. The steps to build a simulation model are identified as surveying the system, defining the logistics processes, building the system model, building the simulation model, model validation, running the model, and outputting and analysis of simulation results. At this point, the layout and path for the AGVs have been defined, the sequence of operations has been identified, and the number of necessary AGV vehicles has been determined. Therefore, the primary goal of this section is to provide details on the construction of the simulation model and analyze the simulation results. The main operational parameters that will be tested through this simulation model will be the utilization rate to verify that the system would meet TMMI's 85% target and confirm that the system can complete at least 35 full cycles per shift.

7.5.1. Data Collection

The construction of the simulation model will require some technical data from the chosen AGV model selected through the decision matrix in Appendix B. The data needed for this model include:

- Distance: This will be introduced directly from CAD layout
- Speed:
    - Max Speed: 1.8 m/s – Straight and non-congested paths
    - Average Speed: 1 m/s – Straight but congested paths as well as curved paths
    - Low-speed: 0.5 m/s – Near stops and highly congested paths
- Loading & unloading time: Extracted from *Section 7.2: Number of Vehicles*

- Battery Management: AGV must be recharged and taken out of production if the battery level is below 50%.

7.5.2. Assumptions

Simplifying the model to avoid unnecessary complexity that will make the model developing process too long is important. Efforts to refine the model and increase its complexity are executed as the validation procedure dictates (Giordano, et al. 67). Consequently, the assumptions displayed in Table 7 will be considered:

Table 7: Real System Description & Model Translation

No.	System Description	Model Translation
1	AGV transports different parts.	AGV transports the same part. For the purposes of this simulation model, it only matters whether the AGV has a part to transport.
2	AGV loads a different number of parts per cycle.	AGV loads one single part per cycle. Loading and unloading time will account for this assumption.
3	Each AGV is allocated to transport specific parts.	For the purposes of this model, it only matters whether there is an AGV available to complete the task or not.
4	AGV interacts with multiple routes that are manually driven.	TMMI sets AGVs above production vehicles and pedestrians in their "Right of way" standards. Thus, only other AGV Systems that interact with the route heavily will be considered
5	AGV interacts with manual operators who exchange dollies and forklift operators who load parts directly onto dollies.	AGV will load and unload parts with no manual support since it only matters whether the part has been loaded/unloaded for the AGV to run.

7.5.3. Simulation Model Results

Appendix F displays a detailed step-by-step approach to the development of the simulation model on FlexSim. After the construction of the simulation model, a dashboard that displayed the various

AGV states and utilization rates based on the congestion predicted by the simulation model was created. The utilization rate considers every time the AGV is blocked as unutilized time.

The simulation model predicts an average utilization rate among all six AGVs of about 92%, which exceeds the 85% target set by TMMI standards. This projected utilization rate also represents roughly a 10% improvement from the previous system's utilization rate of 82.7%. Figure 19 displays six pie charts that show the breakdown of the different states that each AGV experiences along with their respective utilization rate. Additionally, the reduction in distance traveled also supports the feasibility of this project and its projected success as it operates with other systems within TMMI.

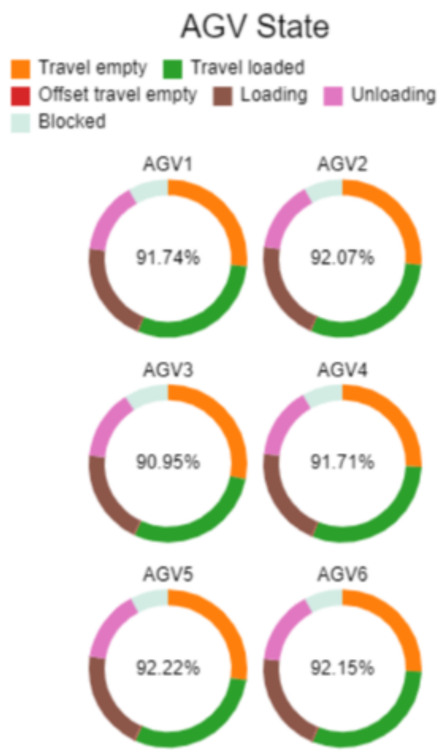


Figure 19: Utilization Rate per Shift Simulation Results

Furthermore, based on the calculations conducted to determine the number of vehicles needed, the AGV system must be able to complete at least 35 cycles per shift to meet TMMI's build plan and takt time. The simulation model considers traffic and congestion due to other AGV systems that operate within the same path and predicts that the AGVs will be able to complete at least 36 cycles and up to 38 cycles in a single shift as it can be seen in Table 8. Not only does the simulation validate the number of cycles that the system will be able to perform, but it also suggests that there will be some flexibility and charging opportunities since the 35-cycle requirement only considers the worst-case scenario for the entire system. On average, the routes need 28 complete cycles to meet the current takt time.

Table 8: Number of Cycles per Shift Simulation Results

Route	Number of Cycles per Shift
Mochi 4	37
DT-4	37
DT-5	36
DT-13	38
DT-14	37
DEX-17	38

7.6. RELIABILITY AND MAINTAINABILITY

The role of maintenance is critical to ensure the survivability and proper functioning of equipment in a manufacturing environment. Reliability and Maintainability are both important considerations in this project because it is critical that the AGV system completes its tasks successfully, and efficiently. Reliability is that characteristic of design concerned with the successful operation of the system for the duration of its life cycle while maintainability reflects the ease, accuracy, safety, and economy of performing maintenance actions (Blanchard and Fabrycky 114). One way to consider reliability and maintainability in this AGV system design is through the acquirement of maintenance support that can perform:

- Daily shift tasks
- Total Productive Maintenance (TPM)
- Breakdown repair
- Manual interventions.

To do this, it is important to study the maintenance burden with existing AGV systems across TMMI and determine the maintenance labor support required to address the mentioned concerns.

7.6.1. Maintenance Burden with Existing AGV Systems

Daily Shift Tasks include cleaning the view scanner, lubricating, and checking the overall performance of the equipment. This takes roughly 10 minutes per AGV each day, which is approximately 0.83 hours a week. Total Productive Maintenance tasks last 1.55 hours as communicated by the existing maintenance team. Breakdown Repair data from the maintenance time was also provided and suggests that it takes on average 0.5 hours a week per AGV to solve approximately two unexpected breakdowns. Also, 0.95 hours a week per AGV is spent driving the AGV manually about 25 times a week. These occur due to team members interacting with the AGV, objects in the path, the AGV system running behind the expected cycle time, etc. The available operating time during a single week for the AGV systems at TMMI is 37.5 hours per shift.

7.6.2. Manual Intervention Study

We can study the manual intervention data provided by the maintenance team further by quantifying reliability, maintainability, and statistical availability (Santos et al.156). The maintainability can be measured through the Mean Time to Recovery (MTTR), which can be calculated using Equation 3.

$$MTTR = \frac{Total\ time\ in\ the\ failed\ state}{Number\ of\ failures} \qquad \text{Equation 3}$$

$$MTTR = \frac{0.95\ hours}{25}\left(\frac{60\ minutes}{1\ hour}\right)$$

$$MTTR = 2.28\ min$$

$$MTTR = 2\ \text{min}\ 17\ sec$$

Currently, the maintenance team takes on average 2 min and 17 sec driving the AGV manually and identifying the root cause of the unexpected malfunction. This is a relatively low number, which suggests that the training for team members has been sufficient from a maintenance perspective. To quantify reliability, the Mean Time Between Failures (MTBF) for the existing system can be calculated using Equation 4.

$$MTBF = \frac{Operating\ Time}{Number\ of\ failures} \qquad \text{Equation 4}$$

$$MTBF = \frac{37.5\ hours}{25}\left(\frac{60\ minutes}{1\ hour}\right)$$

$$MTBF = 90\ min$$

The interventions occur, on average, every 90 min, which means that the AGV systems must be checked about five times each shift. The higher the time between failures, the more reliable the system. Finally, to quantify the statistical availability, Equation 5 can be used below.

$$Statistical\ Availability = \frac{MTBF}{MTBF+MTTR} \quad \text{Equation 5}$$

$$Statistical\ Availability = \frac{90}{90+2.28}$$

$$Statistical\ Availability = 0.975$$

Lastly, the statistical availability represents the average between the middle time used in the equipment and the required production time. The existing system is 97.5% available, which is above the requirement of 85% described in *Section 4.2 Productivity Operational Requirements*. It is important to mention, however, that this does not include unprecedented necessary breakdown repairs nor any other idle times. Figure 20 visually displays the operational metrics discussed such as MTTR and MTBF.

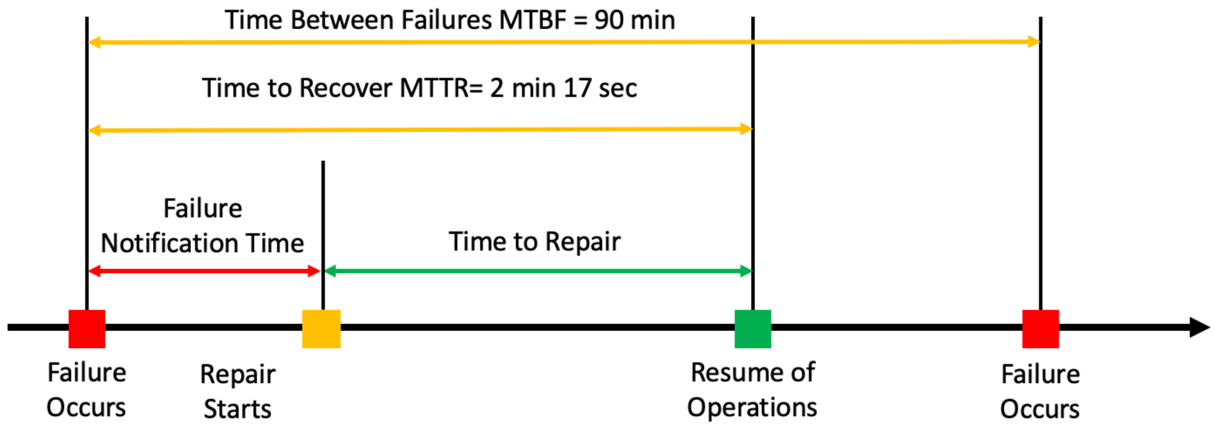


Figure 20: AGV System Operational Metrics

7.6.3. Maintenance Labor Requirements

Along with technological growth and manual labor reduction in the manufacturing environment, maintenance labor must increase to match the technology levels implemented. In this section, the number of hours spent on maintenance tasks is calculated and maintenance labor requirements are determined. Using the data provided by the maintenance team on the existing AGV systems at TMMI and with the decision of implementing 6 AGVs for the UR process, Table 9 displays the number of maintenance hours required for this system.

Table 9: UR AGV System Maintenance Labor Requirements

Item	Maintenance Category	Hours/Week/AGV	Number of AGVs	Total time (Hours/week)
1	Daily Shift tasks	0.83	6	5
2	TPM Tasks	1.55	6	9.3
3	Breakdown Repair	0.50	6	3
4	Manual Intervention	0.95	6	5.7
Total				23

As the UR AGV system suggests that 23 hours of maintenance labor are necessary, a comprehensive table that displays maintenance labor requirements including sibling AGV systems that will be implemented simultaneously can be seen in Table 10. There are a total of 20 vehicles being implemented at TMMI as the UR process is a part of a much larger innovation project.

Table 10: All AGV Systems Maintenance Labor Requirements

Item	Maintenance Category	Hours/Week/AGV	Number of AGVs	Total time (hours/week)
1	Daily Shift tasks	0.83	20	16.6
2	TPM Tasks	1.55	20	31
3	Breakdown Repair	0.50	20	10
4	Manual Intervention	0.95	20	19
Total				76.6

As seen above, a total of 76.6 hours is required to alleviate maintenance requirements by 20 Automated Guided vehicles, which translates into two maintenance members. Maintenance members will be a part of the economic analysis and included in the budget for this project.

7.7. *ANTICIPATED BENEFITS*

The main goal of this project is to improve the internal logistics Under Rear (UR) process by reducing manual transportation and repurposing as many team members as possible. A tugger AGV system can be implemented to transport empty and full containers of vehicle parts from the lineside location to the loading dock back and forth.

1. Labor cost reduction by $395,000 annually.
2. Increased automation levels at TMMI achieving more flexibility and productivity.
3. Reduction of distance traveled by 30.45 m.
4. Use as Proof of Concept to expand to other commodities across Toyota Manufacturing plants worldwide.
5. Simulation Modeling supports the theoretical increase in utilization rate by approximately 10%.
6. Improved ergonomics and safety through the elimination of unnecessary motion.
7. Positive environmental impact through the reduction of CO_2 emissions and energy consumption.
8. Positive social impact through non-profit partnerships in various areas such as education, inclusive mobility, community resilience, health services, arts, and culture.

8. COST AND ECONOMIC EVALUATION

The economic analysis explored in this project involves the comparison of an initial cost with future savings. A simple way to make this comparison is through a simple payback period analysis with no return expected. Per TMMI standards, this project must have at least a two-year payback. Despite the benefits associated with the conceptual AGV system integration, if the project is not economically justified, it would become burdensome to pursue it. The cost and economic implications of the AGV system are examined through an annual worth analysis and a payback analysis. The annual worth analysis will be conducted to confirm that the AGV system is more economically satisfactory than the current system. The payback analysis is examined to confirm TMMI's two-year payback period requirement.

8.1. Annual Worth Analysis

To compare the current system and the AGV system from an economic standpoint, the annual worth of each one over a fixed five-year study period can be conducted. Ultimately, the system with the highest annual worth will be selected as the better alternative economically because it yields a lower cost.

8.1.1. Current System Yearly Operating Cost

The yearly operating costs associated with the activities that would be automated through the AGV system integration include the labor of 9 tugger drivers as well as the tugger leases associated with their vehicles. Table 11 describes the total cost associated with both items in the Under Rear process.

Table 11: Current System Yearly Operating Cost

Item	Description	Unit Cost	Qty	Total Cost
1	Labor	$99,477.00	9	$895,293.00
2	Tugger Lease	$4,615.00	9	$41,535.00
Totals				$936,828.00

As displayed in Table 11, the total yearly operating cost is $936,828.00. Figure 21 displays the cash flow diagram for the current system with an annual negative cash flow during a five-year study period.

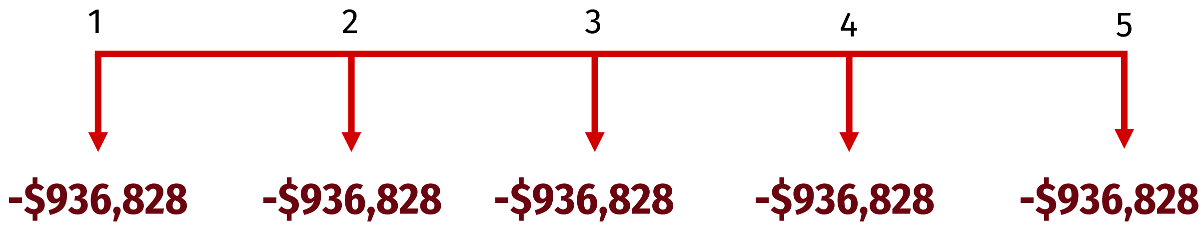


Figure 21: Current System Cash Flow Diagram

8.1.2. AGV System Cost Summary

The cost associated with the AGV system consists of a large one-time investment which includes the total equipment cost as well as the total installation cost. In addition to this initial investment, an annual cost associated with skilled team members to support the maintainability of the AGV system is considered. Table 12 shows the total investment required to implement the studied AGV system.

Table 12: AGV System Cost Summary

Item	Description	Unit Cost	Qty	Total Equip. Cost	Total Installation Cost	Total Cost
1	AGV	$128,975.00	6	$773,850.00	$250,000.00	$1,023,850.00
2	Skilled Team Member	$99,477.00	2	-	-	$198,954.00

To compare the annual operating cost of the current system with the AGV system, the costs associated with the latter must be annualized. Let AW be the annual worth of the system, P be the initial payment, A be the annual cost, i the interest rate, and n the time in years. Then, the system can be annualized with Equation 6 adjusted with the variables involved in this system (Newnan, et al. 390-392).

$$AW = P\left({}^{A}/_{P}, i, n\right) + A \qquad \text{Equation 6}$$

For the purposes of this analysis, an interest rate of 20% is a reasonable assumption for TMMI, and using the five-year study method Equation 6 becomes:

$$AW = -\$1{,}023{,}850\left({}^{A}/_{P}, 20\%, 5\right) - \$198{,}954$$

The $\left(A/_{P}, 20\%, 5\right)$ term is entitled the "compound interest factor" and can be calculated using the table found in Appendix H (Newnan, et al. 1246). Thus,

$$AW = -\$1{,}023{,}850(0.3344) - \$198{,}954$$

$$AW = -\$541{,}329.44$$

Therefore, the annualized cost over a five-year period of the AGV system is $541,329.44. Figure 22 displays the cash flow diagram for the current system with an annual negative cash flow during a five-year study period.

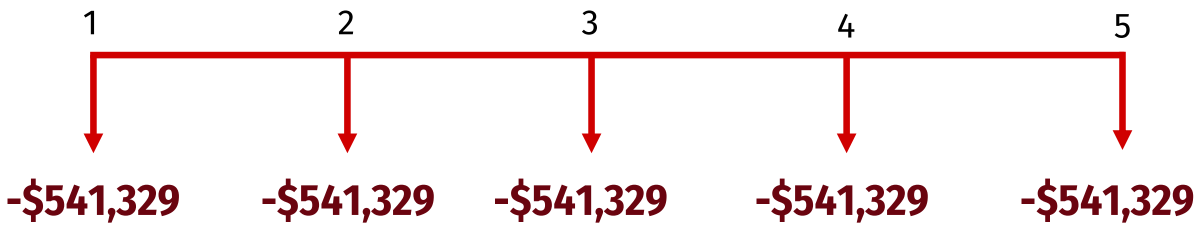


Figure 22: AGV System Cash Flow Diagram

Since $AW_{AGV} > AW_{Current}$, the AGV system yields a lower annual cost than the current system. Therefore, the AGV system would be selected as the better alternative. The savings per year, denoted as ΔA, is just the difference between the annual worth of each alternative system as described in Equation 7.

$$\Delta A = AW_{AGV} - AW_{Current} \qquad \text{Equation 7}$$

$$\Delta A = (-\$541{,}329.44) - (-\$936{,}828.00)$$

$$\Delta A = (-\$541{,}329.44) - (-\$936{,}828.00)$$

$$\Delta A = \$395{,}498.56$$

Thus, the projected annual savings accomplished when the AGV system replaces the current system is $395,498.56.

8.2. Payback Analysis

For the purposes of this payback analysis, let n_p be the payback period. This project is economically justified when $n_p \leq 2\ years$. Table 13 shows the annual cash flow for the AGV system denoted as investment, the current system denoted as savings, the annual cash flow, and the cumulative cash flow over a five-year period.

Table 13: Annual Cash Flow Analysis

	Year 1	Year 2	Year 3	Year 4	Year 5
Investment (AGV System)	-$1,222,804	-$198,954	-$198,954	-$198,954	-$198,954
Savings (Current System)	$936,828	$936,828	$936,828	$936,828	$936,828
Cash Flow	-$285,976	$737,874	$737,874	$737,874	$737,874
Cumulative Cash Flow	-$285,976	$451,898	$1,189,772	$1,927,646	$2,665,520
Payback Period	**1.4**				

As it can be seen in Table 13, in year 2, the cumulative cash flow sign changes from negative to positive, meaning that at some point between years 1 and 2, costs would be recovered by generated cost savings. Thus, the payback period is somewhere in the first year. To calculate the fraction associated with the first year, one can simply divide the cumulative cash flow in year 1 by the cash flow in year 2:

$$n_p = 1 + \left(\frac{\$285{,}976}{\$737{,}874}\right)$$

$$n_p = 1.4\ years$$

The payback period for this AGV system is 1.4 years. Therefore, the AGV system integration along with the repurposing of team members in this process is economically justified, and the capital investment is worthwhile. Figure 23 visually displays the cumulative annual savings accomplished through the AGV system implementation over the continuation of the current system.

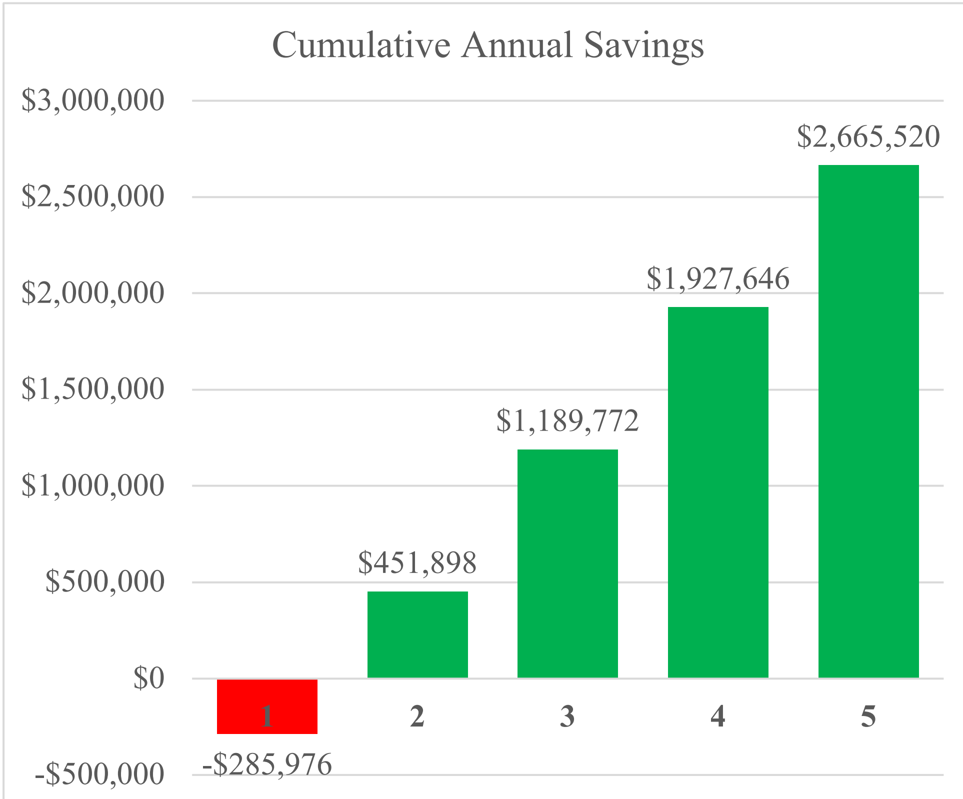


Figure 23: Cumulative Annual Savings

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Work Collaboration with TMMI

Working at TMMI has given me the opportunity to work collaboratively with highly skilled professionals. Working in the Internal Logistics Engineering – Body Weld Pilot department has given me the chance to work closely with Tyler Brames, an Engineering Specialist. Tyler Brames has assisted me in various projects including the AGV integration project for Under Rear Internal Logistics. This involved him teaching me how to apply project management principles while also communicating with me the steps that are necessary to safely launch an AGV system. Moreover, I had the chance to work closely with Tracy Fortune, who is Production Group Leader in Conveyance. Tracy Fortune provided me with specific information regarding the visits the innovation team was able to have with the two potential AGV vendors. This information included pricing, functional requirements, and other relevant selection criteria that were critical in the development of the decision matrix that can be seen in Appendix B. I also worked closely with Aaron Wilson and Jeremy Raff who are familiar with all the production activities related to the Under Rear process and kept me up to date with all relevant layout and process changes. Finally, having the responsibility of having weekly meetings with Randy Pfeiffer, Engineering Manager in Body Weld Conveyance, and reporting progress updates on the project was a challenging and rewarding experience.

9.2. Current Progress and Future Actions

The activities involved in the development of the AGV system that will operate in the Under Rear Internal logistics system within TMMI reported in this document reflects the High-Level Schedule and the project schedule that can be found in Appendix A. Relating this back to the System Development Life Cycle, the activities addressed in this report include the preliminary study, system analysis and requirements, and systems design. The actual system development, integration and testing, implementation, and maintenance are the next phases that need to be executed for full system deployment by Winter Shutdown in December 2022. Next, the innovation team will start the Scope of Work (SOW) and purchasing process. This became feasible due to the comprehensive system design specifications discussed in this report as well as the operational and economic validations through simulation modeling and cost analysis.

9.3. Lessons Learned

The Internal Logistics Process Improvement through AGV Integration project has been conceptually designed, meticulously analyzed, and engineered since January and has made excellent progress towards being implemented at TMMI. As of April 22nd, the project is ahead of schedule, the stakeholders whose input affects the system design have provided feedback, and a substantial implementation plan has been developed. The system has been thoroughly designed, but not yet developed as Scope of Work and Purchasing orders are necessary. As of the writing of this document, the AGV system is planned to be integrated into the Under Rear internal logistics process at TMMI during Winter Shutdown 2022 in December. Thus, the system will be completed by that time.

The success of the conceptual design of this system has shown positive theoretical results and advanced smoothly because of the overwhelming number of teamwork and support from coworkers. An important lesson learned from this design activity has been that teamwork and communication with stakeholders affected by the system are critical to assure the effective progress of a project. Overall, the system meets the requirements specifications discussed in this report while also considering various design factors such as safety, global, social, environmental, and economic factors. The anticipated benefits of this system are a labor cost reduction, reduction of distance traveled, an increase in utilization rate, and an improvement in ergonomics and safety.

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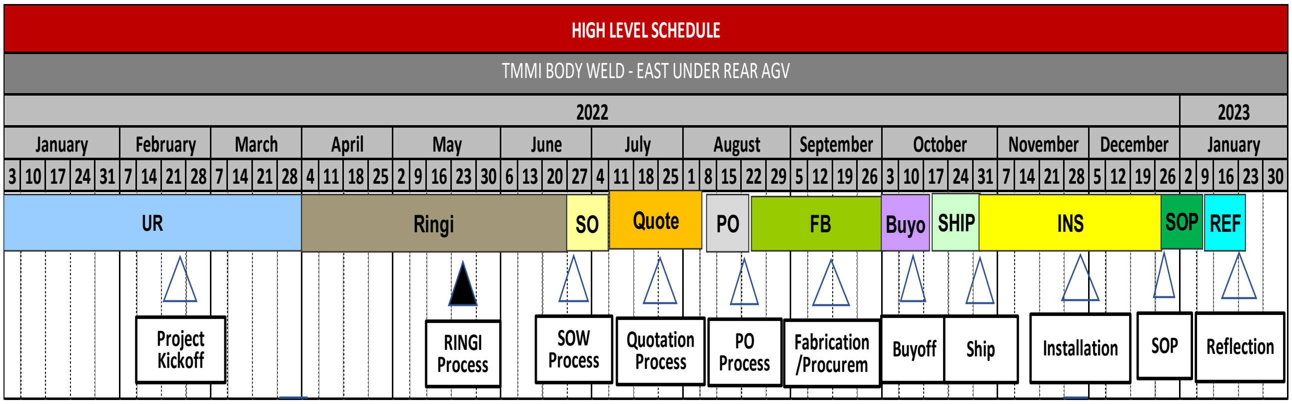
APPENDIX

APPENDIX A: PROJECT TIMELINE

1. High Level Schedule



2. Project Schedule

Project Schedule

Task	Duration (Weeks)
Preliminary Study	**2**
Identify wasteful activities in the UR process	1
Investigate the capability of an AGV system integration	1
System Analysis & Requirements	***8***
Construct a System Hierarchy	1
Capture the existing layout configuration	3
Study the current sequence of operations	1
Identify skilled labor needed in the existing system	1
Identify improvement opportunities	1
Identify requirement specifications from stakeholders	1
System Design	**19**
Identify AGV selection criteria	1
Construct a decision matrix with TMMI's rating system	1
Select AGV vendor based on decision matrix results	1
Propose a AGV flow path layout	1
Identify design considerations (Safety, environmental, etc.)	1
Determine number of AGVs required	2
Propose an improved sequence of operations	2
Perform a Failure Mode & Effect Analysis (FMEA) on the system	2
Construct a simulation model to verify conceptual design	2
Create a maintenance plan to ensure reliability and operability	1
Develop a cost and economic evaluation plan	5
System Development	**20**
Develop scope of work for vendor	2
Develop quote and purchase order	2
Maintain communication with vendor regarding fabrication	16
Integration & Testing	**4**
Lead buy off and confrim correct functionality of technology	2
Lead testing and kanban activities during non-production time	2
Implementation	**8**
Lead installation activities with vendor at TMMI	6
Lead training activities with production team members	2
Operation and Maintenance	**6**
Identify punchlist items and propose corrective actions with vendor	2
Lead maintenance handover activities to ensure long-term operability	2
Reflect on lessons learned and document them for future use	2

APPENDIX B: DECISION MATRIX

Section 1: Functional

	Score	Score	Note	Score	Note
AGV - Safety					
CANTILEVER LOAD DETECTION		1.0		1.0	
POKA-YOKE CONNECTIVITY		1.0		0.5	Can Develop
Dynamic Scanner setting Without slowing down the AGV (blind spots detection)		0.0		0.0	
Off path detection mechanism (auto detection)		1.0		0.5	Object Avoidance
Object in path stopping distance (> 5 ft)		1.0		1.0	
Comments:	5	4.0		3.0	
Weighted Score		0.80		0.60	
AGV - Hardware					
NETWORK ACCESS (Wifi) (0.0) Virtual Server only (0.5) Local Server only (1.0) Both		1.0		1.0	
TOYOPUCK PLC INTEGRATION		1.0		0.5	In Process
ANDON/API SUPPORT		1.0	Freedom Integration Confirmed	0.5	Freedom Integration Needed
Battery (Opportunity Charging)		1.0		0.0	In Development
HMI screen on AGV		0.5	Limited Function	0.5	Limited Function
Stack light (AGV status)		1.0		1.0	
Turn indicator light		0.0		0.0	
Manual mode support		1.0		1.0	
Comments:	8	6.5		4.5	
Weighted Score		0.81		0.56	
AGV - Application (Software)					
Centralized trafic control system		1.0		1.0	
Alarm alert (via email, text or Andon)		1.0		1.0	
Alarm history		1.0		1.0	
Dynamic insertion point		0.5	Retains old order	0.5	Retains old order
Independent route update		0.5	60 second auto restart	1.0	Can change on the fly
Battery display on UI (user interface)		1.0		0.0	
Independent view setting for payload		1.0		0.5	Worst Case Scenario
Access AGV status remotely		1.0		1.0	
Mapping function (auto turn guidance)		0.5	Limited Viewsets	0.5	Limited Viewsets
Comments:	9	7.5		6.5	
Weighted Score		0.83		0.72	
Maintenance					
Spare part list		1		1	
As build drawings (electrical & mech)		1		1	
Operation manual		1		1	
PM manual		1		1	
Comments:	4	4.0		4.0	
Weighted Score		1.00		1.00	
General Requirement					
Weight = 10,000lb		1		1	
Speed		0.5	4 MPH	1	6.7 MPH
Comments:	2	1.5		2.0	
Weighted Score		0.75		1.00	
Totals Raw Score	28	23.5		20.0	

Section 2: Viability

	Score	Score	Note	Score	Note
Company					
Years in business: (0.0) 0-5 (0.5) 5 to 10 (1.0) 10+		1.0		1.0	
Hardware & Software R&D In House		1.0		1.0	
Comments:	2.0	2.0		2.0	
Totals — Raw Score		2.0		2.0	
Average Score		1.00		1.00	

Section 3: Existing Presence

	Score	Score	Note	Score	Note
Systems					
Number of company's vendor has deployed AGV in Auto Industry: (0.0) 0-1 (0.5) 2-4 (1.0) 5+		0.5	Ford, Toyota	0.0	None
Number of AGVs deployed: (0.0) 1-100 (0.5) 101-149 (1.0) 150+		1.0	200 units	0.0	80 units
Number of years vendor has had AGV deployed: (0.0) 1-2 (0.5) 2-3 (1.0) 3+		1.0		1.0	
Comments:	3.0	2.5		1.0	
Totals — Raw Score		2.5		1.0	
Average Score		0.83		0.33	

Section 4: Professional Services

	Score	Score	Note	Score	Note
Professional Services (Installation)					
Does the vendor have internal professional services group		1.0		1.0	
Size of the Professional Services Group (0) = 1 - 3 (0.5) = 4 - 10 (1.0) = >10		0.5	Will deploy 4 to remain onsite and assist with troubleshooting/launches	0.0	
Vendor's level of interest in working with Toyota (0) Little to No interest (.5) Some interest (1) Very interested		1.0		1.0	
Vendor demonstrates knowledge of Toyota business processes (0) No knowledge (.5) Some knowledge (1) Very knowledgeable		1.0		0.5	
Comments:	4	3.5		2.5	
Totals — Raw Score		3.5		2.5	
Average Score		0.88		0.63	

Final Evaluation Summary

System Evaluation	Functional Safety	Functional Hardware	Functional Application	Functional - Maintenance	Functional - General	Viability	Existing Presence	Professional Services (Installation)	Evaluation summary
Supplier 1	**0.80**	**0.81**	**0.83**	**1.00**	**0.75**	**1.00**	**0.83**	**0.88**	**0.77**
Supplier 2	**0.60**	**0.56**	**0.72**	**1.00**	**1.00**	**1.00**	**0.33**	**0.63**	**0.65**

APPENDIX C: FAILURE MODE & EFFECTS ANALYSIS (FMEA)

Risk Category	Failure Mode	Effect	Analysis - RPN (Risk Priority number)				Countermeasure
			Probability of occurrence	Severity of Occurrence	Ease of detection	RPN	
1.1 1.2 1.3 1.4 1.5 1.6	AGV could run into a nearby team member standing in the AGV's line of travel or waiting at a crosswalk.	The collision could result in a severe injury or death.	5	10	3	**150**	1. Clean scanner to detect objects and team members daily. 2. Audible notifications/warning signals (honks and driving lights) 3. Clearly mark crosswalks and AGV path
1.1 1.2 1.3 1.4 1.5 1.6	Team member could have a hand or arm trapped between the AGV, dollies, and fixed objects as the AGV travels.	Loss of a limb or other major injuries	3	9	3	**81**	1. 500 mm safe distance when possible 2. Pinch points identified with red and white stripes 3. Emergency stops accessible to team member 4. Audible notifications / warning signals / slow accelration rate
1.6	AGV could contact another route in its path with a larger top than its base.	Damage of equipment and possbile injury to team memebers around collision	2	7	5	**70**	1. Driving path clearly marked 2. Mark the outside corners of all cantilevered loads that share the same aisles with the AGV 3. Audible alarm when moving 4. Tallest Route determined to be 85". Cantilever Load Detector scan height to be set to that.
1.1 1.2 1.3 1.4 1.5 1.6	TM crosses dolly train into traffic.	Injury to team members and possible death	4	10	1	**40**	1. Standardized work through the training of team members 2. AGV honks before moving 3. Caution barried added between all dollies
1.1 1.2 1.3 1.4 1.5 1.6	AGV trailing dolly could strike objects while turning.	Injury to team members and damage of equipment	5	8	7	**280**	1. Increase view of scanner to avoid object collission 2. Visual indicator when turning against traffic 3. Traffic warning lights installed in the drive path 4. Additional obstacle scanner to detect "blind spots" while turning
2	AGV does not slow down through a turn and loses control and veers off path.	If a team member is near the path then the AGV could strike the team member resulting in severe injury or death.	2	10	3	**60**	1. Fleet Management software utilizes turn view settings 2. Emergency stop condition if AGV is off path by at least 200 mm 3. Proximity sensors to detect objects and team members
2	Team member is performing schedule or corrective maintenance on the AGV when the AGV starts to move.	The incident could result in severe injury or death.	3	10	1	**30**	1. Lockout/logout training to maintenance personnel 2. Standarized work for maintenance procedures 3. Emergency stops accessible to team member 4. Switching to manual mode disables all AGV functions
19	Team member could ride AGV and fall into moving equipment	The incident could result in injury or death	3	10	2	**60**	1. AGV stops if standing on carriage mat 2. 'Authorized Personnel Only' label 3. Caution barried added between all dollies 4. Standarized work through training of team members

APPENDIX D: NUMBER OF VEHICLES CALCULATIONS

- First Iteration

East UR AGV Delivery Routes

Mochi 4

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
1	1.8	DMS	12	377.7	209.84	25.00	58.00	103.00	96.82	25.78	22.10	18.42	14.73	855.03
2	1	DMS	22	133.9	133.93	25.00	58.00	104.00	97.76	14.06	12.05	10.05	8.04	216.91
3	1	DMS	24	80.4	80.36		58.00			12.89	11.05	9.21	7.37	69.60
4	1	DMS	36	53.6	53.57		58.00			8.59	7.37	6.14	4.91	69.60
5	0.5	DMS	50	27.5	55.02		58.00			6.19	5.30	4.42	3.54	69.60
				673.1								70%	# AGVs	1.00
												60%	# AGVs	0.86
												50%	# AGVs	0.71
												40%	# AGVs	0.57

DT-4

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
6	1.8	DMX	9	377.7	209.84	45.00	58.00	76.00	71.44	34.38	29.47	24.56	19.64	848.58
7	1	DMX	9	133.9	133.93	45.00	58.00	78.40	73.70	34.38	29.47	24.56	19.64	212.04
	1			80.4	80.36									
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	1.35
												60%	# AGVs	1.16
												50%	# AGVs	0.96
												40%	# AGVs	0.77

DT-5

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
8	1.8	DEX	6	377.7	209.84	50.00	58.00	94.80	89.11	22.10	29.47	36.83	44.20	875.78
9	1	PRO	9	133.9	133.93	30.00	58.00	103.60	97.38	14.73	19.64	24.56	29.47	222.46
	1			80.4	80.36									
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	0.84
												60%	# AGVs	1.12
												50%	# AGVs	1.40
												40%	# AGVs	1.68

DT-13

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
10	1.8	DEX	8	377.7	209.84	50.00	58.00	125.00	117.50	16.58	22.10	27.63	33.15	909.85
11	1	DEX	8	133.9	133.93	50.00	58.00	127.00	119.38	16.58	22.10	27.63	33.15	272.86
	1			80.4	80.36									
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	0.73
												60%	# AGVs	0.97
												50%	# AGVs	1.21
												40%	# AGVs	1.45

DT-14

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
12	1.8	DEX	18	377.7	209.84	50.00	58.00	133.60	125.58	7.37	9.82	12.28	14.73	919.55
13	1	DEX	18	133.9	133.93	50.00	58.00	135.40	127.28	7.37	9.82	12.28	14.73	282.33
	1			80.4	80.36									
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	0.33
												60%	# AGVs	0.44
												50%	# AGVs	0.55
												40%	# AGVs	0.66

DEX 17

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
14	1.8	DEX	12	377.7	209.84	50.00	58.00	60.00	56.40	25.78	22.10	18.42	14.73	836.53
	1			133.9	133.93									
	1			80.4	80.36									
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	0.80
												60%	# AGVs	0.68
												50%	# AGVs	0.57
												40%	# AGVs	0.46

AGV total	70% Model B	5.04	7
	60% Model B	5.22	8
	50% Model B	5.40	8
	40% Model B	5.58	8

- Second Iteration

East UR AGV Delivery Routes

Mochi 4

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
1	1.8	DMS	12	377.7	209.84	25.00	58.00	103.00	96.82	25.78	22.10	18.42	14.73	855.03
2	1	DMS	22	133.9	133.93	25.00	58.00	104.00	97.76	14.06	12.05	10.05	8.04	216.91
3	1	DMS	24	80.4	80.36					12.89	11.05	9.21	7.37	0.00
4	1	DMS	36	53.6	53.57					8.59	7.37	6.14	4.91	0.00
5	0.5	DMS	50	27.5	55.02					6.19	5.30	4.42	3.54	0.00
				673.1								70%	# AGVs	0.93
												60%	# AGVs	0.80
												50%	# AGVs	0.66
												40%	# AGVs	0.53

DT-4/DEX 17

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
6	1.8	DMX	18	377.7	209.84	45.00	58.00	76.00	71.44	17.19	14.73	12.28	9.82	805.72
7	1	DMX	9	133.9	133.93	45.00	58.00	78.40	73.70	34.38	29.47	24.56	19.64	212.04
14	1.8	DEX	12	80.4	44.64	50.00	58.00	60.00	56.40	11.05	14.73	18.42	22.10	197.28
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	0.86
												60%	# AGVs	0.78
												50%	# AGVs	0.69
												40%	# AGVs	0.61

DT-5

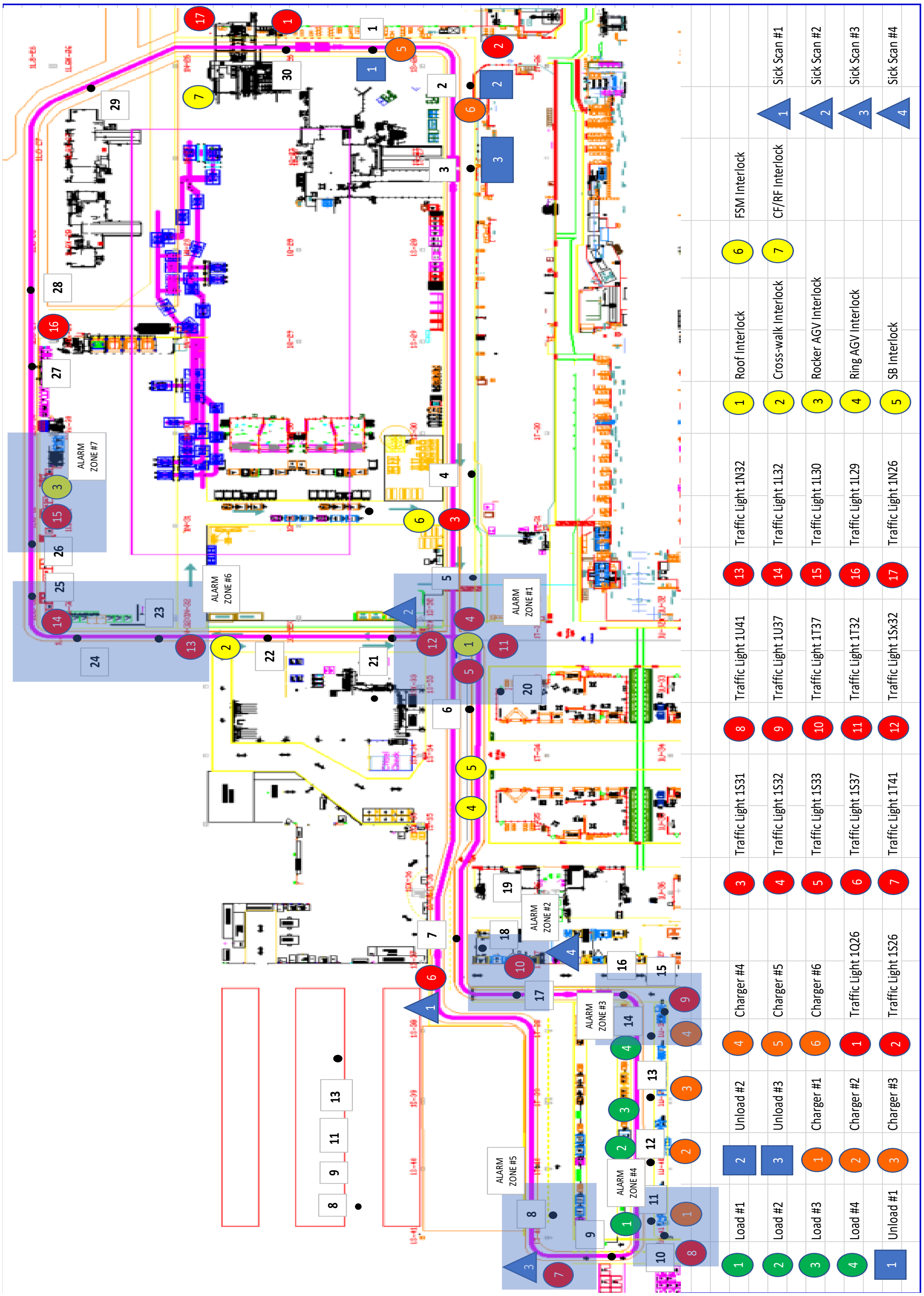
Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
8	1.8	DEX	6	377.7	209.84	50.00	58.00	94.80	89.11	22.10	29.47	36.83	44.20	875.78
9	1	PRO	9	133.9	133.93	30.00	58.00	103.60	97.38	14.73	19.64	24.56	29.47	222.46
	1			80.4	80.36									
	1			53.6	53.57									
	0.5			27.5	55.02									
												70%	# AGVs	0.84
												60%	# AGVs	1.12
												50%	# AGVs	1.40
												40%	# AGVs	1.68

DT-13/14

Part #	m/s	Delivery Type	QPC	Distance in Meters	Travel Time	Dolly Transfer	Dock Load Time	Fork Truck Drive Distance	Fork Truck Drive Time 0.47 sec/m	70% Model B Deliveries	60% Model B Deliveries	50% Model B Deliveries	40% Model B Deliveries	Cycle Time/ Delivery
10	1.8	DEX	8	377.7	209.84	50.00	58.00	125.00	117.50	16.58	22.10	27.63	33.15	909.85
11	1	DEX	8	133.9	133.93	50.00	58.00	127.00		16.58	22.10	27.63	33.15	129.60
12	1	DEX	18	80.4	80.36	50.00	58.00	133.60		7.37	9.82	12.28	14.73	129.60
13	1	DEX	18	53.6	53.57	50.00	58.00	135.40	63.64	7.37	9.82	12.28	14.73	205.97
	0.5			27.5	55.02									
												70%	# AGVs	0.73
												60%	# AGVs	0.97
												50%	# AGVs	1.22
												40%	# AGVs	1.46

AGV total			
	70% 550	3.36	4
	60% 550	3.67	5
	50% 550	3.97	6
	40% 550	4.28	6

APPENDIX E: SEQUENCE OF OPERATIONS



Position	Condition	I/O Mapping	Mission	Symbols
1	AGV unload location #1 Charge location #5		Unhook dolly train Hook up empty train Turn on traffic light #2 Turn off traffic light #1	1 1 2 5
2	AGV unload location #1 Charge location #6		Unhook dolly train Hook up empty train Turn off traffic light #2	2 2 6
3	AGV unload location #3		Once delivery is completed, proceed to position #4	3
4	Turn on traffic light #3 Lock out FSM Interlock		Hold until clear Proceed to position #5	3 6
5	Lock out alarm zone #1 Turn on traffic lights #4, 5, 11, and 12 Lock out roof interlock zone Turn off traffic light #3		Check sick scanner #2 If clear proceed to location #6 If not available, hold position until clear	4 5 11 1 2 12
6	Unlock alarm zone #1 Turn off traffic lights #4, 5, 11, and 12 Unlock roof interlock zone Lock out Ring AGV interlock Lock out SB AGV interlock		Proceed to position #7 If not clear, hold until clear	4 5 4 5 11 12
7	Unlock Ring AGV Interlock Unlock SB AGV Interlock Turn on traffic light #6		Check sick scanner #1 If clear proceed to location #8 If not available, hold position until clear	4 5 6 1
8	Lock out alarm zone #5 Turn on traffic light #7 Turn off traffic light #6		Check sick scanner #3 If clear proceed to location #9 If not available, hold position until clear	7 3 6
9	Turn off traffic light #7 Unlock alarm zone #5 Turn on traffic light #8 Lockout alarm zone #4		Proceed to position #10	7 8
10	Turn off traffic light #8 Unlock alarm zone #4		Proceed to position #11, #12, #13, or #14 as defined by the specific AGV route	8
11	AGV Load location #1 Charge location #1		Unload empties Load full pallet Proceed to #15	1 1
12	AGV Load location #2 Charge location #2		Unload empties Load full pallet Proceed to #15	2 2
13	AGV Load location #3 Charge location #3		Unload empties Load full pallet Proceed to #15	3 3
14	AGV Load location #4 Charge location #4		Unload empties Load full pallet Proceed to #15	4 4
15	Lock out alarm zone #3 Turn on traffic light #9		If clear, proceed to position #16 If not, hold until clear	9
16	Unlock alarm zone #3 Turn off traffic light #9		Proceed to position #17	9
17	Turn on traffic light #10 Lock out alarm zone #2		Check sick scanner #4 If clear proceed to position #18 If not clear, hold position until clear	10 4
18	Turn off traffic light #10 Unlock alarm zone #2		Proceed to position #19	10
19	Lock out Ring AGV interlock Lock out SB AGV interlock		If clear proceed to position #20 If not clear, hold position until clear	4 5
20	Lock out alarm zone #1 Turn on traffic lights #4, 5, 11, and 12 Lock out roof interlock zone		Check sick scanner #2 If clear proceed to location #21 If not available, hold position until clear	4 5 11 12 1 2 4 5
21	Unlock alarm zone #1 Turn off traffic lights #4, 5, 11, and 12 Unlock roof interlock zone		Proceed to position #22	4 5 11 12 1
22	Turn on traffic light #13 Lock out cross-walk interlock		If cross-walk interlock is clear proceed to position #23 If not, hold until clear	13 2
23	Lock out alarm zone #6 Turn off traffic light #13 Unlock cross-walk interlock zone		If AGVs clear proceed to position #24 If not clear, hold until clear	13 2
24	Turn on traffic light #14		If AGVs clear proceed to position #25 If not clear, hold until clear	14
25	Unlock alarm zone #6 Turn off traffic light #14		Proceed to position #26	14
26	Lock out alarm zone #7 Lock out Rocker AGV Interlock Turn on traffic light #15		If clear proceed to location #21 If not available, hold position until clear	15 3
27	Unlock alarm zone #7 Unlock Rocker AGV Interlock Turn off traffic light #15 Turn on traffic light #16		If clear proceed to position #28 If not clear, hold position until clear	15 16 3
28	Turn off traffic light #16		Proceed to position #29	16
29	Turn on traffic light #17 Lock out CF/RF Interlock		If clear proceed to location #30 If not available, hold position until clear	7 17
30	Turn off traffic light #17 Turn on traffic light #1 (Stop sign) Unlock CF/RF Interlock		Proceed to position #1 or #2 as defined by the specific AGV route If not available, hold position until clear	1 17 7

APPENDIX F: SIMULATION MODELING DEVELOPMENT WITH FLEXSIM

First, the updated CAD design of the flow path layout was imported into FlexSim. Secondly, the path was constructed using the AGV path and join paths objects provided by the simulation software. Then, control points as the one seen in Figure 24 were inserted along the path. These are opportunity points for the AGV to find work.

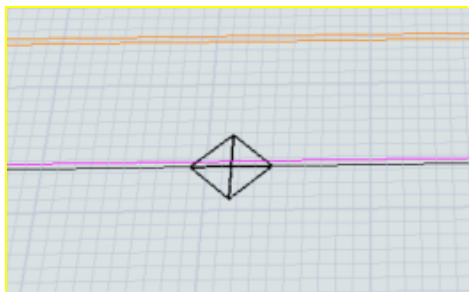


Figure 24: Control Point

The processes described in the sequence of operations were then represented through various objects. Task executers were used to represent the AGVs as seen in Figure 25, a source object was used to represent the forklift loading activity, and a sink was utilized to represent the unloading activity as seen in Figure 26. After this, all the objects were connected through a built-in FlexSim workflow logic that lets the AGVs complete tasks and travel along the defined path. This workflow logic can be seen in Figure 27. Finally, Figure 28 displays the loading dock section of the simulation model which shows the objects previously described. The finalized simulation model yielded the results found in Figure 19 and Table 8 in *Section 7.5.3: Simulation Model Results.*

Figure 25: Task Executer Object

Figure 26: Source & Sink objects

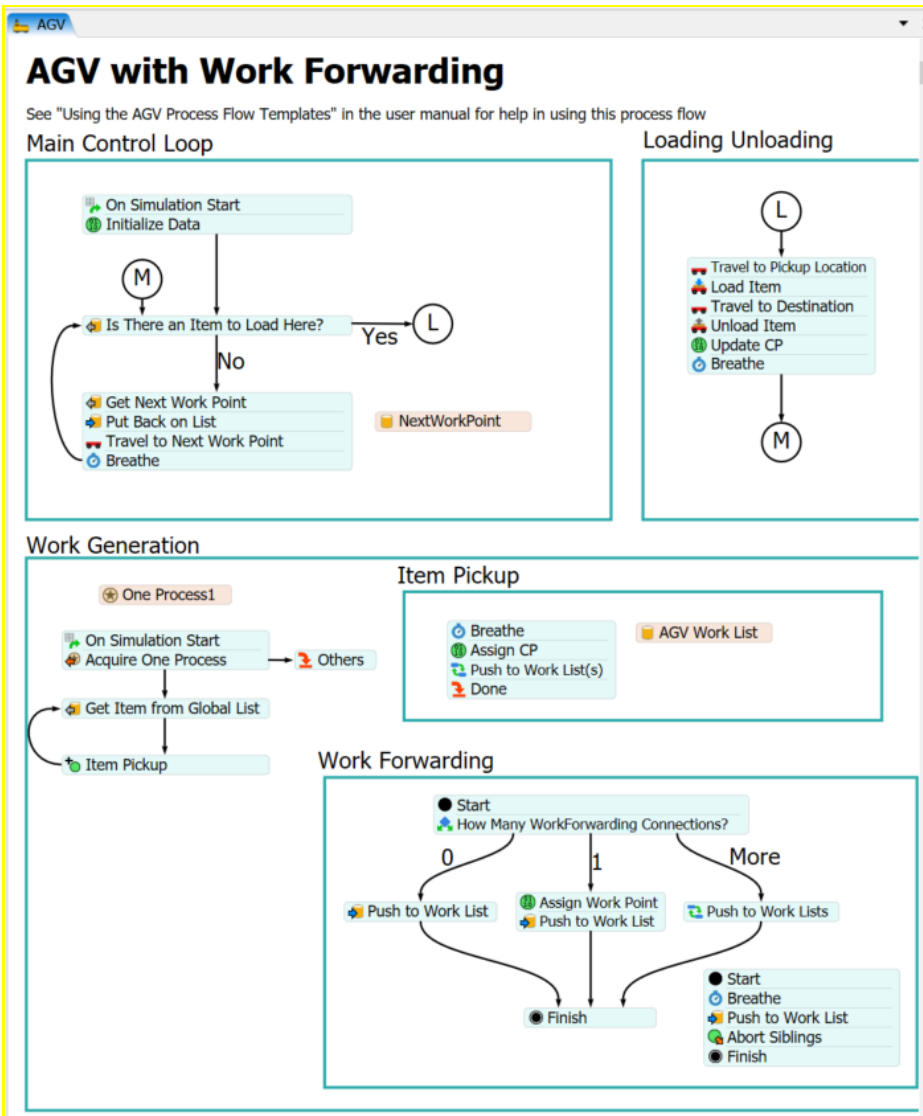


Figure 27: Workflow Logic

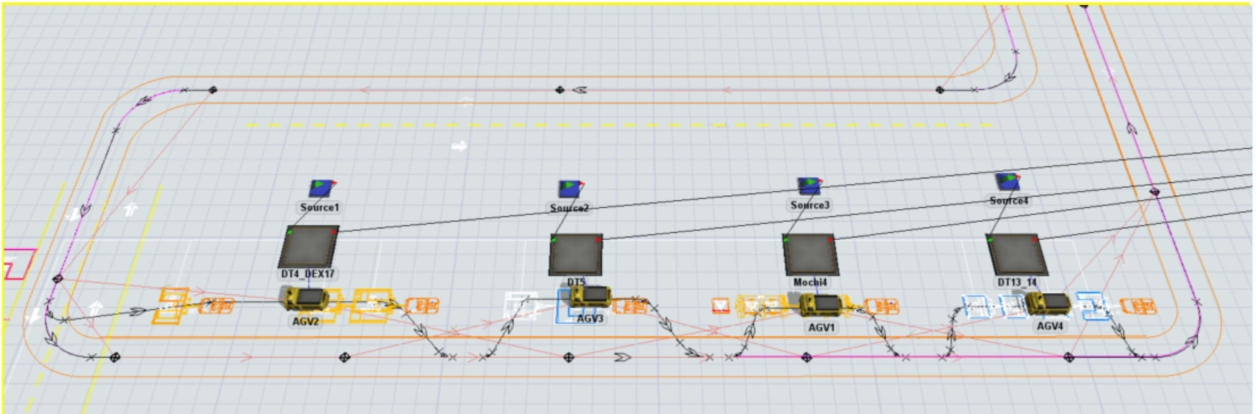


Figure 28: Loading Dock Section in Simulation Model

Appendix G: High Level Hazard Identification

HAZARD (HAZARDOUS SITUATION/EVENTS) IDENTIFICATION					
WHO *(O=operator, M=maintenance, C=conveyance, etc.)*			*O*	*M*	*C*
1. MECHANICAL HAZARDS					
X	1.1 Crushing		X	X	X
X	1.2 Shearing		X	X	X
X	1.3 Cutting or severing		X	X	X
X	1.4 Entanglement		X	X	X
X	1.5 Drawing-in or trapping		X	X	X
X	1.6 Impact, striking		X	X	X
	1.7 Stabbing or puncture				
	1.8 Friction or abrasion				
	1.9 High pressure fluids				
2. ELECTRICAL					
	2.1 Contact with live parts - shock-burn				
	2.3 Approach to live parts under high voltage				
	2.4 Electrostatic phenomena				
	2.5 Arc flash (eye hazard)				
X	2.6 Centralized Lockout not provided		X	X	X
3. THERMAL HAZARDS					
	3.1 Burns, scalds				
		Hot solid			
		Hot liquid			
		Hot Gas			
		Friction			

		Sparks/particles			
	3.2 Hot or cold working environment				
4. NOISE					
	4.1 Noise				
	4.2 Interference with communication				
5. VIBRATIONS					
	Segment vibration				
6. RADIATIONS					
	Radiation (X or gamma rays, Lasers, microwaves)				
7. MATERIAL & SUBSTANCES					
	7.1 Harmful Materials				
		Fluids			
		Gas			
		Mists or Vapors			
		Fumes			
		Dusts			
	7.2 Fire or Explosion				
	7.3 Biological				
	7.4 Shortage of oxygen				
8. ERGONOMICS					
	8.1 Postures or excessive Efforts				
		Material handling			
		Carrying			
		Push			
		Pull			
	8.2 Extended Reach or clearance				

	8.4 Lighting				
	8.5 Mental Overload (alarms, lights, etc.)				
18. LOSS of STABILITY OVERTURNING MACHINERY					
		Trapped by collapse			
		Trapped by overturn			
		Drop of Entire equipment			
		Drop of part of equipment			
19. SLIP, TRIP AND FALL OF PERSONS					
		Slip on substance, floor			
	X	Fall < 2 meter			X
		Fall same level			
		Fall> 2 meter			
		Trip on Step/stair			
		Trip uneven floor			
		Trip over object			

Appendix H: Compound Interest Factor Table for 20% Interest Rate

20%	Compound Interest Factors								20%
	Single Payment		Uniform Payment Series				Arithmetic Gradient		
	Compound Amount Factor Find *F* Given *P*	Present Worth Factor Find *P* Given *F*	Sinking Fund Factor Find *A* Given *F*	Capital Recovery Factor Find *A* Given *P*	Compound Amount Factor Find *F* Given *A*	Present Worth Factor Find *P* Given *A*	Gradient Uniform Series Find *A* Given *G*	Gradient Present Worth Find *P* Given *G*	
n	*F/P*	*P/F*	*A/F*	*A/P*	*F/A*	*P/A*	*A/G*	*P/G*	*n*
1	1.200	.8333	1.0000	1.2000	1.000	0.833	0	0	**1**
2	1.440	.6944	.4545	.6545	2.200	1.528	0.455	0.694	**2**
3	1.728	.5787	.2747	.4747	3.640	2.106	0.879	1.852	**3**
4	2.074	.4823	.1863	.3863	5.368	2.589	1.274	3.299	**4**
5	2.488	.4019	.1344	.3344	7.442	2.991	1.641	4.906	**5**
6	2.986	.3349	.1007	.3007	9.930	3.326	1.979	6.581	**6**
7	3.583	.2791	.0774	.2774	12.916	3.605	2.290	8.255	**7**
8	4.300	.2326	.0606	.2606	16.499	3.837	2.576	9.883	**8**
9	5.160	.1938	.0481	.2481	20.799	4.031	2.836	11.434	**9**
10	6.192	.1615	.0385	.2385	25.959	4.192	3.074	12.887	**10**
11	7.430	.1346	.0311	.2311	32.150	4.327	3.289	14.233	**11**
12	8.916	.1122	.0253	.2253	39.581	4.439	3.484	15.467	**12**
13	10.699	.0935	.0206	.2206	48.497	4.533	3.660	16.588	**13**
14	12.839	.0779	.0169	.2169	59.196	4.611	3.817	17.601	**14**
15	15.407	.0649	.0139	.2139	72.035	4.675	3.959	18.509	**15**
16	18.488	.0541	.0114	.2114	87.442	4.730	4.085	19.321	**16**
17	22.186	.0451	.00944	.2094	105.931	4.775	4.198	20.042	**17**
18	26.623	.0376	.00781	.2078	128.117	4.812	4.298	20.680	**18**
19	31.948	.0313	.00646	.2065	154.740	4.843	4.386	21.244	**19**
20	38.338	.0261	.00536	.2054	186.688	4.870	4.464	21.739	**20**
21	46.005	.0217	.00444	.2044	225.026	4.891	4.533	22.174	**21**
22	55.206	.0181	.00369	.2037	271.031	4.909	4.594	22.555	**22**
23	66.247	.0151	.00307	.2031	326.237	4.925	4.647	22.887	**23**
24	79.497	.0126	.00255	.2025	392.484	4.937	4.694	23.176	**24**
25	95.396	.0105	.00212	.2021	471.981	4.948	4.735	23.428	**25**
26	114.475	.00874	.00176	.2018	567.377	4.956	4.771	23.646	**26**
27	137.371	.00728	.00147	.2015	681.853	4.964	4.802	23.835	**27**
28	164.845	.00607	.00122	.2012	819.223	4.970	4.829	23.999	**28**
29	197.814	.00506	.00102	.2010	984.068	4.975	4.853	24.141	**29**
30	237.376	.00421	.00085	.2008	1 181.9	4.979	4.873	24.263	**30**
31	284.852	.00351	.00070	.2007	1 419.3	4.982	4.891	24.368	**31**
32	341.822	.00293	.00059	.2006	1 704.1	4.985	4.906	24.459	**32**
33	410.186	.00244	.00049	.2005	2 045.9	4.988	4.919	24.537	**33**
34	492.224	.00203	.00041	.2004	2 456.1	4.990	4.931	24.604	**34**
35	590.668	.00169	.00034	.2003	2 948.3	4.992	4.941	24.661	**35**
40	1 469.8	.00068	.00014	.2001	7 343.9	4.997	4.973	24.847	**40**
45	3 657.3	.00027	.00005	.2001	18 281.3	4.999	4.988	24.932	**45**
50	9 100.4	.00011	.00002	.2000	45 497.2	4.999	4.995	24.970	**50**
55	22 644.8	.00004	.00001	.2000	113 219.0	5.000	4.998	24.987	**55**
60	56 347.5	.00002		.2000	281 732.6	5.000	4.999	24.994	**60**

APPENDIX I: ABET OUTCOME 2, DESIGN FACTOR CONSIDERATIONS

ABET Outcome 2 states "*An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health safety, and welfare, as well as global, cultural, social, environmental, and economic factors.*"

ABET also requires that design projects reference appropriate professional standards, such as IEEE, ATSM, etc.

Table 14: Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	12, 31-33
Global	33
Cultural	33-34
Social	33
Environmental	33
Economic	46-50
Professional Standards	23, 27, 30, 32-33, 35, 40, 47