AME 4553 / ISE 4393 – Section 02/04

A Semi-Automated Solution for Unboxing and Loading Multiple Chassis into Transport Carts

Industry Sponsor: Hitachi

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Submitted to: Dr. Dodd

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Executive Summary

The goal of this project is to develop a semi-automated solution for unboxing and loading 2U drive storage chassis into transport carts, addressing inefficiencies and safety risks in the current manual process. Through feedback from Hitachi, we determined that full automation would not be feasible due to operational constraints, making semi-automation the primary focus. This approach enhances efficiency, minimizes human error, and ensures consistency in handling procedures while maintaining flexibility in workflow. Workers will experience reduced physical strain, lowering the risk of injuries while improving overall workplace safety. By implementing robotic systems and advanced vision technologies, the task can be executed with minimal human intervention, leading to repeatable and reliable operations. Variability in placement, aging equipment, and potential product damage will be significantly reduced, streamlining the entire process. Semi-automation allows for predictable cycle times and improved reliability, creating a more efficient and standardized workflow. Additionally, this project will improve equipment longevity, reduce operational disruptions, and enhance overall system sustainability for long-term success and continuous operational improvement across multiple production environments, boosting efficiency and worker satisfaction. Hitachi's current manual chassis handling process poses ergonomic risks to the operator and inefficient loading processes. While full automation was considered, space limitations, cost considerations, and product fragility necessitated a semi-automated approach. This project focused on improving operator ergonomics, increasing chassis throughput, and improving lift control. To reach this goal, a three-tiered solution was developed. This three-tiered solution encompasses workstation redesign, improved layout, and the implementation of a custom loading machine. Ergonomic evaluations using RULA and REBA revealed reductions in risk scores, from 7 to 6 and 9 to 3, respectively. ARENA simulation confirmed the efficacy of a three-tiered upgrade strategy, demonstrating statistically significant improvements in throughput. The proposed solution provides a phased implementation plan, allowing for incremental improvements over time suitable for Hitachi's budget.

Future Actions

To continue the project, there are two main paths. Either or both of these can be done. These are to (I) begin implementing the recommendations, starting with S1, and (II) to fully design all aspects of the Custom Loading Machine.

For implementing the recommendations, asking operators for their ideas for improvement on (I) the Utility Station, and (II) the Scissor Lift Remote will enable a rapid honing in on what is best for Hitachi. Coupling these ideas, a cycle of (I) rapid prototyping (i.e. rough wooden, metal, plastic, or 3d printed mockups) (II) implementing these in production, and (III) getting feedback from the operators will enable a rapid conversion to the best setup for Hitachi's chassis loading operators.

For fully designing the Custom Loading Machine, we have created all CAD models and a comprehensive bill of materials. However, the two biggest things that still remain are: (I) a full wiring diagram and (II) robust supply chains for material procurement. These represent further AME interdisciplinary capstone opportunities with Electrical Engineering and Industrial & Systems Engineering, respectively.

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Introduction to the Company

Hitachi is a Japanese multinational conglomerate that was founded in 1910 by Namihei Odaira. The company started as an electrical machinery repair shop in a copper mine [1]. Today, Hitachi is a global technology and engineering company headquartered in Tokyo, Japan. Hitachi integrates information technology (IT) and operational technology (OT) to develop advanced solutions across various industries. These industries include transportation, healthcare, energy, and more. Hitachi's R&D facilitates this with innovation in materials science, electron microscopy, RFID technology and more [2].

This project is for Hitachi Vantera. This branch of Hitachi assembles and ships server racks. The project sponsor was J'Bob Phelps. Mr. Phelps is a development engineer at Hitachi, and introduced the key components and problem context.

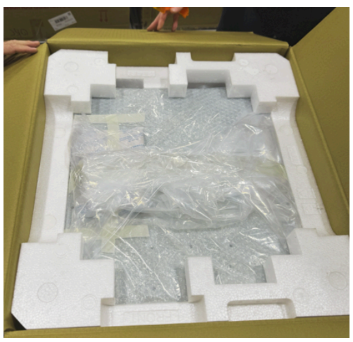


Figure 1: Product Box

Figure 2: Chassis

Figure 3: Vacuum Lift

Figure 4: Rack

The key components necessary to understand this project are the product box, chassis, vacuum lift, and rack. The product box contains the chassis, bag, styrofoam and desiccant (Figure 1). The chassis contains hard drives and solid state drives (Figure 2). The vacuum lift manually moves each chassis into the rack (Figure 3). The rack stores up to eight long or short chassis (Figure 4). All of these are necessary to understand the context of the problem (figures 5 through 7).

Figure 5: Current Layout

Figure 6: Arrival of Chassis

Figure 7: Overhead Box Return

In this context, the two biggest problem genres are (I) non-value-adding times, and (II) a less than ideal ergonomic workstation. The biggest obstacles to increasing value-adding times are repetitive walking and a manual press scissor lift. On the ergonomics side, the current workstation relies on overhead box return, operator twisting, and a difficult to control vacuum lift.

Problem Definition

Two main areas for improvement were identified. These were (I) physical opportunities, and (II) process opportunities. There are four main physical opportunities. These are (I) chassis loading, (II) workstation layout, (III) the vacuum lift, and (IV) chassis control. The chassis loading is time consuming and physically demanding, the workstation has excessive walking, and the vacuum lift is difficult to handle. This culminates in a risk of dropping the chassis and accidentally breaking the costly chassis tabs upon loading (Figure 9).

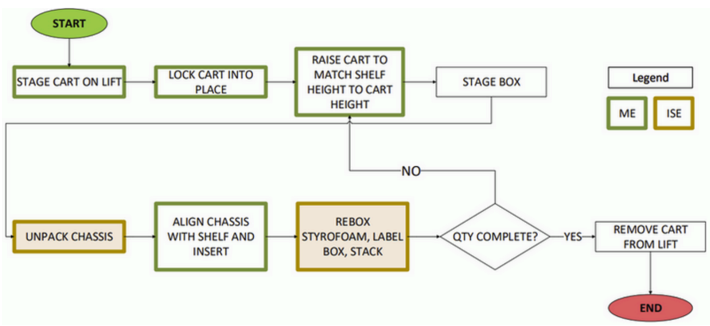


Figure 8: Process and Areas for Improvement

Figure 9: Chassis Tabs

On the process side, there are areas for both ISE and AME tools to be applied (Figure 8). Overall, the biggest opportunity for process improvement is in the walking time. According to the time studies, this takes an average of 26 seconds each chassis loading. Accordingly, the goal of the project is to create a semi-automated solution for chassis loading that (I) increases ergonomics, (II) decreases cycle time, and (III) increases chassis control.

In order to achieve success, success must be defined. This is done through quantifying each goal area of increasing ergonomics, increasing throughput, and increasing lift control. To do this, RULA and REBA, cycle time per chassis, and the number of hands required to load the chassis into the transport cart were used as KPIs (Figure 10).

Area	KPI	Current	Desired
Ergonomics	RULA	7	≤ 3
	REBA	9	≤ 4
Throughput	Cycle Time per Chassis	2 min 18 sec	≤ 1 min 40 sec
Lift Control	Hands Required	2	≤ 1

Figure 10: Measuring Success

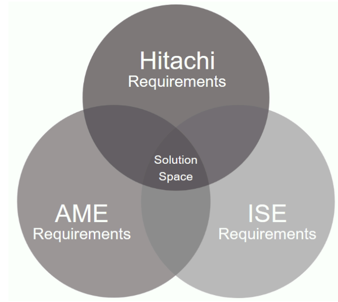


Figure 11: Direct Stakeholders

All solutions must meet constraints. These are that the project is limited by a $100k budget, a 14ft x 12.5ft floor space, and requirements to preserve the box, styrofoam, and desiccant for reuse. Throughput was required to be the same or better. Further, the project must satisfy all direct stakeholders involved. These include Hitachi, the ISE ABET requirements, and AME ABET requirements (Figure 11). Going further, all indirect stakeholders on a global, economic, environmental, and societal scale must be satisfied.

Problem Analysis

Technical Analysis

The current manual process of unboxing and loading 2U drive storage chassis into transport carts presents significant challenges. The main challenges relate to ergonomics, cycle time, and chassis control. Operators manually lift the chassis using an unergonomic and difficult to control vacuum lift. A lack of chassis control results in rare, but costly, chassis drops–ranging from $80,000 to $100,000 cost per drop. Additionally, non-value added time is spent walking back and forth to manually raise and lower the rack scissor lift.

Hitachi initially requested a fully automated solution. Our team performed extensive research pertaining to six axis robot arms, conveyors, scissor lifts, carousels, and robotic de-baggers, which is detailed in the Decision Analysis section of the Solution Process. Upon completion of this research, it was determined that full automation is infeasible given the budget, space, and company constraints (Appendix K). The decision was made to pivot the project away from full automation towards a semi-automated solution.

However, in coming up with these solution bundles (Table 2), there were some trade offs considered, especially when it came to full automation. Although Hitachi initially requested full automation, our project constraints of a $100k budget, a 14ft x 12.5ft floor space limited this implementation. Further, even if there was space for full automation, the entire process would be limited by the slow unbagging machine [17] (Figure 12).

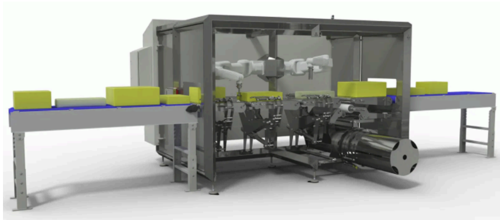


Figure 12: Unbagging Machine

Figure 13: Robotic Arm

Due to these constraints, we made a tradeoff and shifted to a semi-automated solution.

- The cart dimensions cannot change due to interaction with the final assembly process.
- Shipping box and foam are reusable and must not be damaged during the process.
- Cycle time - 8 chassis unboxed and loaded in the cart in under 15 minutes.
- Loading must be performed from bottom to top to prevent instability.
- Utilize existing work areas.
- Only 1 operator should be required to manage the process.
- End effector should not leave any witness marks, deform, or otherwise damage the chassis.
- Electromagnets cannot be used to pick up the chassis.

Figure 14: Solution Requirements from Hitachi

Literature Review

To develop well-informed proposals and an effective course of action, the team conducted thorough research into existing solutions and prior implementations. This included analyzing commercially available technologies as well as innovative techniques and ideas developed by others. A key focus of the research involved evaluating workstation redesigns and assessing the applicability of vacuum lifts to the project [18], [19]. Additionally, the team reviewed relevant codes and standards (Appendix O1 and O2) to ensure compliance and feasibility. These efforts aimed to avoid redundant development and instead prioritize the most relevant, efficient, and impactful solutions for both the project's objectives and its sponsors.

Solution Process

Decision Analysis

Prior to pivoting the project to a semi-automated design, extensive research was completed by the team in an effort to automate as much of the process as possible (Appendix G). Many options had to be outright dismissed due to cost, while others did not offer a level of precision needed to complete the desired tasks or occupied too much floor space. After pivoting, the team focused on identifying and researching new vacuum lifts, scissor lift remotes, and workstation options. Appendix G outlines the applications and benefits of each tool.

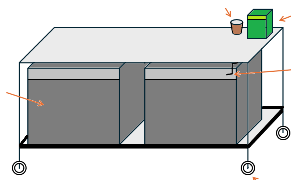


Figure 15: Concept of Workstation Table

Figure 16: Utility Station

Figure 17: DIHOOL Remote Scissor Lift Raiser

Figure 18: Schmalz JumboFlex Generation 2 with Multi Gripper

Solution Component 1: Worktable/Utility Station

The utility table was designed to mitigate operator travel for box work (Figure 16). This reduces non-value added time, thereby increasing throughput. The proposed table had a working height range of 38.4 to 46.4 inches and was adjustable via a hand crank. This range allows for accommodation percentages of 93.1% of male users, 70.9% female users, and a combined 82.0% rate of all users. An Excel tool created by Drs. Matt Parkingson and Matt Reed were utilized to calculate these percentiles [3]. The utility table features plastic and desiccant bins, a sticker dispenser, and box cutter holder. The table has locking wheels and can be moved away from the area for storage when not in use. To augment the use of this table, the workstation will be redesigned such that the pallet for empty boxes will be shifted to be closer to the full pallet. In addition, the table would be height adjustable.

After a meeting with a Hitachi operator, the team pivoted from this design due to lack of buy-in. The table was converted to a utility station that utilizes a 55-gallon rolling trash can. The can itself would be used as a receptacle for desiccant packs while the added component would serve as a consolidated location for stickers and tools. The station may be constructed from metal or wood. For ease of implementation and cost, our team recommends using plywood for its construction. This solution component centralizes the stickers and work tools. It does not provide a working area for the operator to unbox the chassis, and the operator will continue to utilize the incoming chassis pallet as their workstation.

Solution Component 2: Remote Scissor Lift

An Amazon search yielded multiple types of remote scissor lift adaptors. Our selection criteria included the ability to use a remote and unit programmability. The existing scissor lift will be upgraded with a DIHOOL remote scissor lift raiser (Figure 17). It offers various control methods including remote, Wi-Fi, button, and photoelectric options. This wide variety of options will insure compatibility with the existing scissor lift while reducing implementation costs.

Solution Component 3: Vacuum Lift

A trade study of three different vacuum lift brands was conducted (Appendix H). The criteria of focus for selection was lift capacity (minumim 100 lbs), radio remote control, gripper types, and one hand control. The Schmalz JumboFlex 50 features both a radio remote control SRC, and a control head with a wide variety of gripper types. The radio remote control SRC will reduce cycle time by removing the need for the operator to tediously walk back and forth to the crane at the beginning and end of the process. Additionally, Schmalz is the only brand to offer a multiple vacuum gripper (Figure 18). This gripper is 3D printed, can be customized to size, and has a larger footprint resulting in less stress on the chassis during handling while providing increased surface-to-surface contact. These features make the Schmalz JumboFlex 50 the default choice for this application.

Solution Component 4: Chassis Loading

The decision to design the CLM was influenced by both onsite observations and external research. During a tour, the team encountered a machine with similarities to the CLM and initially considered implementing it in the project. However, it did not meet speed requirements, and no design files were accessible. Additionally, the machine offered more functionality than necessary for the project. Using pictures, videos, and external research, the team adapted it as a template for the CLM. Throughout the design process, features from the observed machine were excluded unless they provided measurable benefits to one or more solution tiers, ensuring a streamlined and efficient implementation.

Solution Component 5: Facility Layout

The current work area layout is inefficient for the process (Figure 19). The operator must leave the primary workstation, the unboxing station, a minimum of five times during a single chassis loading cycle. This non-value added time can be eliminated with implementation of our solutions in conjunction with floor layout adjustments. Layouts were designed to reduce route time while also improving ergonomics by reducing twisting and bending.

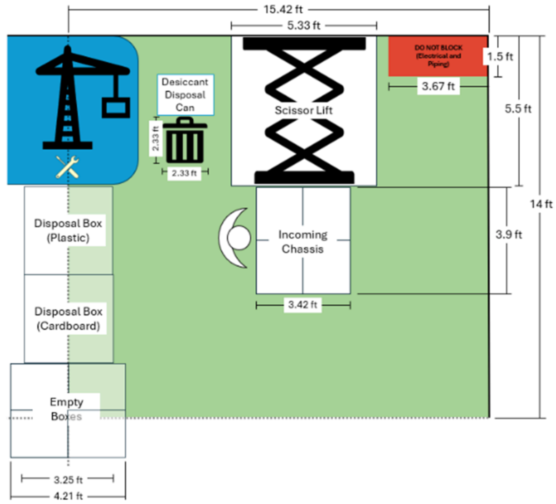


Figure 19: Current Facility Layout

Solution Component 6: Ergonomics

All aspects of this project were evaluated for their improvement contributions relating to ergonomics. The process was studied in detail by video and showed high RULA and REBA scores (Appendix E1 and E2).

Solution Description and Data Collection

Solution Tiers

A three tier scaling roadmap was devised to allow Hitachi step-by-step implementation. Table 1 outlines each solution and its components, as well as the process impacts of each solution.

Table 1: Solution Tiers & Scaling Roadmap

Solution Name	Cost	Design Components	↑ Automation	↓ Cycle Time	↑Ergonomics	↑ Chassis Control
S1	$768	 + 	🥉	🥉	🥉	🥉
S2	$40,768	 +  + 	🥈	🥈	🥈	🥈
S3	$80,547	 +  + 	🥇	🥇	🥇	🥇

Solution 1

Solution 1 features the utility station and remote scissor lift. This is the least costly of the solutions and can be implemented with the fastest return on investment (see Economic Analysis). The facility layout ensures the operator is close to the required tools and stations (Figure 20). The pallet for empty boxes may be adjusted to allow for ease of operator access to the space, but every attempt to keep the pallet within reach of the operator should be made. The plastic disposal box is replaced with a wheeled 55 gallon trash can. We estimated four racks (24 chassis) worth of material can fit in the receptacle. Hitachi's average number of racks loaded per day is two.

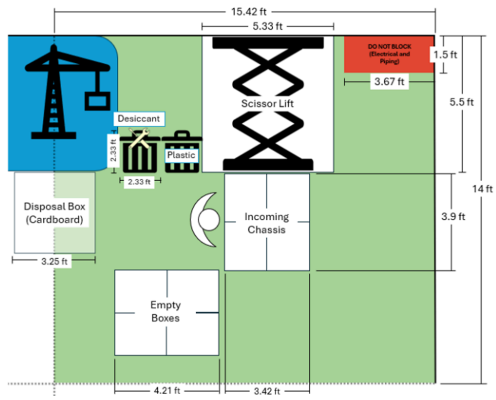


Figure 20: Solution 1 and 2 Facility Layout

Solution 2

Solution 2 builds on Solution 1 with the addition of a new vacuum lift. This is the mid-rage cost solution with a median ROI. The facility layout is identical to Solution 1.

Solution 3

Solution 3 is the highest cost solution with the longest ROI. This solution utilizes the utility station, new vacuum lift, and the CLM. The facility layout is significantly different from Solutions 1 and 2 (Figure 21). The existing scissor lift is removed and the CLM is placed in that space. The operator is within reach of all necessary stations and tools. All related stations are within the designated area.

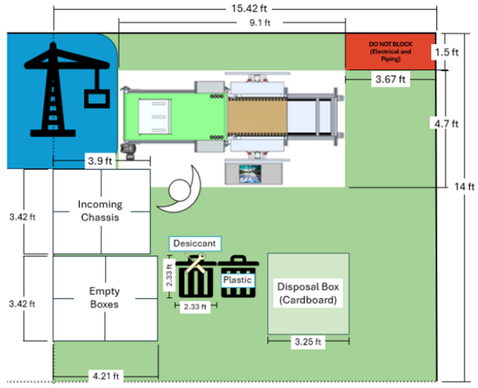


Figure 21: Solution 3 Facility Layout

The CLM is the most automated, the most costly, and is anticipated to perform the best across all of the project goals. It will significantly decrease cycle time when used with a line-balanced operator in tandem. Due to the complexity of the machine, multiple CAD designs were developed to ensure seamless integration. The system primarily consists of a conveyor belt and a loading machine, occupying approximately 9.1 x 4.7 feet of floor space

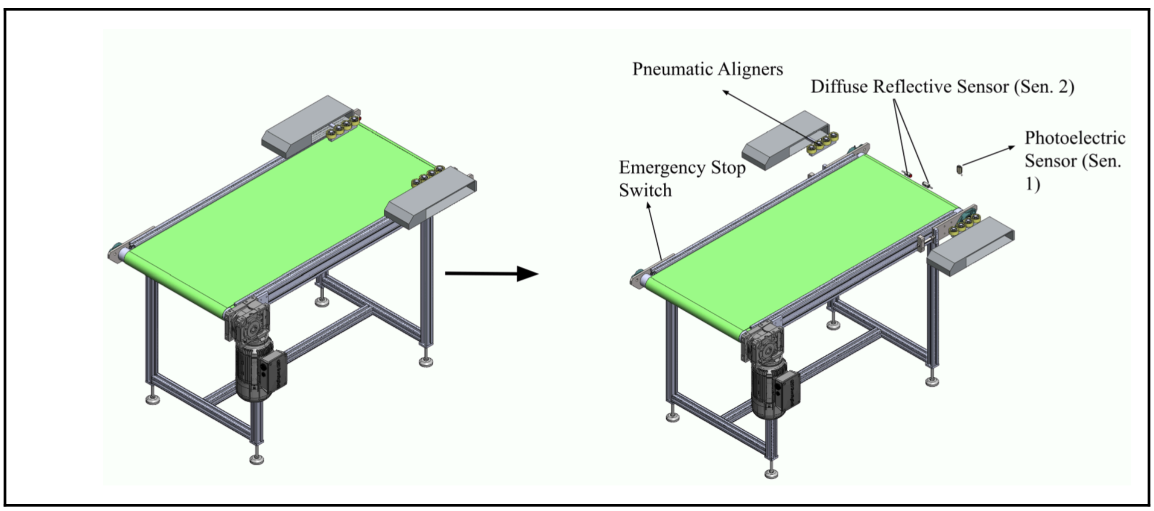


Figure 22: Conveyor Belt

Explanation of Process

The automated chassis loading system is designed to streamline the process of placing chassis into the rack with minimal manual effort. The process begins when an operator places a chassis onto the conveyor belt after unboxing it. The conveyor belt is designed to be wide enough to reduce the need for precise manual alignment, allowing operators to place the chassis quickly and efficiently without worrying about exact positioning. As the chassis approaches the end of the conveyor, a photoelectric sensor (Sen. 1) detects its presence and temporarily stops the conveyor to ensure that alignment takes place before loading.

At this point, a pneumatic aligner mechanism activates, consisting of two pneumatic cylinders positioned on either side of the conveyor. These cylinders extend to gently push the chassis into a perfectly aligned position relative to the loading machine. This step is critical because misalignment at this stage can lead to inefficiencies or even potential damage to the chassis during the loading process. Once alignment is achieved, the pneumatic cylinders retract, and the conveyor belt resumes movement, guiding the now-aligned chassis directly into the loading machine.

Upon entering the loading machine, the chassis must be securely held in place to ensure smooth insertion into the rack. The system incorporates diffusive reflective photoelectric sensors (Sen. 2) at the loading machine's home position to confirm that it is ready to receive the next chassis. If the loading machine is occupied or not in position, the system holds the chassis at the end of the conveyor until it becomes available. Once confirmed, the CLM secures the chassis in its designated slot, preventing unnecessary movement or misalignment during the loading process.

A key discussion point was whether a conveyor belt is necessary or if the chassis should be placed directly onto the loading machine. Our analysis concluded that incorporating a conveyor belt is beneficial due to the following reasons:

1. **Operational Efficiency:** The conveyor belt allows operators to continuously place additional chassis while the loading machine is in operation. This enables line balancing, resulting in low cycle times.
2. **Operator vs. Machine Speed:** The conveyor belt is essential when the operator is faster than the loading machine. The conveyor belt acts as a queue in this case.
3. **Pre-Alignment Advantage:** Unlike the existing PTL system at Hitachi, which aligns chassis within the loading machine—leading to slower operation—our design performs alignment at the conveyor belt stage. This eliminates extra alignment steps within the loading machine. This reduces the cycle time.

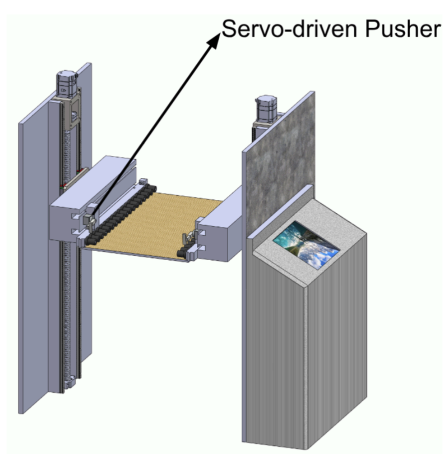


Figure 23: CLM Assembly

The next step involves inserting the chassis into the rack at the correct height. The CLM is designed to move vertically along a guided track, allowing it to adjust its position based on the height of the specific rack level. This method also removes the need for the existing scissor lift the facility has for raising and lowering the rack. To achieve precision in loading, the system utilizes servo-driven actuators that push the chassis into the rack with controlled force. The box seen in the picture with the screen is where the operator can program the machine according to their requirement. That's also the place where all the electronic wiring will be located.

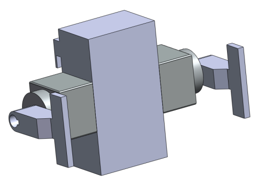


Figure 24: Initial Design of Servo-driven Pusher

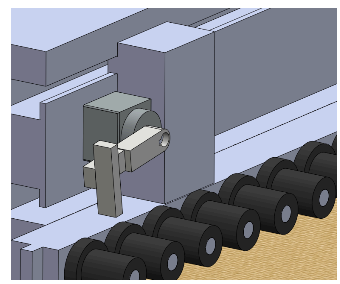


Figure 25: Final Design of Servo-driven Pusher

The servo-driven pusher system is designed to ensure precise chassis placement by compensating for insufficient forward movement from the conveyor belt. Initially, the design included two separate motors—one to pull the chassis closer when necessary and another to push it into the rack. While this configuration effectively accomplished the task, it presented certain drawbacks, including slower operation due to the need to coordinate two motors, increased electrical wiring complexity, and higher costs associated with additional motor components. To optimize efficiency and reduce overall system complexity, the final design consolidates these functions into a single motor. Instead of using two independent motors, the revised system leverages a single servo-driven mechanism capable of both pulling the chassis closer when needed and subsequently pushing it into the transport cart.

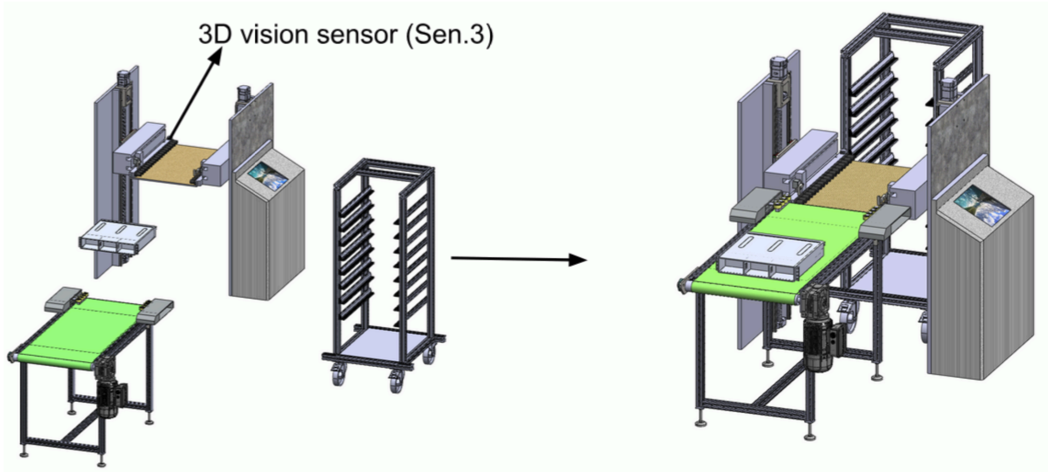


Figure 26: Exploded and Collapsed View of Final CLM Assembly

Additionally, a vision sensor (Sen. 3) detects the edges of the rack to ensure that the chassis is aligned correctly before being inserted. This sensor prevents errors by verifying that the chassis is positioned precisely to fit within the rack slots, reducing the chances of misalignment or mechanical failure. Once the chassis is fully inserted into the rack, the CLM automatically retracts, returning to its home position. This movement is detected by photoelectric sensors (Sen. 2), which signal to the conveyor that the loading machine is now available for the next chassis. The entire process resets, allowing the system to handle the next chassis efficiently. This automation minimizes downtime, improves consistency, and enhances the overall safety and ergonomics of the loading process. The following flow chart shows the control logic.

Ball Screw Linear Actuator Motor Selection

One of the most critical design decisions in this system is the selection of the motor for the ball screw linear actuator. The overall positioning accuracy of our system depends not only on the precision of the ball screw itself but also on the motor's ability to provide accurate and controlled movement. If the selected motor lacks precise control, we risk compromising the system's required accuracy. For high accuracy and better control, we have chosen a servo motor over a stepper motor. Servo motors provide superior precision, closed-loop feedback, and smoother motion, making them ideal for our application.

Another key factor in motor selection is torque rating. The motor must generate sufficient torque to lift both the static and dynamic loads involved in the system. These are **(I)** a maximum chassis weight of 18 kg, **(II)** additional weight of CLM that moves up and down of ~30 kg, and **(III)** a total moving load of 48 kg. Considering a ball screw efficiency of 80% and a lead distance of 10mm, we calculate the required torque using Equation 1.

$$Torque\ (T) = \frac{Axial\ Force\ (N)\times Lead(mm)}{1000\times 2\times \pi \times \mu} = \frac{480\times 10}{2000\times 3{,}14\times 0.8} = 0.955\ Nm$$

Equation 1: Ball Screw Torque Calculations

To ensure a sufficient safety margin, we selected a servo motor rated at 2.39 Nm, which meets our application's requirements.

FEA of load bearing components

There were two main load bearing components in our solution S3. One was a linear actuator fixture and the other was a servo- driven pusher's arm.

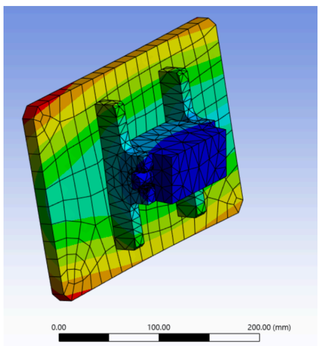


Figure 27: Total Deformation of Linear Actuator Fixture

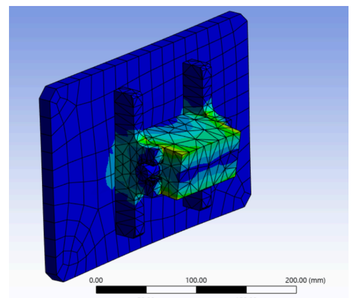


Figure 28: Equivalent (von-Mises) Stress of Linear Actuator Fixture

To ensure the structural integrity of the linear actuator fixture, we conducted a static structural analysis under the assumption that it must support the combined weight of both the CLM (Custom Loading Machine) and the chassis. The maximum estimated weight of the chassis is 18 kg, and when combined with the CLM (approximately 30 kg), the total expected load becomes around 48 kg, which translates to ~480 N under standard gravity. Since there are two fixtures, one on each side of the linear actuator, the load is symmetrically distributed. Therefore, each fixture experiences a force of approximately 240 N, acting in the negative Y-direction (downward). A fixed boundary condition was applied to the rear side of the fixture, highlighted in blue in Figure 27. This assumption is valid as this section of the fixture is mounted in a way that restricts its movement.

The results of the FEA simulation show a maximum total deformation of only 0.00094 mm at the outer edges of the fixture, a value that is negligible and confirms structural rigidity. Additionally, the maximum von Mises stress observed was 0.9 MPa, localized at the joint between the fixture plate and the ball screw float mounting, as shown in Figure 28. Given that the fixture is made from stainless steel with an approximate yield strength of 250 MPa, the induced stress is significantly below the material's yield limit. This suggests that under normal operating conditions, the fixture will neither deform plastically nor fail.

To further validate this, we calculated the safety factor (SF) using the formula:

$$SF = \frac{Ultimate\ Strength}{Max\ Stress} = \frac{250}{0.9} = 277.8$$

Equation 2: Safety Factor

This extremely high safety factor (also reflected in ANSYS with a reported SF > 15) confirms that the fixture can theoretically withstand stresses over 270 times higher than what will be experienced during normal use. Such a high safety factor is not only sufficient but also provides assurance for long-term durability and safety

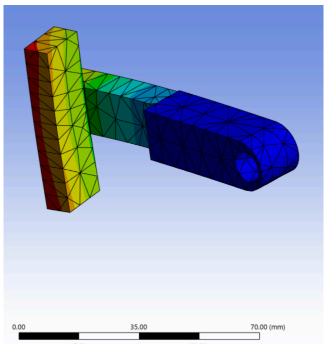


Figure 29: Total Deformation of Servo Driven Pusher's Arm

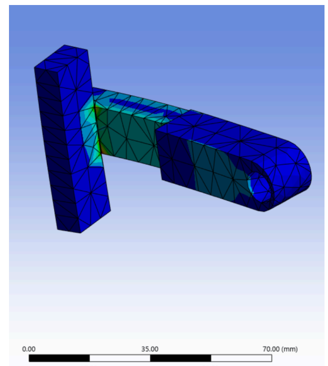


Figure 30: Equivalent Stress of Servo Driven Pusher's Arm

This component is mechanically coupled with a servo motor, functioning as a pusher arm to guide the chassis into the cart by exerting force on the ears of the chassis. Since the chassis rests on freely rolling rollers, it encounters minimal resistance, and thus the pusher arm is not expected to undergo significant deformation. To determine the total load exerted on the pusher arm by the chassis ear, we used the equation:

Equation	Constants	Result
F=c · m · g	c=0.01 (coefficient of rolling resistance) m=18kg (mass of the chassis) g=9.81 m/s^2 (acceleration due to gravity)	F=0.01×18×9.81=1.77 N

Equation 3: Total Pusher Load

Since the tip of the pusher is in full contact with the chassis ear, the load is applied as a distributed pressure over the contact area rather than a point load.

$$Contact\ Area\ =\ 52mm\ \times\ 15mm\ =\ 780mm^2\ =\ 0.00078mm^2$$

$$P\ =\frac{F}{A}=\ 2269pa\ =\ 0.00227\ Mpa$$

Equation 4: Contact Area and Pressure

Since the pushing system is symmetrical, and two pusher arms are used, the pressure experienced by each arm is half of the total which is 0.0011 Mpa. A fixed support boundary condition was applied to the region of the arm connected to the servo motor shaft, as shown in Figure 20, to simulate its anchored state. After the simulation, the total deformation was found to be 1.4e−7 mm at the tip of the pusher which is negligible. Similarly, the maximum von mises stress was found to be 0.0003 Mpa. Given that the pusher arm is made from stainless steel with a yield strength of 250 MPa, the induced stress is vastly lower than the material limit. This indicates a very high safety margin and confirms that no plastic deformation or structural failure will occur under standard operating conditions.

Data Collection

Data was collected via live and recorded observations. Ergonomic analysis was performed on the initial recorded video supplied by Hitachi at the beginning of the project. Twelve chassis cycle times were observed live. Four recordings were provided by Hitachi. These recordings were broken down into the individual action times. The recordings were also used as chassis cycle times, with a total of 16 cycles averaging to 138 seconds per chassis.

Solution Verification

Individual actions were processed with ARENA's Input Analyzer to create distributions (Appendix F). It should be noted that due to the limited number of data points there is a high amount of uncertainty regarding their accuracy. Despite this, 5000 replications of the current system model yielded an average cycle time per chassis of 122 seconds, calculated using Excel (Appendix J1). The average cycle time was calculated by adding the non-value added time, which for the sake of the simulation was all steps of the process, and the transfer time. Time spent by chassis in the queue was disregarded because it had no bearing on the process. The variation of 16 seconds between the observed cycle time and simulated cycle time was deemed to be acceptable due to observed cycles being variable due to the observer effect.

Solution Validation

Solutions 1, 2, and 3 were simulated with 5000 replications each (Appendix M2, M3, and M4). The average cycle times per chassis for all simulations can be found in Appendix J1 and are further illustrated in Appendix J4. Statistical analysis was performed using ARENA's Output analyzer (Appendix J2). Paired t-test comparison of means showed that all three solutions were statistically significant when compared to the current system (Appendix J1). Additionally, by utilizing RStudio, a Tukey Test confirmed that S3 is the most impactful solution, followed by S2 and S1 respectively (Appendix J3).

Ergonomic Outcomes

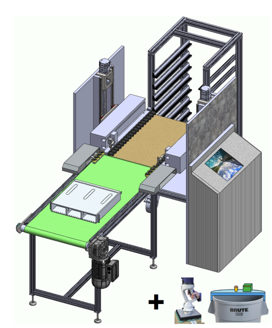
The desired outcome for REBA, with implementation of Solution 2 and increased operator awareness and training, can be achieved with a score of 3, reduced from 9 (Appendix I1). However, RULA may only be reduced from 7 to 6 (Appendix I2). This result is due to the physical nature of the task. Without additional automation, this process will remain high risk.

Economic Analysis and Systems Impacts

Economic Analysis

Now that the process, parts, and ergonomics have been validated using ARENA, ANSYS, RULA and REBA, it is time to economically validate the proposed solutions. The costs and break even points of each solution are shown in Table 2.

Table 2: Solution Costs and Break Even Points

Name	Solution 1 (S1)	Solution 2 (S2)	Solution 3 (S3)
Cost	$768	$40,768	$80,547
Entails			
Break Even	0.5 Years	5.3 Years	7.8 Years

It is important to note that the entire scaling process from S1 to S2 to S3 can take place in less than 8 years. This is because each solution builds upon the previous solution. This enables a low risk, easy way to begin improving the process. As an addition to Table 2, the story behind each break even point is shown in Figure 31.

	S1	S2	S3
Hrs Saved / Year [1] [2]	19	24	29
$ Saved [3] ↓ Cycle Time +	$560	$728	$868
$ Saved [4] [5] ↑ Lift Control =	$1,000	$7,000	$9,500
$ Saved Total / Year	$1,560	$7,728	$10,368
Break Even	0.5 yrs	5.3 yrs	7.8 yrs
10 Year Return	**$14,832**	**$36,512**	**$23,133**

Figure 31: ROI Analysis

Figure Y shows that S1, S2, and S3 each save Hitachi approximately $1.5k, $7.7k, and $10.4k per year. Further, in a decade, S1, S2, and S3 will each save Hitachi approximately $15k, $37k, and $23k. This leads to the conclusion that S1, S2, and S3 are most appropriate for the short, middle, and long term use. The formulas to calculate each number in this ROI analysis can be found in Appendix A and B.

Ethical and Systems Impacts

In the modern world, industry, society, culture, and the environment are deeply interconnected. This means that a proper consideration of the project needs to go beyond just a ROI analysis. For this reason, systems implications, trade offs, and impacts in global, economic, environmental, societal contexts were considered. This was done by considering the effects on both direct and indirect stakeholders (Appendix C).

Systems implications

For the direct stakeholders, direct systems implications manifested in three key areas. These were human factors, throughput, and cost.

Human factors are a priority. The solutions demonstrate this by improving ergonomics. This is shown in reductions in both the RULA and REBA risk scores, where reductions were from a 7 to a 6, and a 9 to a 3. This is also shown in an estimated reduction of chassis drops by 10%,70%, and 90%. This both reduces musculoskeletal risks and reduces strain from lifting, twisting, and repetitive motions. These improvements imply an improvement in the operator's workday.

Throughput implications were also considered. As validated by ARENA, the current average chassis cycle time of between 122 to 138 seconds was improved to 102, 96 seconds, and 91 seconds (Appendix D). This was largely due to the utility station and scissor lift remote saving walking time, the vacuum lift increasing ergonomics and reducing drops, and the Custom Loading Machine (Appendix K). This frees up operator time, lowers fatigue, and reduces workplace injury.

Cost implications were considered as well. The combination of reducing strain, saving time, and reducing drops saves Hitachi 1.6k, 7.7k, and 10.4k per year, respectively (Figure 31) .

Improved chassis control, with the vacuum lift and the CLM's guided loading system significantly reduced the risk of costly chassis drops. These drops cost Hitachi $80K to $100K per incident. This cost reduction will likely result in trickle down effects. This can be assumed to make the chassis cheaper, more available, and improve cloud computing infrastructure.

Tradeoffs Considered in Design

Out of these three implications, increasing human factors also led to increased throughput. This is due to saving the operators time and unneeded motion. As such, the biggest tradeoff was the cost. Hitachi's values regarding human factors, throughput, and cost were also implemented in design considerations. Accordingly, the three tiered solution was introduced (Appendix K) with each of the associated layouts (Figure 20, Figure 21). Operator safety was non-negotiable and couldn't be traded off.

Impact in economic, global, economic, environmental, and societal contexts

For the indirect stakeholders, the project had environmental, economic, societal, and social effects.

Environmentally, this project maintains Hitachi's sustainable practice of reusing packaging. Because all solutions introduce electrically powered components, this increases energy consumption. Implementation also necessitates responsible e-waste disposal when parts break. A future Life Cycle Analysis (LCA) could quantify the full environmental impact of the new components.

Economically, these beneficial returns could inspire similar solutions to be implemented across Hitachi's plants (Figure 31). This would increase Hitachi's revenues, and potentially trickle down to the consumer in terms of reduced cost, more reliable servers, and increased computing bandwidth.

Societally, these solutions promote health and safety. The ergonomic improvements that lowered musculoskeletal disorder risks. Further, the design facilitates workforce familiarity with semi-automated solutions. This is especially the case with S3. These positive effects could be optionally augmented through information sessions on ergonomics, lifting posture, and familiarity with the CLM.

Socially, each solution prioritizes operator well-being and incorporates the feedback received from them. Reducing this station's time could free up operators to work in other areas of the plant. This could increase workplace interaction between the operators, leading to improved morale. Overall, our solutions provide a strong starting place for improvements that Hitachi could transfer to other areas and facilities.

Project Schedule

In order to manage and record the timelines of our project, a gantt chart was used. At the start of the project, the task was decomposed down into subtasks. Then the initial project schedule was created (Figure 32). However, as the project progressed some tasks took longer than others. As such, the gantt chart had to be actively managed and revised. This was in response to issues and delays. Figure 33 shows the finalized gantt chart.

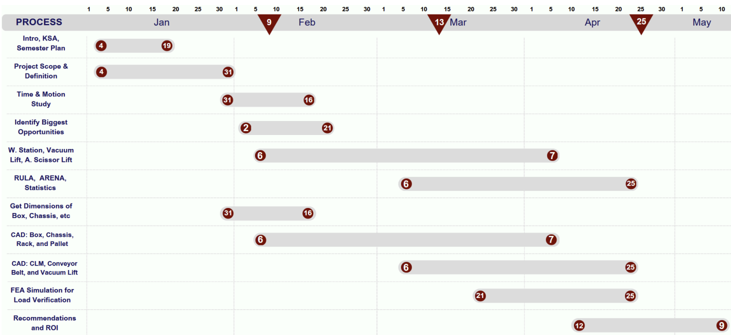


Figure 32: Initial Gantt Chart

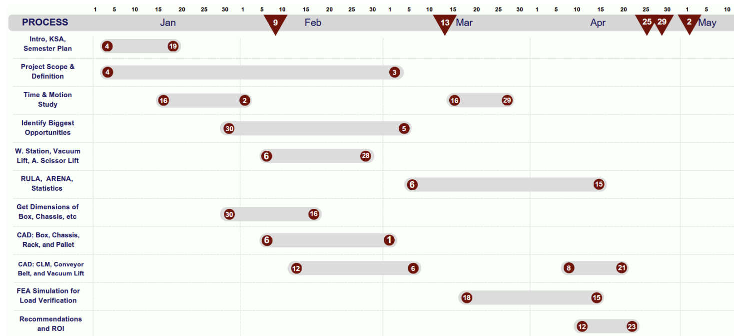


Figure 33: Final Gantt Chart

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The main issues causing the gantt chart to change were in (I) understanding the project scope and definition, and (II) identifying the biggest opportunities. This was partially due to a delay in alignment of objectives between Hitachi, the ISE ABET requirements, and the AME ABET requirements. Fortunately, through collecting the data and frequent meetings these issues were able to be overcome.

Summary, Conclusions and Recommendations

In the KPIs of ergonomics, the REBA metric was met and the RULA metric was not. Without additional automation, an expanded budget, and increased floor space, this process will remain physically risky to the operator. Our team recommends additional operator training for increased ergonomic awareness. For throughput, the KPI of reduced cycle time of greater than a 38 second reduction was achieved by Solutions 2 and 3. The addition of the new vacuum lift in Solution 2 and the corresponding route eliminations results in this KPI being achieved. The addition of the vacuum lift in Solution 2 is also the primary factor in the lift control KPI result. Solution 1 is the recommended immediate implementation to Hitachi, with the goal of implementing Solution 2 as soon as possible. Solution 2’s impact on the process when compared to Solution 1 is too great to ignore and it offers a clear benefit to Hitachi. Implementation of Solution 3 is a long term goal. The CLM requires additional design, including full wiring diagrams and robust supply chains. These aspects are ideal capstone opportunities for future electrical, mechanical, and industrial and systems engineering students who work with Hitachi.

Limitations and Reservations

While the proposed semi-automated solution offers significant improvements in efficiency, ergonomics, and safety, several limitations and reservations must be acknowledged regarding the project's conclusions and recommendations. First, the system is only semi-automated due to spatial, financial, and operational constraints identified by Hitachi.

Although this choice is practical, it limits the potential for full automation and future scalability without significant redesign. Moreover, the solution continues to rely on human operators for certain tasks, such as cutting the chassis box, operating the scissor lift, and positioning the chassis for vacuum lifting. This introduces variability based on operator behavior and training, which could affect the consistency of the results.

Additionally, although a custom loading machine has been conceptually designed with complete CAD models and a bill of materials, the lack of a full wiring diagram and the absence of a working prototype present challenges. Without physical testing, the proposed benefits remain theoretical and simulation-based. The ARENA simulations used to validate throughput improvements depend on several assumptions and may not fully capture real-world factors such as mechanical issues or operator fatigue, potentially impacting performance. The ergonomic analysis, while showing improvements in REBA and RULA scores, is limited to specific scenarios and does not account for individual worker differences like height, strength, or habits. This restricts the generalizability of the results. Furthermore, the implementation relies on timely procurement of materials and successful integration with existing systems, both of which carry risks due to potential supply chain disruptions or technical compatibility issues. Lastly, the project's success depends on iterative feedback from operators. While this approach is beneficial for user-centered design, it introduces subjectivity and potential delays that could affect the refinement process.

These limitations highlight the importance of phased implementation, careful monitoring, and continuous testing to ensure the proposed solution meets practical needs in real-world manufacturing environments.

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Data Appendices

Appendix A: Assumptions in ROI Calculations

[1] 8 Chassis / 1 Rack	**[3]** Operator pay: $30/hr	
[2] 1.68 racks done / day	**[4]** Est. 10%,70%,90%	**[5]** 10k Avg. yearly drop cost

Appendix B: ROI Calculations

Hours Saved / Year

Equations

$$\frac{Hours\ Saved}{Year} = \left(\frac{Hours\ Saved}{1\ Chassis}\right) * \left(\frac{8\ Chassis}{1\ Rack}\right) * \left(\frac{1.68\ Racks\ Loaded}{1\ Workday}\right) * \left(\frac{250\ Workdays}{1\ Year}\right)$$

$$\frac{Hours\ Saved}{1\ Chassis} = \left(\frac{Seconds\ Saved}{1\ Chassis}\right) * \left(\frac{1\ Hour}{3{,}600\ Seconds}\right)$$

$$\frac{Seconds\ \ Saved}{1\ Chassis} = Avg(Cycle\ time\ of\ current\ state) - Avg(cycle\ time\ of\ this\ solution)$$

Constants

$Avg(cycle\ time\ of\ current\ state) = 122\ seconds$
$Avg(cycle\ time\ of\ S1) = 102\ seconds$
$Avg(cycle\ time\ of\ S2) = 96\ seconds$
$Avg(cycle\ time\ of\ S3) = 91\ seconds$

** these numbers were derived using ARENA simulation **

$Number\ of\ chassis\ 1\ rack\ can\ hold = 8$ **[1]**
$Average\ number\ of\ racks\ done\ in\ a\ day = 1.68$ **[2]**

$ Saved (from decreasing cycle time)

Equations

$$\$\ Saved_{\downarrow cycle\ time} = \left(\frac{Hours\ Saved}{Year}\right) * (Operators\ hourly\ rate)$$

Constants

$Operators\ hourly\ rate\ (assumed) = \frac{\$30}{Hour}$ **[3]**

$ Saved (from increasing lift control)

Equations

$$\$\,Saved_{\uparrow lift\ control} = Avg(\frac{Chassis\ drop\ cost}{Year}) * (Est.\ \%\ decrease\ in\ chassis\ drops)_{this\ solution})$$

Constants

$$Avg(\frac{Chassis\ drop\ cost}{Year}) = Avg(\$100k\ drop\ cost) * Avg(\frac{1\ Chassis\ drop}{10\ Years}) = Avg(\frac{\$10k\ drop\ cost}{Year})$$

[5]

$(Est.\ \%\ decrease\ in\ chassis\ drops)_{S1} = 10\%$ **[6]**

$(Est.\ \%\ decrease\ in\ chassis\ drops)_{S2} = 70\%$ **[6]**

$(Est.\ \%\ decrease\ in\ chassis\ drops)_{S3} = 90\%$ **[6]**

$ Saved Total / Year

Equations

$$\frac{\$\,Saved\ Total}{Year} = \$\,Saved_{\downarrow cycle\ time} + \$\,Saved_{\uparrow lift\ control}$$

Break Even Point

Equations

$$Break\ Even\ Point = \frac{Cost_{this\ solution}}{\frac{\$\,Saved\ Total}{Year}}$$

Constants

$Cost_{S1} = \$768$

$Cost_{S1} = \$40,768$

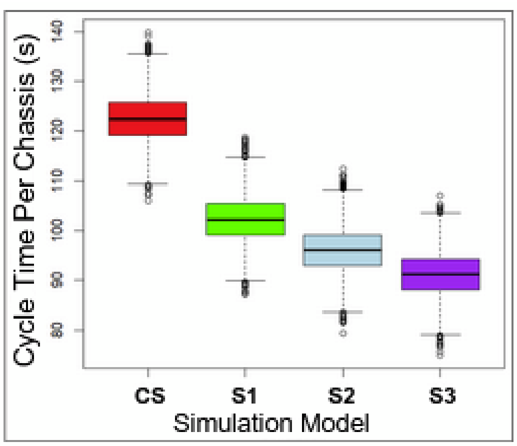
$Cost_{S1} = \$80,547$

Appendix C: Examples of Direct Stakeholders at Hitachi

Stakeholder	Project Impact
Facility Manager	Improved production efficiency leads to better facility metrics.
Operator	Improved ergonomics leads to decreased risk of injury.

Server assembly	Decreased cycle time for rack loading translates to decreased wait time for chassis racks.
Warehouse floor worker	Employees that are responsible for removing waste will see an increased frequency for waste disposal.
Forklift Operators	Increased workload due to the need for new pallets of chassis to be moved more frequently.
Maintenance	Employees will need additional training to maintain the new equipment.
IT	Employees will be needed to program and implement solutions requiring an internet connection.
Assistant manager	Requires additional training and must oversee operators to ensure improvements are continuously implemented.
Safety staff	Needed to insure codes and standards are being met during installation and implementation.
Accounts and billing	Required to process payments and retain purchase records for part acquisition.

Appendix D: Arena Summary



Arena Simulation Software

	Current System	Simulation			
		Current System	S1	S2	S3
Average Cycle Time Per Chassis (s)	138	122	102	96	91

Appendix E1: Rapid Upper Body Limb Assessment - Current Process

Score Category	System Score	Score Justification
Neck Score	2	20+ degrees in extension, no twist or side bending
Trunk Score	4	20-60 degrees, twist motion on reach, no side bending

Leg Score	1	Both legs down
Posture Score A	5	Table A
Force/Load Score	0	< 11 lb
Score A	5	Sum rows 4 and 5
Upper Arm Score	5	Adjusted for arm 90+ degrees, abduction, operator leaning
Lower Arm Score	2	100+ degree
Wrist Score	3	15+ degree, wrist bent from midline
Posture Score B	8	Table B
Coupling Score	3	Based on box only, handles not used
Score B	11	Sum rows 10 and 11
Table C Score	9	Table C
Activity Score	0	
REBA Score	**9**	

Appendix E2: Rapid Upper Body Limb Assessment - Current System

Score Category	System Score	Score Justification
Upper Arm Score	5	Adjusted for arm 90+ degrees, abduction
Lower Arm Score	3	100+ degree, working across midline and outside of body
Wrist Twist Score	1	Twist in mid-range
Wrist Score	4	15+ degree, wrist bent from midline at suction release step
Posture Score A	6	Table value
Muscle Use Score	1	Repeated action
Force/Load Score	2	
Wrist & Arm Score	9	Sum score rows 5 through 7
Neck Score	3	20 + degrees, no twist or side bending
Trunk Score	4	20-60 degrees, twist motion on reach, no side bending
Leg Score	1	Supported feet
Posture B Score	4	Table value
Muscle Use Score	1	Repeated action
Force/Load Score	2	
Neck, Trunk, Leg Score	7	
RULA Score	**7**	Table score

Appendix F: Video recorded cycles of chassis loadings broken into individual components and their distributions.

Action	Task Time (sec)	Task Time (sec)	Task Time (sec)	Task Time (sec)	ARENA Distribution
Raise lift	10	n/a	n/a	30	9.5 + 21 * BETA(0.338, 0.368)
Cut tape	8	6	6	4	3.5 + 5 * BETA(0.672, 0.672)
Turn on vacuum lift	1				
Open flaps	4	5	4	7	3.5 + EXPO(1.5)
Remove styrofoam	6	4	3	2	UNIF(1.5, 6.5)
Open bag	7	21	25	22	6.5 + 19 * BETA(0.185, 0.102)
Remove desiccant	5	1	1	1	0.5 + LOGN(1.36, 1.65)
Apply lift	17	9	9	4	3.5 + 14 * BETA(0.301, 0.374)
Remove chassis	11	8	5	3	2.5 + 9 * BETA(0.738, 0.79)
Load chassis	4	5	10	4	3.5 + LOGN(2.17, 3.1)
Dispose plastic	4	7	6	5	UNIF(3.5, 7.5)
Repack styrofoam	1	2	2	3	0.5 + 3 * BETA(2.21, 2.27)
Close box	3	2	3	3	1.5 + WEIB(1.39, 3.72)
Route - retrieve stickers	8	14	12	5	UNIF(2.04, 7)
Collect Stickers	2	2	2	2	Constant = 2
Apply stickers to box	6	4	4	7	POIS(5.25)
Stack box	1	1	1.5	1	0.999 + WEIB(0.0207, 0.336)
Route - workstation to empty pallet and back	4	17	11.5	10	UNIF(2, 9)
Walk back to lift button	2	0	1	0	-0.5 + 3 * BETA(0.578, 0.809)

Appendix G: Researched and Rejected Tools

Researched Solution	Proposed Application(s)	System Benefit(s)	Reason(s) for Dismissal
Workstation Table	• Used as an all-in-one station for chassis unloading, tool consolidation, and waste disposal.	• More ergonomic. • Route elimination. • Not a permanent fixture.	• No operator buy-in.
Tab safety jig	• Protect black tab on the back of the chassis from breaking.	• Decreased cost due to damage of chassis.	• Hitachi does not want additional fixtures.
Scissor lift jig	• Fixes rack in place on the scissor lift.	• Rack alignment is consistent.	• Low priority improvement opportunity.
Scissor lift replacement	• Replace current lift with a programmable, faster-moving alternative.	• Route elimination. • Decreased cycle time.	• Cost.
Six-axis robotic arms	• Transport full and empty boxes on and off of the workstation. • Chassis unpacking. • Lift and transportation of chassis from box onto conveyor. • Lift and transportation of chassis from box into rack.	• Increased automation. • Increased ergonomics through task elimination. • Route elimination.	• Complicated packaging. • Not precise enough. • Cost. • Risk to operators through close proximity.
Conveyors and Carousels	• Transport full and empty boxes to and from the operator. • Transport unboxed chassis to the rack.	• Decreased cost due to damage of chassis.	• Multiple chassis lengths must be accommodated. • Only viable when used with a six-axis arm.
Robotic De-bagger	• Cut open and remove plastic surrounding the chassis.	• Increased automation.	• High likelihood to damage chassis. • Cost. • Large space footprint.

Appendix H: Improved Vacuum Lift Trade Study

Brand Name	Schmalz	Anver	Vacu Cobra
Distributer	Ergonomic Partners	ANVER	TAWI

Lift System	JumboFlex 35/50 Gen 2	VT100-4.0-A-B-PG	TP35
Lift Capacity	35 kg / 50 kg	20-29 kg	34-63 kg
Noteable gripper types	Round, double, quadruple, multiple	Not interchangeable, only round option	Round, double, quadruple
Radio remote control SRC for vacuum generator	Yes (Optional)	Yes (Optional)	No
Suspension height adjustment (no load)	Yes	No	Yes
Changeable filter without tools	Yes	No	No
Continuous rotation, lockable in 90° increments	Yes	No	Yes
Tool-free quick-change gripper adapter	Yes	No	Yes
One or two-finger load control	Yes	Yes	Yes
One hand control	Yes	Yes	Yes
Two-handed control	No	No	No
Vertical hand placement	Yes	Yes	Yes
Horizontal hand placement	No	No	No
Winner: Schmalz JumboFlex 50 Generation 2			

Appendix I1: Rapid Entire Body Limb Assessment - Recommended Actions

Score Category	Proposed Solutions Score	Recommended Actions
Neck Score	1	Increase height of workstation
Trunk Score	2	Increase height of workstation, do not bend trunk
Leg Score	1	n/a
Posture Score A	2	
Force/Load Score	0	n/a
Score A	2	
Upper Arm Score	3	Do not load the empty box pallet above shoulder height, keep the trunk straight.
Lower Arm Score	1	Do not bend arm above 100 degrees or below 60 degrees
Wrist Score	1	Keep hand a wrist straight, avoid bending from midline or twisting
Posture Score B	3	

Coupling Score	1	Handle on box, should use. Scored 1 because it's a good handle but not ideal.
Score B	4	
Table C Score	3	
Activity Score	0	
REBA Score	**3**	

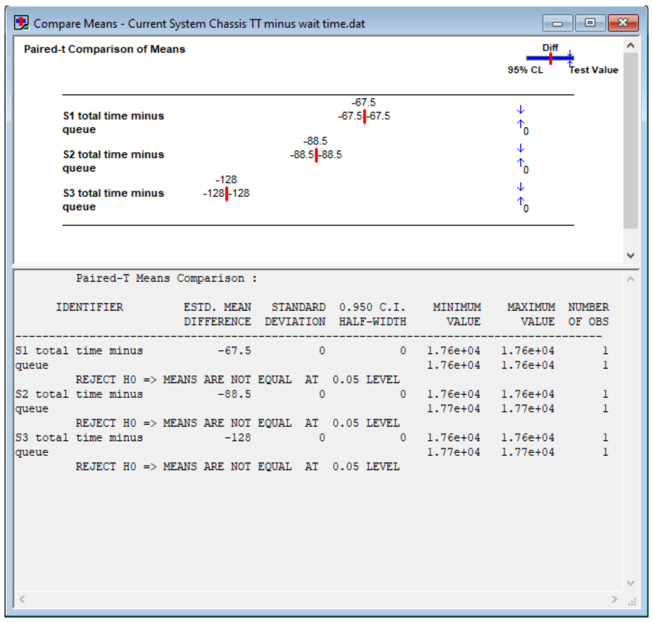
Appendix I2: Rapid Upper Body Limb Assessment - Recommended Actions

Score Category	Proposed Solutions Score	Recommended Actions
Upper Arm Score	3	Keep vacuum lift below shoulder height at all times. Keep your arm close to your body. Try not to reach far from your body.
Lower Arm Score	1	Keep your arm in the 60-100 degree range. Do not cross arm past midline or out to the side of the body.
Wrist Twist Score	1	Keep wrists as straight as possible while cutting open boxes
Wrist Score	1	New lift control keeps wrist straight and eliminates twists and bends
Posture Score A	3	Table value
Muscle Use Score	1	Multiple tasks involving wrist and arm movements throughout the process.
Force/Load Score	2	
Wrist & Arm Score	6	
Neck Score	2	Raise workstation.
Trunk Score	2	Raise the workstation/pallet jack to avoid bending.
Leg Score	1	
Posture B Score	2	
Muscle Use Score	1	
Force/Load Score	2	
Neck, Trunk, Leg Score	5	
RULA Score	**6**	

Appendix J1: Average cycle time per chassis in seconds.

	Current System	Simulation			
		Current System	S1	S2	S3
Average Cycle Time Per Chassis (seconds)	137.925	122.3913	102.273	96.02534	91.26626

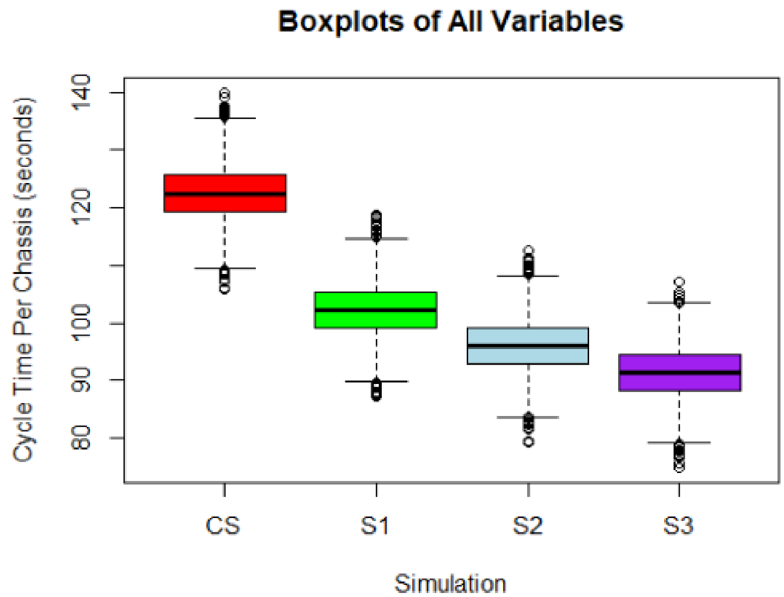
Appendix J2: ARENA Output analyser results



Appendix J3: Tukey Test differences

Comparison	Difference
S3-CS	-31.13
S2-CS	-26.37
S1-CS	-20.12
S3-S1	-11.01
S2-S1	-6.25
S3-S2	-4.76

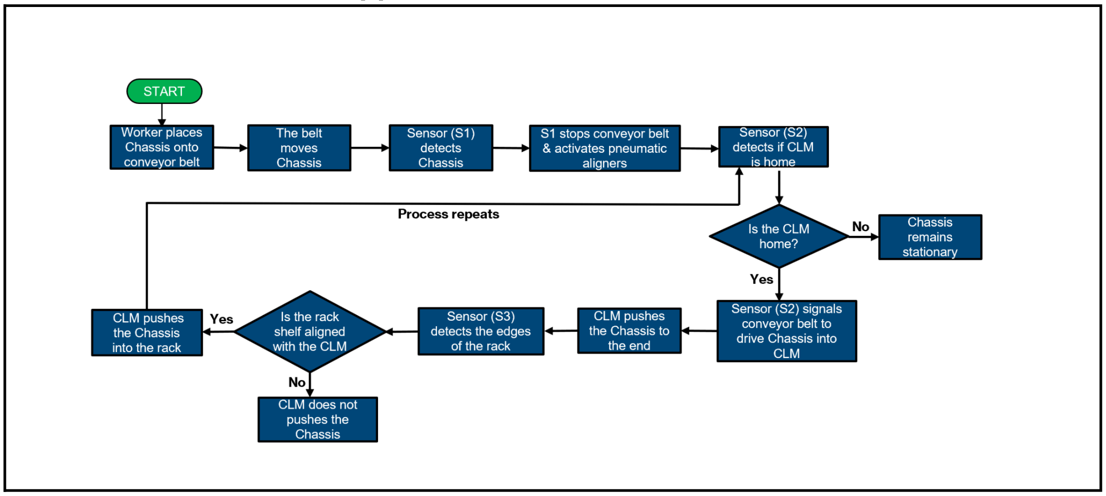
Appendix J4: Box and whisker plot of current system and all solutions



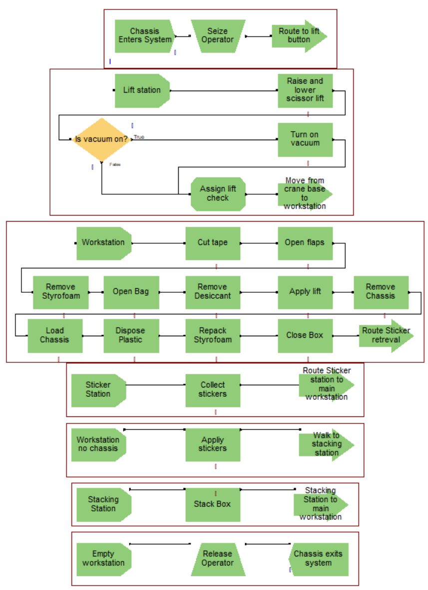
Appendix K: Researched and selected tools.

Researched Tool	Proposed Application(s)	System Benefits
Vacuum Lift Replacement	• Chassis movement.	• Brings lift system up-to-date. • Power button on controller. • Increased surface area between gripper and chassis. • Ergonomic design. • Increased chassis control.
Utility Station	• Use as a centralized location for tools and stickers.	• Route elimination.
Remote Scissor Lift Raiser	• Remotely raise and lower the scissor lift holding rack.	• Route elimination.
Custom Loading Machine	• Loads the chassis into the rack.	• Decreased cost due to damage of chassis. • Increased chassis control. • Decreased cycle time.

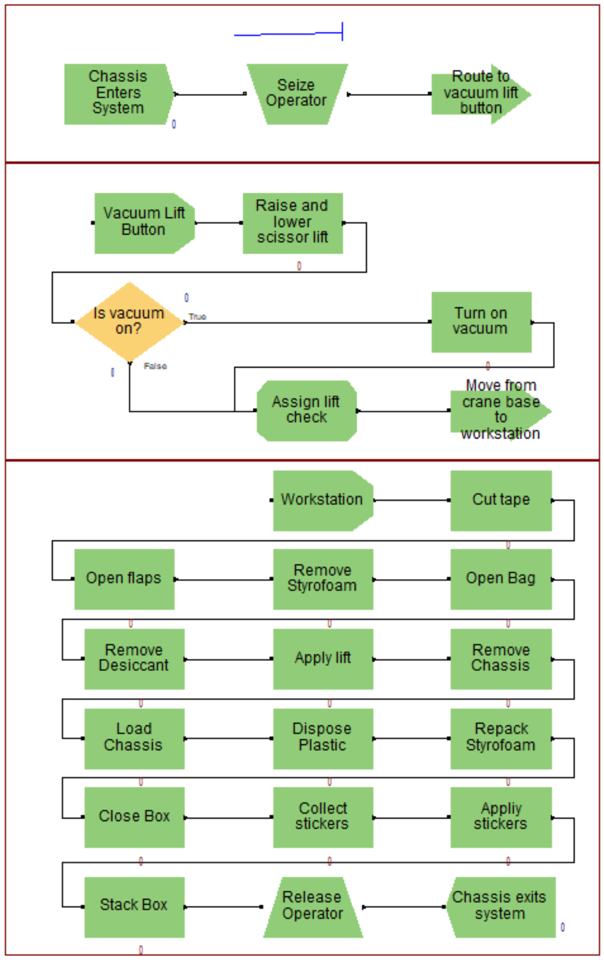
Appendix L: S3 Control Flowchart



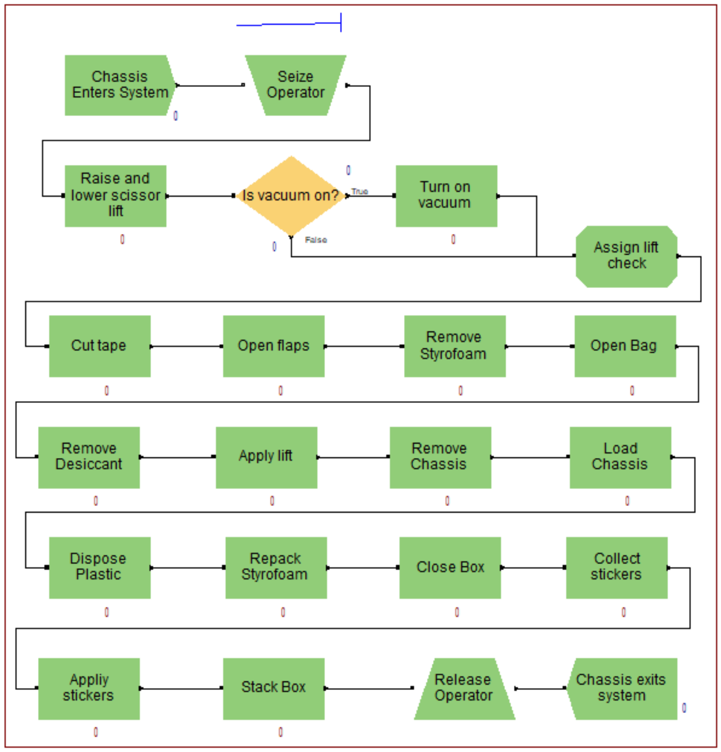
Appendix M1: ARENA Simulation Model of Current Process



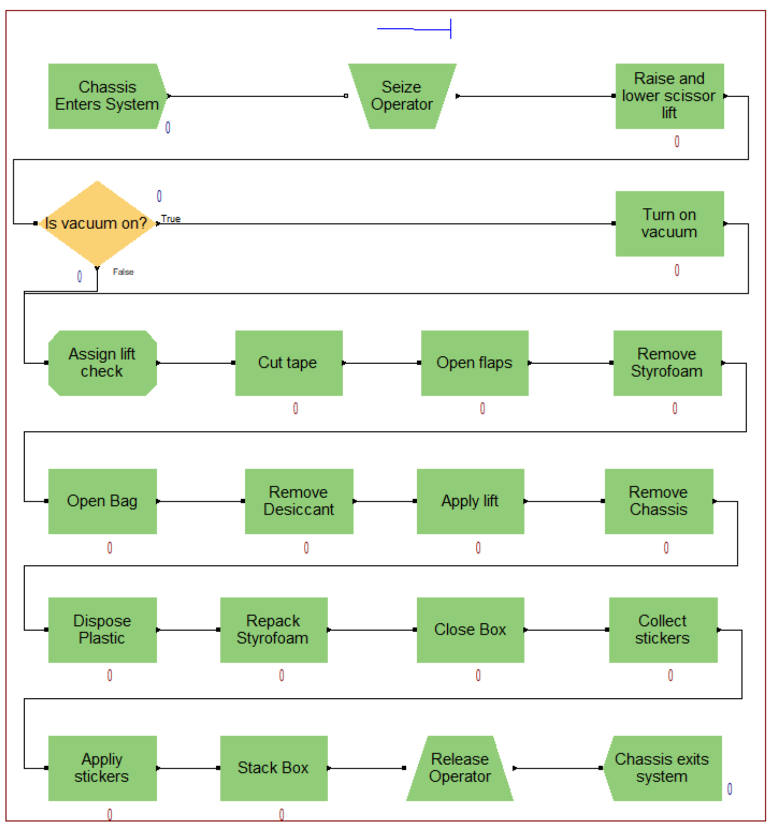
Appendix M2: ARENA Simulation Model of Solution 1



Appendix M3: ARENA Simulation Model of Solution 2



Appendix M4: ARENA Simulation Model of Solution 3



Appendix N1: S1 Solution Bill of Materials

Part No.	Model Name	Description	Vendor	Qty	Unit Cost	Total Cost
1	FG265500 GRAY	Rubbermaid Commercial Products BRUTE Heavy-Duty Round Vented Trash Can Without Lid, 55-Gallon	Amazon	4	$102.95	**$412**
2	FG264000 BLA	Rubbermaid Commercial Products Brute Trash Can Dolly with Wheels, Black, Transports 20, 32, 44 and 55G Brute Containers	Amazon	4	$41.97	**$168**
3	103M-TAL-5M	5 inch Pull and Take Label Dispensers	DWC Packaging Systems	1	$56.05	**$56**
4	AMZME013	Amazon Basics Wire Mesh Pen Cup, Black	Amazon	1	$8.79	**$9**
5	IPS-S1	Electric Linear Actuator Controller 12V 24V eWeLink Smart Wireless WiFi Relay Switch, RS485 DC Motor Controllers (Current Limit, Rebound When Obstacles)	DIHOOL	1	$108.88	**$109**
6	716OSB	4'x8'x7/16" OSB Panel	Lengefeld Lumber Co.	1	$14.01	**$14**
Total Estimated cost						**$768**

Appendix N2: S2 Solution Bill of Materials

Part No.	Model Name	Description	Vendor	Qty	Unit Cost	Total Cost

1	FG265500 GRAY	Rubbermaid Commercial Products BRUTE Heavy-Duty Round Vented Trash Can Without Lid, 55-Gallon	Amazon	4	$102.95	**$412**
2	FG264000 BLA	Rubbermaid Commercial Products Brute Trash Can Dolly with Wheels, Black, Transports 20, 32, 44 and 55G Brute Containers	Amazon	4	$41.97	**$168**
3	103M-TAL-5M	5 inch Pull and Take Label Dispensers	DWC Packaging Systems	1	$56.05	**$56**
4	AMZME013	Amazon Basics Wire Mesh Pen Cup, Black	Amazon	1	$8.79	**$9**
5	IPS-S1	Electric Linear Actuator Controller 12V 24V eWeLink Smart Wireless WiFi Relay Switch, RS485 DC Motor Controllers (Current Limit, Rebound When Obstacles)	DIHOOL	1	$108.88	**$109**
6	JumboFlex 35	Vacuum Lift	Schmalz	1	$40,000	**$40,000**
7	716OSB	4'x8'x7/16" OSB Panel	Lengefeld Lumber Co.	1	$14.01	**$14**
Total Estimated cost						**$40,768**

Appendix N3: S3 Solution Bill of Materials

Part No.	Model Name	Description	Vendor	Qty	Unit Cost	Total Cost
1		Yaskawa motor. Rated T:	Yaskawa	2	$425	**$850**

	SGM-08A 314	2.39Nm, Rated Power: 750 W, rated speed: 3000 rpm				
2	SGD7S-5 R5A00A	Yaskawa Motor drive	Yaskawa	1	$737	**$735**
3	E3AS-F15 00IPD 2M	Omron E3AS-F photoelectric sensors	DigiKey	1	$177.1 9	**$177**
4	E3TCD11 2M	Omron Automation diffuse reflective sensor with sensing distance of 50 mm max	RS online	2	$164.9	**$330**
5	ISD905C-61-3705	Cognex 3D guide/align sensor	Qualitrol international	2	$3600	**$7200**
6	HDCS	Ball Screw Linear Actuators Vendor: Hepcomotion	Hepcomotion	2	$3000	**$6000**
7	Vsttar Machined Wheels	Machined Wheels/Rollers Compatible	Amazon	36	$3.25	**$117**
8	40QE404 0L	40mm x 40mm Smooth Lite T-Slotted Aluminum Extrusion	FAZ Store	9	$23.5	**$212**
9	-	Motorized Conveyor Industrial Transport Conveyor w/ Double Guardrails Anti-static Adjustable Conveyor Table Electric Handling	Vevor	1	$560	**$560**
10	TN32x75s	Pneumatic Air Cylinder 10mm Bore 75mm Stroke	Amazon	2	$16	**$32**
11	BR40010 00M.5	Blackriver Pro Fingerboard Wheels - Blank Street	Blackriver	8	$10.5	**$84**
12	40x65 inches	Aluminum Plate Cast Tool & Jig 0.875"	Buymetal.co m	2	$1800	**$3600**

13	JumboFle x 35	Vacuum Lift	Schmalz	1	$40,000	**$40,000**
14	FG265500 GRAY	Rubbermaid Commercial Products BRUTE Heavy-Duty Round Vented Trash Can Without Lid, 55-Gallon	Amazon	4	$102.95	**$412**
15	FG264000 BLA	Rubbermaid Commercial Products Brute Trash Can Dolly with Wheels, Black, Transports 20, 32, 44 and 55G Brute Containers	Amazon	4	$41.97	**$168**
16	103M-TAL-5M	5 inch Pull and Take Label Dispensers	DWC Packaging Systems	1	$56.05	**$56**
17	716OSB	4'x8'x7/16" OSB Panel	Lengefeld Lumber Co.	1	$14.01	**$14**
18	Others	Electrical wires, drivers, and miscellaneous parts				**$20,000**
Total Estimated cost						**$80,547**

Appendix O1: Relevant ISE Standards.

System Component	Standards	Descriptions and Their Proposed Utilizations in our Project
Consolidated Box Work Table	**ANSI X5.5-2021** [4] Desk and Table Products	**(I)** Covers traditional desks and tables, which may also include drawers or other storage features. In addition, this standard includes Benching, Height Height-Adjustable Tables, Tilt-Top Tables, Keyboard Tables, and Monitor Arms. **(II)** This will be used for the appropriate design or selection of the Consolidated box work table
Process Naming	**ISO/IEC/IEEE 15288:2023** [5] System life cycle processes	**(I)** Provides a framework of consistent process definitions to help with definition, control, and improvement, as well as communicating with stakeholders. **(II)** This will be used to use consistent names for processes in our stakeholder meetings, presentation, and report.

Process Mapping	ISO/IEC/IEEE 15289:2019 [6] Content of life-cycle information items	**(I)** This defines an Information Management process for effective documentation and process mapping. **(II)** This framework will be used in the process mapping and flowchart diagrams.
Gantt Chart	ISO/IEC TR 24748-1:2024 [7] Life cycle management	**(I)** This document provides a definition of the life cycle, and establishes project management standards and risk management provisions. **(II)** Components of this will be included in the gantt chart.

Appendix O2: Relevant AME Standards.

Part	Standards	Description and Proposed Utilization in our Project
Conveyor Belt	ASME B20.1 [8] Safety Standard for Conveyors and Related Equipment	**(I)** Covers safety requirements for the design, construction, installation, and maintenance of conveyor systems. **(II)** Ensures the conveyor belt is designed with proper safety measures, such as emergency stops and guards, to prevent operator injuries.
Sensors	ISO 13849-1 [9] Safety of Machinery: Control Systems	**(I)** Defines performance requirements for safety-related parts of control systems, including sensors. **(II)** Ensures the reliability of your photoelectric sensors in detecting chassis position and stopping the conveyor when necessary.
	ISO 9241-303 [10] Ergonomics of Vision Systems	**(I)** Covers performance requirements for vision-based systems in industrial applications. **(II)** Ensures vision sensors accurately detect the transport cart edges for precise chassis alignment.
Custom Loading Machine (CLM)- Rollers & Motorized Pusher	ANSI B11.19 [11] Machine Guarding Standards	**(I)** Specifies requirements for protective barriers and safeguarding methods around machinery. **(II)** Ensures the CLM is safeguarded to prevent accidental contact with moving parts.
	ASME Y14.5 [12] GD&T (Geometric Dimensioning and Tolerancing)	**(I)** Provides guidelines for dimensioning and tolerancing in mechanical design. **(II)** Ensures proper alignment of freely rolling rollers and the motor-driven pusher for smooth chassis transfer.
	ASTM A36 [13] Standard Specification for Structural Steel	**(I)** Specifies material properties of steel used in machine frames. **(II)** Ensures the structural integrity of the system and its supporting frame.
Vertical Ball Screw Linear Actuator (Motor-Driven CLM Up/Down Motion)	ISO 3408 [14] Ball Screws Standard	**(I)** Specifies dimensions, tolerances, and load ratings for ball screws used in linear motion systems. **(II)** Ensures proper selection of ball screw actuators for smooth vertical movement of the CLM.
	NFPA 70 (NEC) [15] National Electrical Code	**(I)** Regulates electrical wiring and motor-driven systems. **(II)** Ensures safe electrical connections and controls for the motor driving

		the ball screw actuator.
Bolts, Screws, and Threaded Fasteners	**ASME B18.2.1** [16] Square and Hex Bolts and Screws	**(I)** Defines the dimensions, tolerances, and specifications for hex bolts, square bolts, and screws used in mechanical assemblies. **(II)** Ensures the bolts and screws used in our CLM's and conveyor's structural components conform to industry standards, ensuring proper fit and strength.

Signature and Contribution Page

Amalyn Domaille — **5/4/2025**

Judah Anttila — **5/4/2025**

Jacob Huntsman — **5/4/2025**

Rajan Rijal — **5/4/2025**

Jacob Huntsman:

I am going to summarize my contributions to the report by the category of work. I contributed to the Structure, Executive Summary, Literature Review, Team Member Contribution and Signature, Overall Flow and Logic, Overall Appearance, Spelling and Grammar, Data Presentation, Application of Engineering Principles, Clarity and Writing Style, Professionalism & Ethics, Figure/Table/Equation Labels and Organization, References, Codes and Standards, Cover Page, as well as the midterm report which was the foundation of this paper.

Amalyn Domaille:

The following is a list of sections I completed solo for this paper, with only minor portions taken from the midterm report.

- Problem Analysis
- Solution Process
- Decision Analysis
- Solution Component 1: Worktable/Utility Station
- Solution Component 2: Remote Scissor Lift
- Solution Component 3: Vacuum Lift
- Solution Component 5: Facility Layout
- Solution Component 6: Ergonomics
- Solution Description and Data Collection
- Solution Tiers
- Solution 1
- Solution 2
- Solution 3 (not the CLM portion, that was taken from the Midterm)
- Data Collection
- Solution Verification
- Solution Validation
- Ergonomic Outcomes

The following are collaborative sections I participated in.

- Executive Summary
- Summary, Conclusions and Recommendations

Judah Anttila:

In this report, Judah completed multiple sections. These were Future Actions, Introduction / Background, Problem Definition, Economic Analysis, Ethical & Systems Impacts, and Project Schedule.

Rajan Rijal:

In this report, Rajan worked collaboratively on the Summary, Conclusions and Recommendations, limitations and reservations. The CLM portion of Solution 3 was his work from the Midterm. The new thing, he added, was the Ansys Analysis for the critical parts.