

EMULATION AND DIGITAL TWIN FRAMEWORK FOR THE VALIDATION OF MATERIAL HANDLING EQUIPMENT IN WAREHOUSE ENVIRONMENTS

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ABSTRACT

With modern warehouses becoming more automated, there is a growing opportunity to test and validate material handling concepts throughout the project life cycle. Emulation and digital twin pose a capability for material handling system validation from the ideation stage through post-implementation. An emulation model is a virtual replica of a physical system, and digital twin is a transformation of an emulation model via connection to a virtual or physical controller. They can test factors such as design mechanics and layouts, calculate throughput, test controls logic, and perform product flow analysis. Evaluation of these factors can provide a relatively accurate metric for system performance and lead to a more comprehensive return on investment (ROI) analysis. This paper discusses how incorporation of emulation and digital twin into all stages of the project life cycle of material handling systems can improve system efficiency and prevent live system commissioning risk.

1 INTRODUCTION

Material handling equipment (MHE) is any equipment, machine, or system that assists with the transport of material (Bouh and Riopel 2015). The development and installation of new material handling systems in manufacturing and warehouse operations is often time-consuming and costly. Project schedule delays and suboptimal system performance results when system issues go undetected to the implementation phase. The design of hardware, the corresponding software, and their implementation contribute to these scenarios. These concerns are magnified when new MHE must seamlessly integrate with existing infrastructure. Ultimately, there may be a decrease in the return on investment (ROI), lower morale, and less trust between design and operations teams. Testing and validating hardware designs and software early, through a process called virtual commissioning (VC), can be the solution to addressing these risks before they happen. The work displayed in this paper will be prefaced by a discussion of key terms and relevant research.

The volume of MHE available continuously grows as industries relentlessly push for improvements in warehouse efficiency. MHE can be broken down into many categories including unit conveyers, bulk conveyers, manually operated equipment, robots, and automated vehicle systems such as electric pallet jacks (Bouh and Riopel 2015). The focus of this paper is the use of emulation and digital twin for virtual MHE system validation.

With a rise in computing and graphics power over the years, emulation software has become increasingly more powerful and accessible (Åström et al. 1998). All models are an approximation of real world systems, and a "credibility gap" exists between the model and the real world. Emulation attempts to

minimize this gap when compared to simulation (McGregor 2002). In simulation, the physical interaction between entities is neglected, limiting the kind of information that can be gained. In material handling systems, the physical interactions between different components is critical. It aids in virtually determining whether a physical system will properly and optimally function prior to manufacturing. More advanced 3D emulation software can be used to perform physics analysis as well as throughput analysis. The use of continuous-time emulation software enables modeling of mechanisms, mechanism interactions, and physical interactions between entities.

These advanced software options often have a feature enabling connection to different types of external controllers such as programmable logic controllers (PLC's). Emulation software can be used in combination with virtual controllers to more closely replicate a physical system in a virtual environment. This process introduces the concept of digital twin. Many definitions of the term have circulated the manufacturing industry, but it was first introduced by Michael Grieves in 2003 as a conceptual model for Product Life Cycle Management (Grieves 2015).

The term has evolved tremendously over the past 20 years. In this paper, digital twin will be defined as a virtual representation of a physical asset where components of the physical and virtual system are connected and updated (Ugarte et al. 2022). A digital twin can be used to test and validate a system virtually, prior to physical implementation. It can also be used to test updated designs and software post-implementation. Leveraging a digital twin model with new MHE can reduce risk, save time, and conserve resources during the commissioning stage.

Virtual commissioning is the development and testing of PLC code with the assistance of simulation or emulation (Lechler et al. 2019). The PLC logic is written and connected to a virtual PLC and an emulation model in order to mimic the physical MHE and controls. In addition to saving time and costs, safety is improved; potentially hazardous errors can be detected and mended virtually (Lechler et al. 2019). In this work, digital twin is used for various types of material handling systems in a warehouse environment to virtually commission and validate equipment and software prior to physical installation. The process of incorporating emulation and digital twin into the project life cycle for virtual commissioning will be discussed in detail.

2 RELEVANT RESEARCH

Previous research indicates that the use of digital twin for virtual system commissioning is highly effective. In one instance, emulation and digital twin are used to support the reconditioning of an old machine. The aim was to maximize the use, and therefore the benefit, of digital twin in the early stages of the design process. A model was developed using a 3D emulation continuous-time software and a soft PLC. Conversations with stakeholders enabled thorough testing of the digital twin and execution of a virtual factory acceptance test (VFAT) prior to physical system commissioning. This yielded a 60% shorter commissioning time and 50% less rest points (Ayani et al. 2018).

In another instance (Schamp et al. 2018), a small automation project was commissioned in a controlled setting. Students were divided into two groups for this experiment: a reference group and a test group. The reference group was provided with standard software tools akin to those used in traditional commissioning of an automation project. The test group was provided with a virtual twin of the automation system; it was consistent with virtual controls commissioning with a digital twin. The debugging time of the test group was 73% lower than that of the reference group, illustrating the benefits of the virtual twin.

In one study, 12 interviews were conducted with emulation and product development experts to develop a qualitative and quantitative understanding of the impact of VC in the automation industry. The primary finding is that VC leads to controlled and/or shortened project lead times based on these reasons: increased predictability, faster feedback, and flexibility and responsiveness (Shahim and Møller 2016).

A final study in the automation engineering space compares the standard engineering process to the state of the art role of VC. The author indicates that model building for VC requires deep knowledge and resources; this cost is not associated with the standard approach. However, building models early in the engineering process enables use of simple models immediately and improvement of the models as

automation engineering progresses. Model building effort is therefore distributed throughout the lifecycle and is used as a continuously supporting tool (Oppelt and Urbas 2014).

This paper presents a framework and set of projects using emulation and digital twin to validate and virtually commission material handling systems in industrial warehouses. This approach has been used across many industries, but there is minimal literature on its application in MHE systems specifically. Therefore, the framework introduced in this paper is invaluable for potential advancements in the validation of MHE in warehouse environments.

3 EMULATION AND DIGITAL TWIN IN THE MHE PROJECT LIFE CYCLE

In this section, a project life cycle framework is proposed for the design, development, and installation of material handling systems. What distinguishes this framework from traditional approaches is the incorporation of emulation and digital twin in parallel with other phases. Figure 1 shows a traditional approach on the left and the proposed framework on the right. Additional effort and resources are required for digital twin development, seen as additional steps in the flowchart. They occur in parallel with manufacturing, however, yielding significant time savings downstream. System commissioning is shorter and deployment is sooner with digital twin.

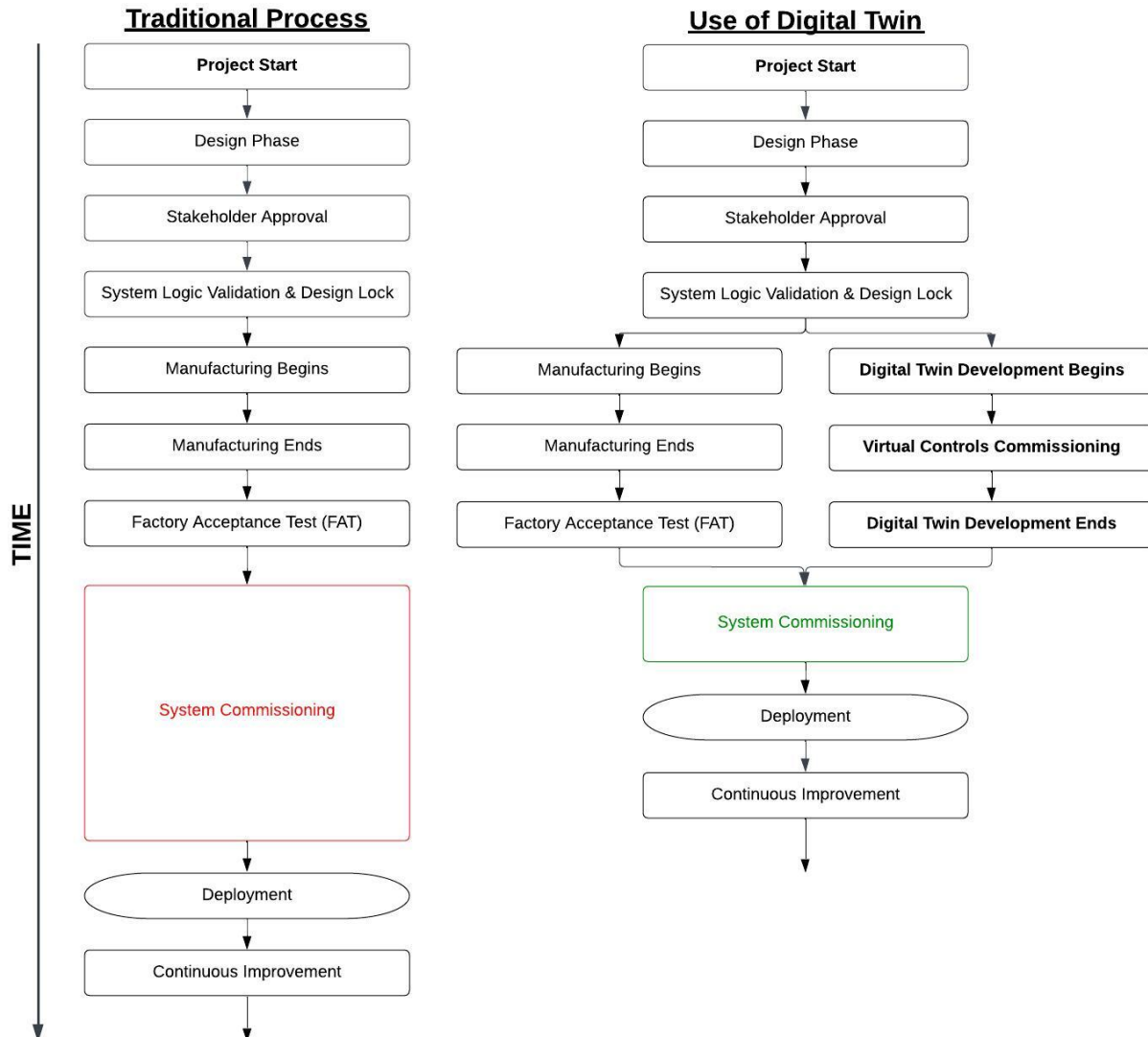


Figure 1: Project life cycle with and without digital twin.

The first stage of the life cycle (i.e. the design phase) begins once there is a clearly defined problem statement and set of project goals. The concept is refined until it is ready to enter the stakeholder approval phase. This stage includes communication with safety, ergonomics, and other teams to validate the design and ultimately obtain support. Once this phase is complete, the system logic validation phase commences and then the design is locked. The proposed framework, at this point, diverges into two separate streams that can operate in parallel if a digital twin is employed. Manufacturing begins as the development of the digital twin begins. Generally, as system complexity increases, digital twin and manufacturing lead time increases. While the virtual model is being built and rigorously tested, manufacturing ends and a FAT is conducted. Finally, the physical system is commissioned and then deployed.

3.1 Design Phase

The concept design phase begins once the problem statement and project goals are defined. It is good practice to obtain a 2D layout of the warehouse space and import it into the emulation software. This sets dimensional and spacing bounds on the MHE concept; the footprint of the new design cannot exceed that of the warehouse layout.

Emulation models can help designers understand the type and dimensions of MHE necessary to convey the material to be handled (MTBH) appropriately. A variety of MTBH can be created by manipulating the dimensions, weight, center of mass, material, and angle of the objects. Many iterations of emulation are performed to narrow down on optimal conveyor and chute speeds, angles and friction coefficients. For more complicated systems, i.e. systems with complex material flow patterns and station availability contingencies, logic can be implemented. Component level logic is written internal to the software to achieve the specific patterns required.

If a concept has any joints, linkages, or similar mechanisms, a kinematic and/ or dynamic analysis can be performed to determine its feasibility. This will give a deeper understanding of the forces that the mechanism will experience. If the rough concept consists of robotic work cells or similar hardware, a general model from the software's library (if available) can be imported into the working file. Various properties can be modified to more closely mimic the desired state. If the concept has a custom work station, it can be prepared using a 3D design software and then imported into the emulation software. Appropriate physics is added, and it is tested iteratively as with the other MHE.

3.2 Stakeholder Approval

Once the design team is satisfied with the new concept, the next step is to obtain stakeholder approval. Relevant parties include but are not limited to safety, ergonomics, maintenance, and operations teams. Each relevant team must review the design and approve it before the project can move forward.

A 3D model helps ensure that the design meets all safety and maintenance requirements. Some example considerations include the guarding of pinch points and accessibility of machinery for maintenance purposes. The ergonomics team can run analysis to help detect and determine potential musculoskeletal disorders (MSD) and risks if a human operator must interact with the MHE. Operations teams can be consulted on how the newly integrated concept may interfere with day-to-day operations. Regardless of the information gained at this stage, it is nearly impossible to capture all the risks that a new installation may carry. In addition, the user experience is still unknown, as a design can follow all safety and operational requirements yet still not be user-friendly. At this stage in the project life cycle, connection to a virtual reality (VR) environment becomes useful.

Advanced emulation software can connect to a VR headset allowing relevant stakeholders to experience the design in a virtual environment. The perspective enables capture of potential risks earlier in the project lifecycle. There is also an opportunity to interact with the objects and equipment in VR. With this capability, the design team can test the reach required by the operator to interact with the material. A warehouse environment in VR can be seen on the left side of Figure 2. A magnified view of what a user in a VR environment sees is on the right side.

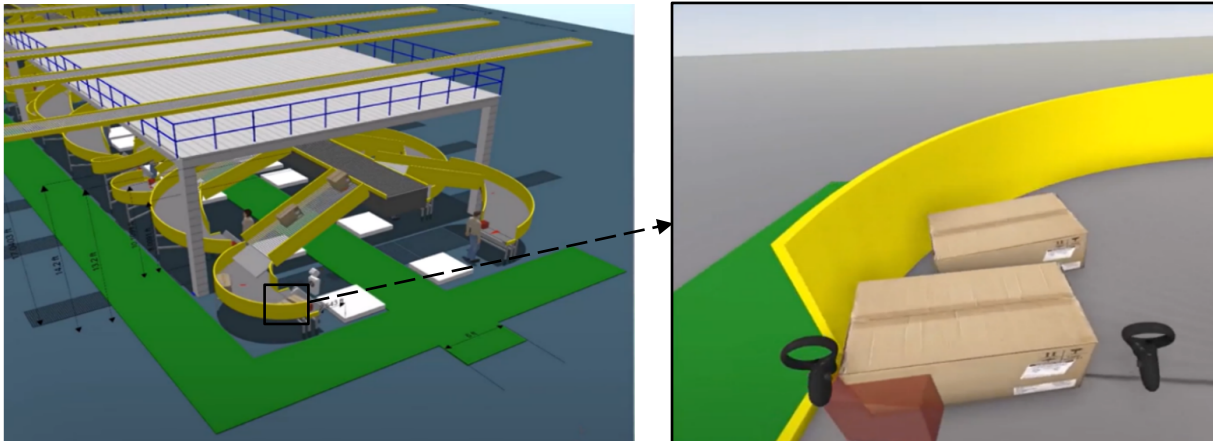


Figure 2: Virtual reality in emulation.

3.3 System Logic Validation and Design Lock

System logic validation comes after stakeholder approval and component-level emulation testing. This step requires preparation of a description of operation (DOO) document. A DOO has details about how each component of the system will operate and how the system will react to different levels of product flow. The logic can be emulated at the system level for system logic validation when a general consensus is reached across design and controls teams regarding system operation. At this stage, the controls team does not need to write the PLC logic; the design team can use tools internal to the emulation software (scripting) to write and validate the logic quickly and locally.

The intent of this testing phase is to validate the overall throughput of the system, test various system modes to avoid jams, and run various what-if scenarios to determine what might break the system. From here, appropriate steps are taken to modify the design and controls logic virtually. This stage has the potential to save time and resources later in the project life cycle by fixing system flaws in advance, similar to virtual controls commissioning. Once these iterations are complete, the design can be locked and released for manufacturing. Generally, there is a lead time of 12 – 24 weeks before the system can be assembled for physical testing.

3.4 Virtual Controls Commissioning

During that lead time, the manufacturing phase of the project life cycle begins. Controls engineers simply wait for the physical hardware during this time. Once the hardware is received and assembled, it is tested at the integrator's site, and this is called a factory acceptance test (FAT). There is usually a cost associated with performing a FAT. If the system is of a larger scope, critical subsections are tested in isolation to save time and money. If issues are identified during FAT, necessary changes to the controls and design are made, and the project timeline is pushed out. Most project managers will add buffer time for the FAT stage in anticipation of modifications. Once the system passes the FAT, it is sent to the site to be installed and commissioned.

Due to the serial nature of hardware testing and system commissioning, a lot of time and resources are often wasted. Digital twin presents an opportunity to perform controls testing in parallel to MHE manufacturing. Instead of waiting for the physical hardware to be ready, controls engineers can start developing controls logic as soon as the design is locked and manufacturing begins. Upon completion, the emulation model and controls logic can be connected to form a digital twin. As system complexity increases, manufacturing lead time is also expected to increase. This permits additional time to the development of a more complex digital twin. There are special cases for which digital twin complexity does not scale with manufacturing lead time. One prevailing factor is proprietary logic in sourced components.

As an example of a digital twin for virtual commissioning, assume the hardware in question uses an Allen Bradley PLC. A controls program can be written in [Studio 5000 Logix Designer](#). A virtual PLC can be emulated using [Factory Talk Logix Echo](#). This virtual PLC can be connected to a model made in an emulation software (ex. [Emulate 3D](#)). Once the PLC and emulation software have been connected, tags can be imported into the model and connected to each property of the virtual components of the model. Figure 3 illustrates the relevant components and connections in physical system commissioning and in virtual system commissioning. In virtual commissioning, there is a 3D emulation model in place of the physical system and a virtual PLC instead of a physical PLC.

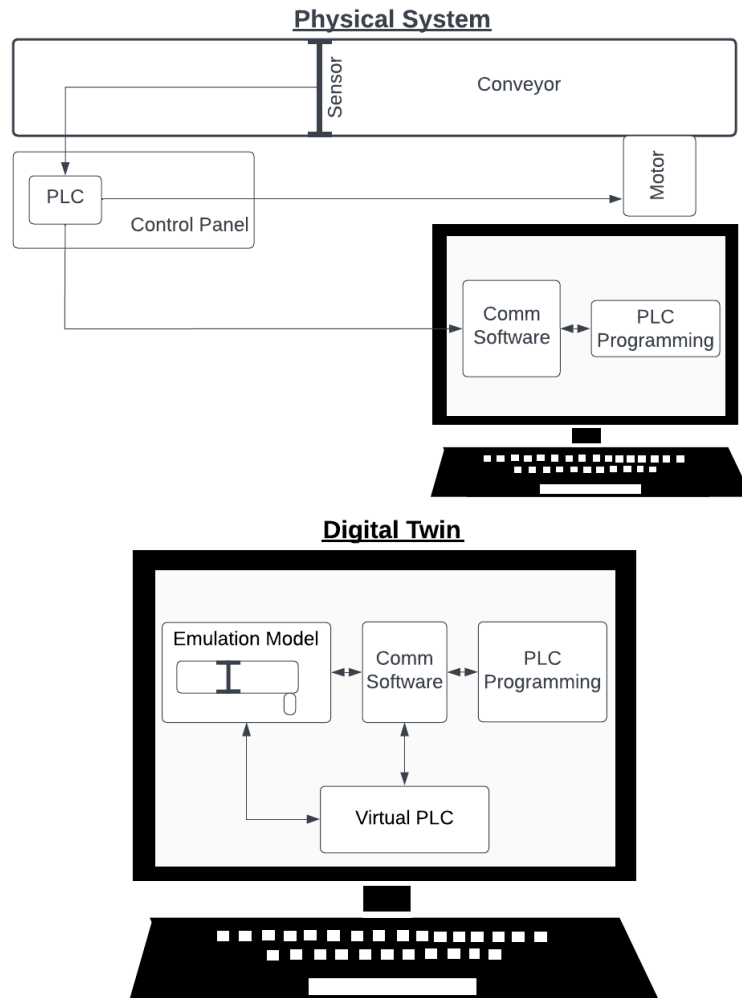


Figure 3: Physical system commissioning vs. virtual system commissioning.

3.5 Post Implementation Validation

The benefits of digital twin continue after the hardware has been installed, tested, and commissioned. Productivity improvements can be identified any time after commissioning. The end goal is to achieve highly productive and efficient operations across all warehouse product streams through continuous improvement. While the physical system can be used to try new logic, throughput may be reduced during testing time. Since the new system is fully integrated and part of warehouse operations at this point, any testing introduces the risk of additional machine downtime. Moreover, if testing leads to a hardware failure, extended downtime may result. Since a digital twin was built earlier in the project life cycle, it can be used again in the post-implementation phase. Similar to prior stages, logic changes can be tested virtually before

implementing them in the physical system, reducing risk and system downtime. This enables a low cost, continuous improvement approach.

In addition to preventing excessive machine downtime, there is an opportunity for increasing system throughput. This is possible through the optimization of product flow and headcount. Digital twin can be used to test and validate optimization logic virtually prior to implementation, similar to the PLC logic. It is possible to represent the current state of the system in the digital twin using historical data.

4 CASE STUDIES

In this section, two case studies will be discussed. The relevant stages of the project life cycle will be referenced along with the savings made possible by emulation, system logic validation, and digital twin.

4.1 Virtual Controls Commissioning of Sorter System

4.1.1 Problem Statement

In this case study, emulation and digital twin were used to streamline the project lifecycle. The system has been broken up into distinct sections and labeled with numbers to assist with descriptions. A new sorter system was conceptualized and built in an emulation software, and it can be seen in Figure 4. It consists of two infeed lines ((0) and (2)). Packages from infeed line (0) are scanned at scanner (1) and inducted into the system. Packages that are pre-scanned are put on infeed line (2). (0) and (2) merge into a single line through merge bed (3). Packages that were not scanned properly are diverted to section (4), and packages that were scanned successfully are diverted to section (5). The combined infeed line (5) sends packages for scanning of destination through scanner (6). It then delivers products to the sorter, which is section (7). The sorter system consists of 26 output chutes. Packages are diverted into specific chutes based on destination. The end of each chute has a two foot drop into a buffer bed, indicated by section (8). The buffer bed has a belted conveyor and two foot high side walls; it is used as a holding space (or buffer) for packages that the operator will work on at a later time.

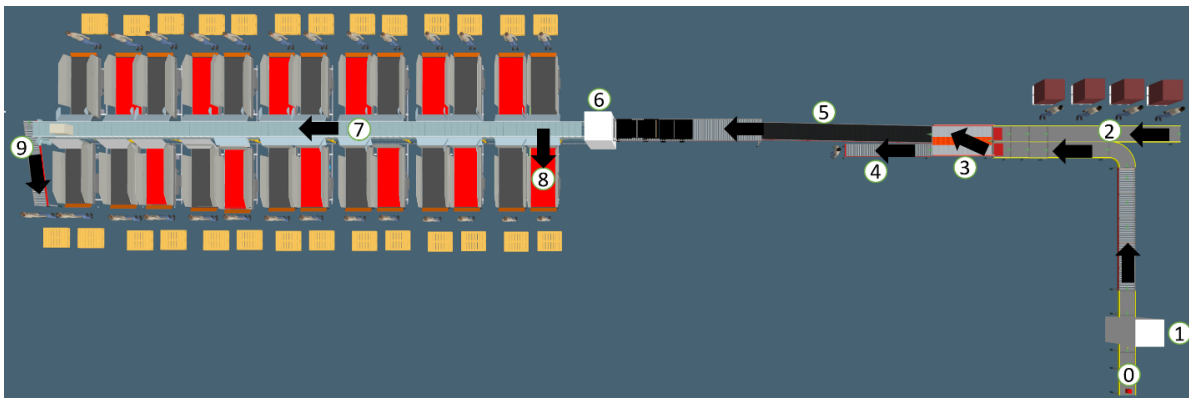


Figure 4: Emulation and digital twin for a sorter system.

There is a sensor array at the start and end of buffer bed (8). Packages begin accumulating at the start of the buffer bed, and once the sensor array gets blocked, a forward signal is sent to the belt motor. The belt moves forward until the sensor array is unblocked. This is known as accumulation mode; it is helpful in buffering a high density of packages in the buffer bed. If the end sensor array gets blocked while the bed is in accumulation mode, it is considered full. Associates can start unloading packages from the buffer bed by changing accumulation mode to forward mode. In forward mode, the buffer bed runs until the end sensor gets blocked. This mode is helpful for bringing products to the associate which are then unloaded into a pallet or cart. Once the unloading of packages is complete, the associate can either put the

buffer bed back into accumulation mode or the buffer bed will automatically go back into accumulation mode based on a set timer. During this transition between modes, the buffer bed conveyor reverses one full belt length. This is done to increase the density of the packages remaining within the bed.

4.1.2 Methodology and Results

The design concept was first modeled in an emulation software and went through various design iterations based on stakeholder feedback. One of the iterations consisted of an elevated sorter that intended to reduce the footprint of the system. However, the design was viewed in VR and ultimately rejected by stakeholders because it was deemed inconvenient and unsafe for associates. The possibility of heads bumping into structural components was high. After a final design was selected, the system level logic was written within the emulation software, the throughput was calculated, and the system was tested. Next, the design was locked and released for manufacturing. In parallel, digital twin development began.

Since the system was a large-scale project, only a few critical subcomponents including the merge bed (3) and the buffer bed (8) were chosen to undergo FAT. Prior to FAT, virtual controls commissioning was performed for these components in isolation. Edge cases were identified that would have either damaged the system or led to suboptimal performance. The PLC program was modified accordingly. Next, some detected issues and fixes during the system logic validation stage will be discussed.

During testing, it was found that switching from forward to accumulation mode when the bed was full of packages could lead to equipment damage. The belt would reverse, as expected, and push packages into the sorter. To avoid this failure mode, a condition was added to prevent the belt from backing up if the chute was full of materials.

The next edge condition is caused by an overload of conflicting system-mode inputs (accumulation or forward). The buffer bed would previously go into a modeless state but show as available to the controller. In actuality, it was not in accumulation or forward mode. This led the buffer bed to stop during operation, yet no faults would be indicated. To prevent this from happening onsite, the possibility of modeless state was eliminated through PLC programming modifications.

The emulation and digital twin displayed one more issue with the merge bed (3) at the infeed. It was not able to meet its expected throughput when the throughput from infeed lines (0) and (2) varied. This caused a decrease in performance for the whole system since the infeed was now the bottleneck. Controls engineers performed a root cause analysis to determine the issue, alleviate the bottleneck, and achieve expected throughput.

All of these changes were made possible through emulation and logic validation. It led to a streamlined, successful FAT. A full system-level virtual controls commissioning study could not be performed due to virtual clock asynchronization between the emulation model and the virtual PLC. Regardless, component-level logic helped to identify gaps early in the project, thereby reducing risk and onsite commissioning time.

4.2 Logic Validation of MHE

4.2.1 Problem Statement

For the next case study, emulation and virtual system logic validation were leveraged to debug new MHE logic before implementation. This study takes place in the continuous improvement stage of the project life cycle because the system already physically exists. The MHE system seen in Figure 5 consists of an infeed bulk conveyor (0) which delivers products to two chutes for processing via (1), (2), (3), and (4). If the two chutes are full, a product is recirculated via Recirc Loop 1 ((5)(1)(2)(3)(4)). Products from the chutes get fed into a sorter (6) manually. The sorter diverts the products into multiple lanes depending on the product's destination. Products that could not be diverted by the sorter go into Recirc Loop 2 ((7)(8)(9)(3)(4)(6)). This new logic was proposed to increase system capacity and reduce gridlock.

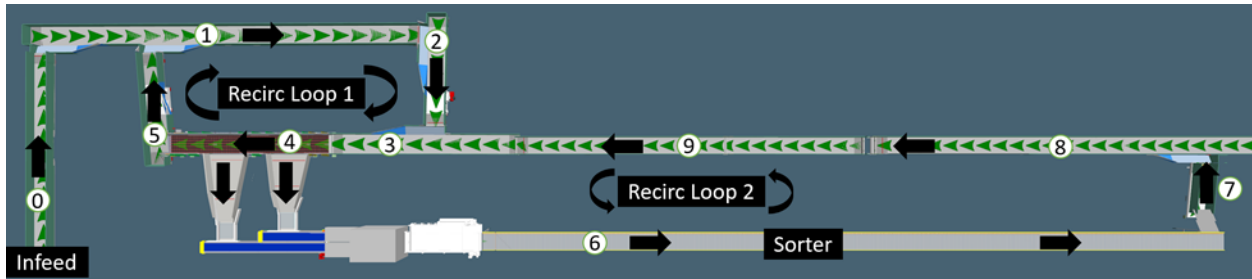


Figure 5: Emulation for MHE logic validation study.

4.2.2 Methodology and Results

A 3D CAD model of the system was imported into the emulation software. Physics properties (including mesh size and friction coefficients) were added to CAD components, and products were generated based on their physical properties and the expected system throughput. Logic was written using the software's internal logic builder. Use of emulation to test the system's logic enabled early detection of potential flaws. Next, certain operations will be described in detail, followed by the risks that were encountered, and the solutions to mend them virtually.

For this system, conveyor section (8) of Recirc Loop 2 inches and collects packages. The run command is prompted when the exit sensor of (7) is triggered by the incoming package. Section (8) will inch forward and collect packages until the exit sensor of (8) is triggered and therefore full. Once (8) is full, it will send all the packages in bulk to the second conveyor (9). After emulation testing, it was found that if sections (8) and (9) are running at the same speed, volume from (8) may not fit in (9). To solve this, section (9) was set to run 5% slower than section (8).

Many different scenarios were emulated for section (9)'s merge with Recirc Loop 1 at (3). This analysis enabled system improvements. Instead of using the exit sensor of section (2) as originally intended, it was suggested that the exit sensor of section (1) be used. Section (9) starts to run when a gap of more than one second is recorded by the exit sensor of section (1). Packages are then transferred from section (9) to section (3). A one second delay from the exit sensor of section (1) ensures that packages coming from section (9) merge smoothly into section (3). It makes sure that the gap in section (3) coincides with the packages coming from section (9) at the merge point. The merge ends when (1)'s exit sensor is blocked again with a delay of 2 seconds. If the exit sensor for section (2) was used, it would result in large gaps in Recirc Loop 1, thereby reducing volumetric efficiency. Using exit sensor of (1) with appropriate times delays allows for higher volumetric efficiency.

When packages accumulate in the two chutes coming out of section (4), they become interlocked and jammed in the chutes. Jam frequency is recorded in the emulation software. Jams are cleared via a jam clearing pole; this was incorporated to emulate the real world more closely. Whenever an associate runs out of packages at the end of the chute, this device is triggered to clear the chute. This change provided a relatively accurate idea of throughput reduction on the chutes due to the jamming of packages.

Lastly, chutes consist of two sensors. One is positioned at the 50% full mark while the other is positioned at the 100% full mark. A chute will start receiving packages when the chute is less than 50% full and will continue to do so until it is 100% full. Emulation analysis indicates that the chutes were getting overfilled. This was due to the proximity of the 100% full sensor to the chute / conveyor interface as well as the momentum of packages from the high conveyor speed. It led to momentary package accumulation on section (4). This was concerning because it could lead to a jam in section (4), thereby stopping Recirc Loop 1. In a worst case scenario, this accumulation could cause mechanical damage to the divert mechanism on section (4) and ultimately, extended downtime. Various emulation iterations were ran to balance the conveyor speed and the placement of the sensor in the chute. This minimized instances of overflowing packages while maximizing throughput.

In this case study, emulation and system logic validation enabled a detailed study and test of conveyor speeds, use and location of sensors, and product jams. The aforementioned issues would have been faced during the system commissioning stage if this analysis was not conducted. To provide a real-life example of timeline impact, many months of delays were encountered during the traditional installation of a similar sorter system in prior years. Since the delays were primarily caused by controls issues, a significant time saving could have been achieved with utilization of the proposed framework.

5 CHALLENGES OF DIGITAL TWIN

Digital twin can be an incredibly useful tool for validating MHE designs and controls logic virtually. However, there are some challenges associated with digital twin that will be described in this section.

In a virtual environment, everything is consistent. All conveyors are perfectly level and have the precise heights and angles inputted. Conveyor surfaces are homogenous, and conveyor connections are exact. However, when the hardware is physically integrated, installation and manufacturing variances can add up, leading to unpredicted system issues. One example is catch points along a conveyor's surface. A package might get caught between the joints of two entities if the transition is not seamless. This type of risk is difficult to capture with a digital twin. Another example involves the collection of dust and foreign debris on surfaces; it can accumulate overtime and lead to altered physics, which affects product flow.

In addition to real world inconsistencies, digital twin can come with MHE logic challenges. If a material handling system is developed in house then all of the logic is accessible and can be tested virtually. However, if the hardware uses purchased components, their source code is needed for complete virtual testing. Obtaining source code files is challenging and sometimes impossible since it is at the owner's discretion. Certain emulation software has the capability to encrypt the logic of the device, and then it can be imported and used within the model. However, not all MHE vendors have the time, resources, or proper motivation to develop this kind of emulator for emulation software.

Another complexity warranting further research is the use of digital twin for high speed applications. In high speed sorters, for example, communication between the emulation software and the virtual PLC can be unreliable. This is due to virtual clock asynchronization between the various components. It can lead to an inaccurate depiction of system performance.

Lastly, in order to reduce system commissioning time with digital twin, it is important to get controls code from system integrators upon design lock. Integrators typically aim to have the first draft of controls code ready by the installation time. However, to perform digital twin, code must be ready for testing as soon as possible. This requires system integrators to modify their standard operating procedures for project execution, and some well-established integrators might not be comfortable modifying those procedures. In conclusion, aligning with stakeholders on the expectations and milestones of a project is critical.

6 CONCLUSION AND NEXT STEPS

This paper demonstrates how emulation, system logic validation, and digital twin are used during the MHE project life cycle to reduce risk, save time, and preserve resources. New concepts are modeled in 3D design and emulation software, physics is added, and system-level logic is written. Then, what-if scenarios are tested to refine the design in less time with less resources. Digital twin also provides the opportunity to test controls logic in parallel to system manufacturing, thereby reducing onsite commissioning time. Logic changes are made virtually before modifying hardware in production lines. This prevents excessive MHE downtime.

Improvements via machine learning and optimization can be explored. Machine Learning (ML) is a promising area that is being rapidly adopted in day-to-day MHE operations. Sensors such as photo eyes can provide the discrete position of MTBH in real time and detect jams after a pre-programmable delay. However, ML assisted cameras can capture the state of the system in more detail and detect jams before they occur. A video recording of a digital twin can be streamed to an ML model for training. When a jam is detected in advance, appropriate recovery logic can be triggered, preventing a jam altogether. Recovery

logic can be tested in the virtual model before implementing the changes in the physical system. In addition, different variations of jams can be presented to the digital twin to test the robustness of the ML model.

Optimization is another technique that can be incorporated into the project life cycle. Data points can be collected from the emulation model and transferred to an excel sheet. The software hosting the optimization logic can read the data from this excel sheet, run the optimization model, and write results back into the same spreadsheet. The emulation software can then interpret the results from the sheet and change model parameters accordingly. A comparison between the base case and optimized case will provide a deeper understanding of the projected throughput improvements.

This paper proposed a framework for incorporating emulation and digital twin into the MHE project life cycle, shared case studies employing this framework, and discussed future innovations in the field. Digital twin is a new and rapidly growing topic and can bring limitless benefits to the warehouse environment when combined with machine learning and optimization.

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