Towards Digital Twin in intra-logistics. A press shop case

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Abstract: Nowadays, dynamic, complex, and uncertain environments may hinder the achievement of optimized production logistics. Digitalization helps improving operations planning and monitoring by enabling more effective decision-making through Digital Twins (DTs). Despite recent DT applications to intra-logistics, it lags behind manufacturing in digitalization and automation due to cost, time, and skill constraints, thus making research and practical applications in the field still limited. This paper presents a case study for the development of a Discrete Event Simulation model ready to evolve into a DT for the press shop end-of-line logistics in an automotive company. The model is applied to analyse the effects on selected Key Performance Indicators (KPIs) of strategies to move finished components to the warehouse. The KPIs concern the time press lines spend in a number of different states, such as set-up, working, or blocked because of unavailability of trains to move finished components from buffer areas, and the number of unit loads in the buffer areas at the end of each press line. As a next step, the simulation model will be further developed to transform it into a fully functional DT. Then, it will assist in studying the introduction of Automated Guided Vehicles to replace traditional tugger trains.

Keywords: Intra-logistics, Press shop, Discrete Event Simulation, Digital Twin, Automotive.

1. Introduction

Intra-logistics refers to the internal logistics processes within a facility or organization, encompassing the movement and handling of materials, products, and information within a specific location, such as a warehouse, distribution centre, or manufacturing plant. The goal of intra-logistics is to optimize the efficiency, accuracy, and speed of these internal processes (Zhur et al., 2022). The automotive industry faces multiple challenges having an impact on the intra-logistics department. For example, external circumstances, such as the existing internationalization, the increasing pressure to innovate, and the individual demands of customers, are responsible for a high variety in vehicles. These aspects may determine an increase in the complexity of vehicle manufacturing and lead to continuous appearance of new challenges for the intra-logistics organization. Thus, in this industry intra-logistics is essential and it plays a crucial role in ensuring the smooth and efficient flow of materials and components within manufacturing and assembly plants (Rohacz and Strassburger, 2021). In such a context, innovative technologies such as Digital Twin (DT), can positively impact the efficiency and the effectiveness of intra-logistics processes. DT can be defined here as a virtual representation or model of a logistics system. This concept involves creating a real-time digital replica of physical assets, processes, and systems, allowing for enhanced monitoring, analysis, and optimization. However, in the intra-logistics processes of the automotive sector, DT has not been largely exploited yet, due to lack of competences, as well as relevant development time and cost (Sommer et al., 2020). In fact, DT in the automotive sector is mostly adopted in manufacturing processes, such as welding or milling (Magyar et al., 2024) Thus, this paper is aimed at providing a contribution for bridging this research gap on studying potential applications of DT in the internal logistics for automotive sector. As a consequence, this paper presents a case study of an automotive industry that is willing to undertake a digitalization process involving the press shop by means of a DT model. The structure of the paper is the following one. First, an overview of the adoption of the DT in manufacturing and automotive sectors and in logistics processes is presented. The proposed model is then described together with its effects on selected Key Performance Indicators (KPIs). Finally, discussions and conclusions are traced.

2. Literature background

2.1 Digital twin in manufacturing and automotive

The integration of DT in mechanical design and advanced manufacturing technology is not just an enhancement; it is a necessity for industries aiming to align with the more recent technology trends. In fact, by bridging the gap between computational and physical processes, DT enables a level of precision, efficiency, and innovation previously unattainable (Nikolakopoulos and Markopoulos, 2024). In particular, it is expected to significantly contribute to the economic growth of a country. For instance, the DT market may reach the value of 35 billion $ in the US by 2025 and its introduction is supporting the diffusion of 4.0 technology in Germany (Lee et al., 2015). For these reasons a lot of literature investigated potential and real applications of DT in manufacturing contexts. The digital representation of manufacturing systems proved to be very useful for reflecting the current status of the system, and to perform real-time optimizations and decision-making processes (Negri et al., 2017). In addition, DT enhances the final performances of products and services in the physical space by integrating cyber and physical space. Thus, DT can be applied at different levels in manufacturing. For prototyping, it allows to create virtual prototypes of products and in turn it is possible to perform testing and simulations before the physical production (Zhang et al, 2024). In the production processes, DT supports the simulation of the operations, improving the production workflows and the use of resources. In addition, via the monitoring of the equipment machineries, it is possible to design maintenance programs more effectively. DTs have been explored for the monitoring of the assembly process for ensuring that the quality expectations are met and for controlling the human-robot collaboration (Zhang et al., 2024).

A lot of applications of DT can be also found in the automotive arena. This industry has increasingly embraced DT for applications such as virtual sensing, homologation, and process simulation (Venturini et al., 2024), for estimating the fuel consumption (de Menezes et al., 2023), and for the electric vehicle motor prognostics (Venkatesan et al., 2019). Damtew (2024) demonstrates that the adoption and implementation of effective and efficient DT strategies have highly accelerated the performance of automotive supply chain process.

2.2 Digital twin in intra-logistics

In recent years, there has been a growing attention on developing DTs to support intra-logistics processes. For instance, Luxenburger et al. (2024) present concepts for human-centred, safe online process planning for intra-logistics and manufacturing processes using an interactive DT. Ulrich et al. (2023) propose a system environment for virtual collision avoidance that uses a DT to estimate collision events with other obstacles, which is continuously updated through a local 5G network to collect device information. Leung et al. (2022) propose a DT-based inbound synchronization framework (order synchronization, process synchronization, and information synchronization) to streamline the operations of a physical-internet-hub in a hyperconnected city logistics system. Coelho et al. (2021) also explore DT applications, developing the architecture of a DT for in-house logistics relying on a simulation-based decision support tool that analyses the activities that can occur in both a distribution facility and a production facility towards logistics 4.0. Additionally, Ferrari et al. (2022) propose an architecture and the implementation steps to develop a DT of an automated warehouse. In the same context of automated storage and retrieval systems (AS/RSs), Ferrari et al. (2023) describe an approach for the development and validation of a Discrete Event Simulation (DES) model with a perspective towards the implementation of a DT. Braglia et al. (2019) propose a DES DT of a large warehouse able to use data collected from the physical system via radio frequency identification sensors, with a particular focus on network communication protocols. Leng et al. (2021) develop a DT solution utilizing a combined optimization model verified through a semi-physical simulation engine, demonstrated through a case study involving a traditional stacker crane AS/RS. Golova et al. (2021) propose a simulation-based approach to help analyse the feasibility of automation of intra-logistics processes and the implementation of Autonomous Mobile Robots (AMRs) of a chemical manufacturer which produces detergents and hand sanitizers. Guerreiro et al. (2019) work towards the creation of a DT for intra-logistics planning to mimic the real-world logistics processes of an automotive car manufacturing scenario. Lichtenstern and Kerber (2022) develop a digital twin model of a system of Automated Guided Vehicles (AGVs) based on real-time data to replicate the driving behaviour of individual vehicles, transport order management, vehicle selection, and travel process control. Zhur et al. (2022) describe the architecture of a framework for intra-logistics DTs, including the description of the relationships between the components.

Despite the increasing recognition of DT as a transformative technology in various industries, its application in intra-logistics, particularly in the context of manufacturing companies in the automotive sector, remains relatively under-discussed (Lin and Yao, 2022). Furthermore, many companies face challenges in developing DT of their intra-logistics operations due to a lack of expertise in this area. This highlights the importance of investigating how DT could support and improve intra-logistics within manufacturing firms. The present paper addresses such a research gap by presenting a case study for the development of a simulation model ready to evolve into a DT of the press shop intra-logistics in an automotive company. By outlining the necessary steps and phases involved in this process, the paper provides a practical guide for companies wishing to embark on the journey towards digital twinning of their intra-logistics operations. In particular, the proposed step-by-step approach facilitates the gradual acquisition of the essential skills required to build, use, and maintain a DT.

3. Methodology

3.1 The Press Shop and model aims

The focus Press Shop, composed by 13 press lines, produces metal body components on a 2-shift per day, 5-day per week basis. Each press is able to work from 200 up to 800 parts per hour. The layout is divided into four homogeneous areas according to the size of the presses: High Tonnage Presses (HTP), Medium Tonnage Presses (MTP/1 and MTP/2), and Low Tonnage Presses (LTP). The LTP area (including 2 press lines) is out of the scope of the present analysis. About 200 Stock Keeping Units (SKUs) are currently produced, 90% of which in the HTP and MTP areas. The moulded components handling system requires an average of 250 daily trips to the warehouse, 98% of which from HTP and MTP areas. Table A.1 in Appendix A shows the assignment of the press lines to HTP, MTP/1, and MTP/2 areas. Moulded components are moved within unit loads transported by traditional, non-automated, tugger trains. Each train tractor pulls up to three trolleys carrying unit loads. The total weight of each trolley depends on the size and weight of the unit loads being carried. However, it varies between 1,700 and 2,800 kg on average, with peaks of 4,000 kg.

The final aim of the Case Company is adopting the DT paradigm to support both short and medium-long term decision-making in its intra-logistics. The simulation model is built in order to provide a digital tool able to manage the daily logistics flows (e.g., calculating the number of workers necessary to handle finished components, assigning trips to drivers, etc.). Also, the model should support production scheduling at the Press Shop by taking into account the required production volumes, the conditions of press lines and material handling equipment, as well as the availability of materials and workers.

3.2 Development of the DT-oriented simulation model

Given the Case Company's goal to start the journey towards a DT of press shop intra-logistics, DES is adopted because it is regarded as a key component of the current DT notion (Agalianos et al., 2020). To this end, Tecnomatix Plant Simulation by Siemens is used thanks to its ability to properly model, simulate, and optimize production systems and logistics flows. The simulation model development is based on the approach by Law (2024) and is described in the following sub-sections.

3.2.1 Analysis of Press Shop logistics flows

The logistics flows affecting the finished moulded components develop along a few main routes that are depicted in Figure 1. In particular, the red route is intended to serve the HTP area, while the green one serves the two MTP areas.

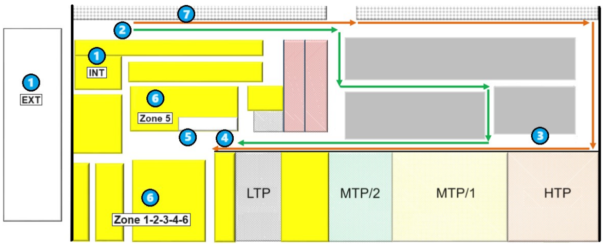

Figure 1: Press Shop logistics flows

To be more precise, tugger trains carry out the following tasks:

1. Loading of empty unit loads on trolleys (1) and arrival at the entry/exit gate (2). Empty unit loads can be stored in either an internal or an external area.
2. From the entry/exit gate (2), travelling along the designated route and arriving at the train staging area (3) adjacent to the press line where full unit loads are to be loaded.
3. Uncoupling trolleys with empty unit loads from the train, and coupling trolleys with full unit loads. Loading and unloading of unit loads onto/from trolleys is performed by forklifts operating in the buffer area at the end of each press line.
4. Departure from the train staging area (3) and arrival at the area where defective components are re-worked (4) or at the receiving area of the finished component warehouse, in case of good-quality components (5).
5. Receiving full unit loads at the finished component warehouse.
6. Arrival at the warehouse zone (6) specific to the unit load type and unloading the full unit loads.

If train tractors enter the power reserve, after full unit loads unloading in the storage area, they enter the charging station (7) where batteries are swapped. Table A.2 in Appendix A shows the distances to be traveled by tugger trains differentiated for individual areas, both internal and external ones. The finished component warehouse is divided into 6 zones (Figure 1): the simulation model considers the distances to reach the entry point of each zone (Table A.3, Appendix A).

3.2.2 Data collection and generation of model input files

The input data for the simulation model can be broadly classified into three types: data associated with the handled finished components, travel distances and times, and data related to production planning and monitoring. Each SKU produced by the press lines has its own characteristics in terms of manufacturing cycle time, size, volume, and weight, which significantly impact the time for logistics flow management. It is therefore necessary to collect, and subsequently implement in the model, all those data that are relevant for calculating production and transportation times. They include information about press line configuration, set-up times, machine cycle times, unit load capacity, location of empty unit loads, operation carried out when receiving finished components at the warehouse, location of warehouse zones, percentage of components to be re-worked, and re-working time. Their numerical values are taken from a specific company database on the characteristics of individual SKUs and cannot be disclosed for confidentiality reasons. Travel distances are directly measured in the physical press shop layout (see also Section 3.2.1). In order to compute reliable values of transportation times, an analysis is performed on travel speeds of material handling equipment and the time necessary to carry out each task. For safety reasons, train tractors have to keep a travel speed equal to 6 km/h in internal areas and 12 km/h in external areas. About the other relevant times, they are estimated by direct observation of the different tasks performed by tugger trains. The average value of the time for each task is shown in Table A.4 in Appendix A. Finally, data on the daily production planning and monitoring are taken from three Excel files, for the HTP, MTP/1, and MTP/2 area respectively, developed by production planners. Examples of such data include the assignment to press lines of SKUs, their production quantities and scheduling, the current status of individual press lines, possible failures to production machines and material handling equipment, and actual availability of workforce.

The input data are all acquired from company databases and organized in Excel files automatically updated as soon as the information in the databases changes. The Excel files are then read by the Plant Simulation file of the model. Therefore, the input data of the simulation model is updated as soon as it changes in the company databases. This makes the current version of the simulation model something more than a digital stand-alone copy of the real intra-logistics process because it enables a direct and continuous update of input information. Such a characteristic paves the way for a complete real time automated flow of data from the physical process to the digital one, which will be a future evolution of the developed model, before also making changes in the digital process directly affecting the physical one, thus completing the DT implementation.

3.2.3 Model development

The DT-oriented simulation model reproduces the current daily logistics flows of moulded components from the press lines to the warehouse. The production process is also modelled, insofar as it influences such an intra-logistics process. The model is composed of a number of sub-models based on the Press Shop layout in Figure 1. Appendix B shows an overview of the simulation model, while Appendix C provides a focus on some sub-models. Plant Simulation is based on object-oriented programming and incorporates a language named SimTalk. It offers a large number of libraries of predefined objects that allow complex systems to be modelled by using their built-in functionalities or, in the case of very specific applications, by customizing them through the development of SimTalk scripts. The remainder of this section will explain the logic on which the construction of the simulation model is based, providing information on the main Plant Simulation objects applied and customized for the purpose. The libraries named *Mobile Units* and *Material Flow Objects* are mainly used. The main physical entities in the logistics flow at issue are modelled by using the Plant Simulation *Mobile Units*, which are objects specifically designed to represent material flows. They are namely: *Part,* representing unit loads carrying moulded components; *Container*, representing train trolleys; and *Transporter,* representing train tractors. Another key element in the simulation model is the correct representation of material flow strategies. This is ensured by the application of the *Flow Control* object provided by Plant Simulation, which enables the modelling of approaches for either partitioning or bringing together material flows in a facility.

In order to start the daily production activities, the press lines need to be provided with empty unit loads and trolleys on which to put the unit loads carrying moulded components. These unit loads and trolleys are usually moved to lines at the beginning of the working day, unless it has already been done the evening before. The press lines (Figure C.1, Appendix C) produce components with a certain rate, which depends on the line and the SKU type. Moulded components are then placed inside unit loads. Press lines and their single workstations are modelled via the *Source* and *Station* objects. Also, the elementary production unit in the model is not the individual moulded component, but the unit load (*Part* object) with the associated processing time. Once unit loads with moulded components are available, they need a specific time before they can actually enter into the logistics flow. In fact, full unit loads are placed in a buffer area at the end of the line (modelled via the *Buffer* object). Then, a forklift picks up unit loads and places them on the trolleys (*Container* object) of the tugger train that is located in the parking area close to the line (Figure C.2, Appendix C). It should be noted that, according to the current organization, the unit loads of components to be sent to the re-working area are first allocated in the buffer and then placed on a dedicated train. Finally, the train will be picked up from the parking area at the end of the line by a tractor (*Transporter* object).

Train tractors depart from the areas where empty unit loads are stored (Figure C.3, Appendix C) shortly before trolleys with full unit loads are ready, in order to avoid them waiting a long time before being picked up. The aim is making tractors arrive close to production lines just before the completion of trolleys. Such an approach is due to the long travel time from the empty unit loads storage areas to the lines. This is essential to avoid production stops because of saturation of the end-of-line buffers, and helps minimizing production costs. The early departure of tractors is not required when unit loads with components to be re-worked are handled. In fact, the production rate of components that need re-working is low. In this case, tractor departure takes place when the necessary number of unit loads is reached to fill a tugger train. Another situation in which early tractor departure is not required is during the line setup. During this time period, the line does not produce, and trains take the moulded components to the warehouse (Figure C.4, Appendix C) to free the line from the batch of the previously produced SKU. Two separate tugger trains are used, one for good-quality components and one for components to be re-worked. Also during line setup, empty unit loads are moved to press lines, especially when SKUs with a high production rate per hour or large size (requiring more unit loads) are processed next. This ensures that all the necessary empty unit loads arrive at the line on time, without the risk of stopping production.

3.2.4 Model validation

The model is first validated by comparing the output of the simulation runs over 16 days with the actual data for the same days taken from the company's production reports (Figure 2). The focus is on the number of unit loads delivered to the warehouse. The number of train tractors used (fleet size), which is an input to the simulation model that can change over time, is also displayed to emphasize the consistency of the simulation results with the actual number of unit loads delivered to the warehouse. The simulated number of unit loads moved into the warehouse on each day considered is very close to the actual one. On the other hand, there is a slightly larger difference between the actual tractor fleet size and one considered in the simulations, as the company only records the average number of tractors used, calculated based on drivers' working hours.

The DES model is also statistically validated by replicating simulations, considering that the current focus is on single-day production. The statistical analysis is carried out on 3 of the days displayed in Figure 2 and shows that validation is obtained with at least 15 replications. For example, in the case of the variable related to the number of unit loads delivered to the warehouse, the Mean Square Pure Error of the mean value is less than 1 unit load with a production fluctuating around 600 unit loads

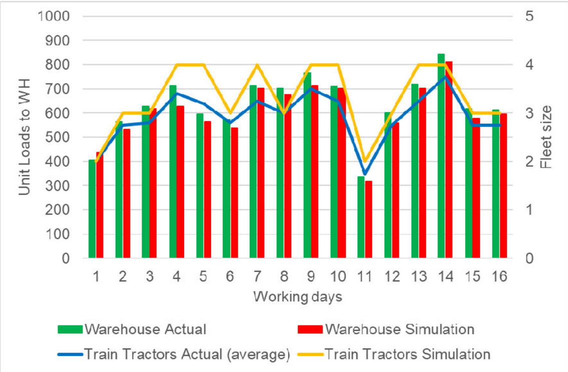

Figure 2: Validation outcomes

4. Results

The simulation model can help to analyze the impact of the adopted intra-logistics strategies on a number of KPIs. Of these, the following two KPIs were considered as the most interesting by the Press Shop management: i: the time press lines spend in a number of different states, as explained in Sub-section 4.1. and ii: the number of unit loads in the buffer areas at the end of each press line. In particular, it is here examined how the values of the two KPIs are affected by the decision on the size of the fleet of train tractors used to transport components to the warehouse.

4.1 Press line states

The KPI on the time the press lines spend in different states allows to compare the production and logistics efficiency under different fleet sizes of tractors. Figure 3 reports a histogram representing the state of each press line over time during one selected day, when 4 tractors are used for handling moulded components. In particular, the diagram shows the percentage of the total available daily time each line spends in the following states. *Working*: regular working. *Setting-up*: line setup is being performed. *Blocked:* the line is stopped because of two reasons. The main one is the unavailability of buffer space for the temporary storage of full unit loads. The secondary one is the lack of available empty unit loads. *Failed*: the line is stopped because of a failure, related for example to breakdowns of moulds, press machines, etc.

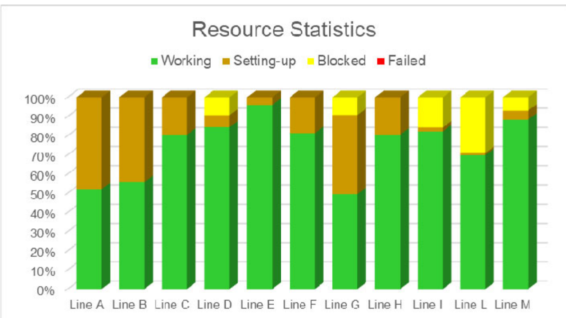

Figure 3: Press lines states (4 tractors)

As can be seen in Figure 3, each line spends at least half of the available daily time in the *Working* state. In addition, due to buffer saturation, production is stopped in 5 of the 11 lines, and for an average percentage of time equal to approximately 18% (*Blocked* state). This means that 4 tractors already ensure a fairly good production and logistics performance. However, the logistics performance can be improved by increasing the tractor fleet size. Figure 4 shows that when an additional tractor is used, the *Blocked* state is reduced from affecting 5 lines to 3 lines out of 11 and the average time each of them stays in such a state is about 7.7% of the available daily time. Thus, increasing the fleet size of 1 unit brings to a 57% decrease of the average time a line spends in the *Blocked* state. So far, the situation without line failures has been considered. Including failures in the simulation model is interesting because they affect the efficiency of the material handling system. In fact, the associated slowing down of production facilitates the work of the tugger trains, which will have more time available to carry out the required tasks, resulting in a lower percentage of time lines spend in the *Blocked* state. Figure D.1 in Appendix D compares the status of press lines when failures are included in the simulation model and when they are not, as shown in Figure 3, with 4 tractors used.

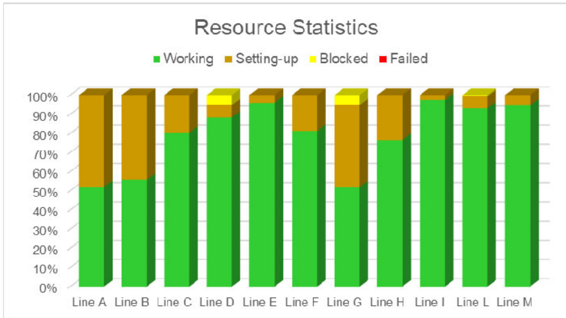

Figure 4: Press lines states (5 tractors)

4.2 Number of unit loads in the buffers

Monitoring the number of unit loads carrying moulded components in the buffer area at the end of each press line allows implementing logistics strategies aimed at reducing the time lines spend in the *Blocked* state. In fact, it is possible to observe when the level of a buffer rises too high and reaches saturation. Back then, it is possible to investigate the causes and identify the production batch that causes such a problem. Further simulations could be carried out by modifying the batch sequence and choosing a configuration that alleviates lines blocks due to logistics reason. Figure 5 compares the trend in the number of unit loads in the buffer of each press line when 4 and 5 train tractors are used, on the same day analysed in Section 4.1. In order to make them more readable, the diagrams show only the situation during the first hour and a half of the first shift of the day.

In both the cases, the lines have pretty low buffer levels, equal to no more than 1 unit load, except for Lines D,G, and I. When 4 tractors are used, Line D reports a peak of 4 unit loads in the buffer after 55 minutes from the start of the shift, however well far from the saturation level of 12 unit loads. On the contrary, the number of unit loads in the buffer of Line G, which works at a low Takt Time, progressively grows from 1 to 12 unit loads. Then, this line spends about 45 minutes in a saturation condition, which causes Line G to be in the *Blocked* state. Finally, the Line I buffer, after being empty for the first 43 minutes, grows up to 10 unit loads. When 5 tractors are used, a larger transportation capacity is available with a significant benefit on the buffer levels. In fact, only the Line G buffer grows to reach the saturation level, while all the other buffers always include a maximum number of 1 unit load. However, the Line G buffer is now saturated only for approximately 10 minutes.

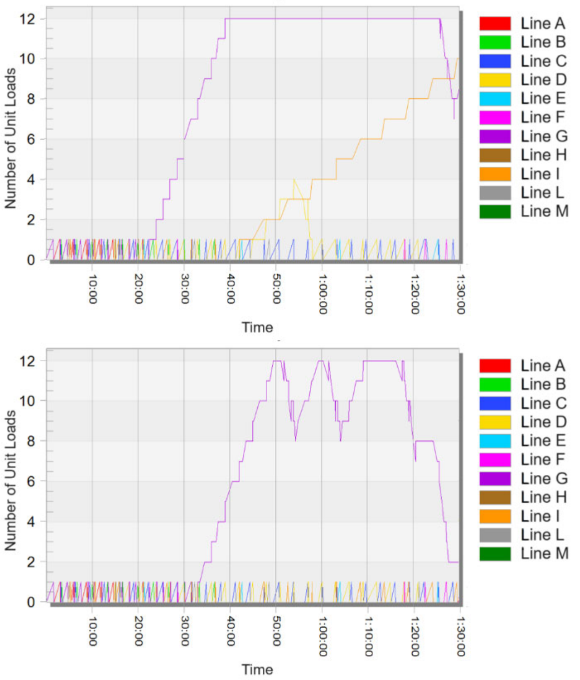

Figure 5: Unit loads in the end-of-line buffers with 4 (top) and 5 (bottom) tractors

5. Discussion and Conclusions

This paper discusses the steps and current progress in the development of a DT-oriented DES model of the intra-logistics of finished components in an automotive press shop. Plant Simulation, the adopted software, demonstrated to be effective and the validation allowed to consider the model reliable. Additionally, the developed simulation model is adopted to quantitatively assess the impacts on selected KPIs of the decision on the number of tractors used. The work offers a contribution on the step-by-step approach that should be taken to integrate DT models in the redesign of those intra-logistics processes that need to be updated. Such an approach facilitates a smoother and more manageable transition from traditional systems to fully functional DTs. In particular, it sheds light on the fact that the digital twinning of manufacturing and logistics systems cannot be achieved in a successful way without going through a number of intermediate phases and goals, such as building a reliable simulation model or enabling a direct and automated flow of input information from the physical to the digital system. Emphasizing the need for intermediate achievements ensures that the integration of DT models into business practices is sustainable. However, the works available in the literature are sometimes too focused on the end result, i.e., the DT, and neglect the importance of the intermediate steps. In such a way, the paper enriches the current literature on the development of DTs of automotive intra-logistics, a sector where this technology is still scarcely addressed (Lin and Yao, 2022). In addition, it helps companies identify what activities they need to perform as they embark on a journey to develop complete DTs, enabling them to understand the skills and effort required (Sommer et al., 2020). In the context of advancing intralogistics processes through DT technologies, it is imperative to address the associated need for workforce training and skill development. As the complexity of digital systems increases, the role of human resources becomes critical to the successful integration and utilization of these technologies. Implementing the proposed approach in a real-world industrial scenario requires a workforce that is skilled not only in operating these advanced systems, but also in interpreting the data and insights they generate. Training programs must be designed to provide employees with a deep understanding of DT principles, simulation techniques, and the specific software tools used in these applications. In addition, training workers in data analysis and real-time decision making will be essential to maximize the benefits of DT integration.

Academic and practical implications can be derived. The present work might inspire researchers in conducting more case studies about DTs in the automotive intra-logistics, thus proving they can effectively contribute not only to automotive design or manufacturing but also to the associated material handling. Moreover, it might foster studies focused on simulating manufacturing processes, internal logistics activities, and their operational relationships. In this context, DTs might enable a better monitoring of the logistics flows within production plants. Practitioners might find the present study beneficial in guiding their transition towards DTs in logistics. Also, the developed DT-oriented simulation model suggests companies how they might use similar models to allow an easy identification of the most appropriate innovative material handling systems. However, the present study suffers from some limitations. As discussed in the previous sections, the current DES model is not yet a DT. In fact, it requires further developments to establish complete double-way automated data flows from the physical to the digital system and vice versa. Additionally, it allows to assess the operational effects of logistics strategies but not the economic ones. Also, the development and implementation of DT-oriented DES models require a significant financial investment, including costs for software, hardware, skilled personnel, and ongoing maintenance. Finally, implementing a DT-oriented DES model in a company can encounter resistance from employees accustomed to traditional processes. All these aspects are not addressed by the present work. Future research efforts will be directed towards advancing the proposed simulation model to make it an actual DT. The associated economic burden on the Case Company and any resistance to change by staff will be analysed. Additionally, the Case Company would like to apply such a DT in studying the introduction of AGVs to replace the current traditional tugger trains. To this end, the cost of different alternative logistics strategies and vehicles will be deeply investigated.

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Appendix A. MAIN INPUT DATA

Area	Press Line				
HTP	Line A	Line B	Line C	Line D	
MTP/1	Line E	Line F	Line G	Line H	Line I
MTP/2	Line L	Line M			

Table A.1: Press line overview

Area	Distances – internal route [m]	Distances – external route [m]
HTP	1,420	1,970
MTP/1 MTP/2	1,090	1,640

Table A.2: Tugger train travel distances

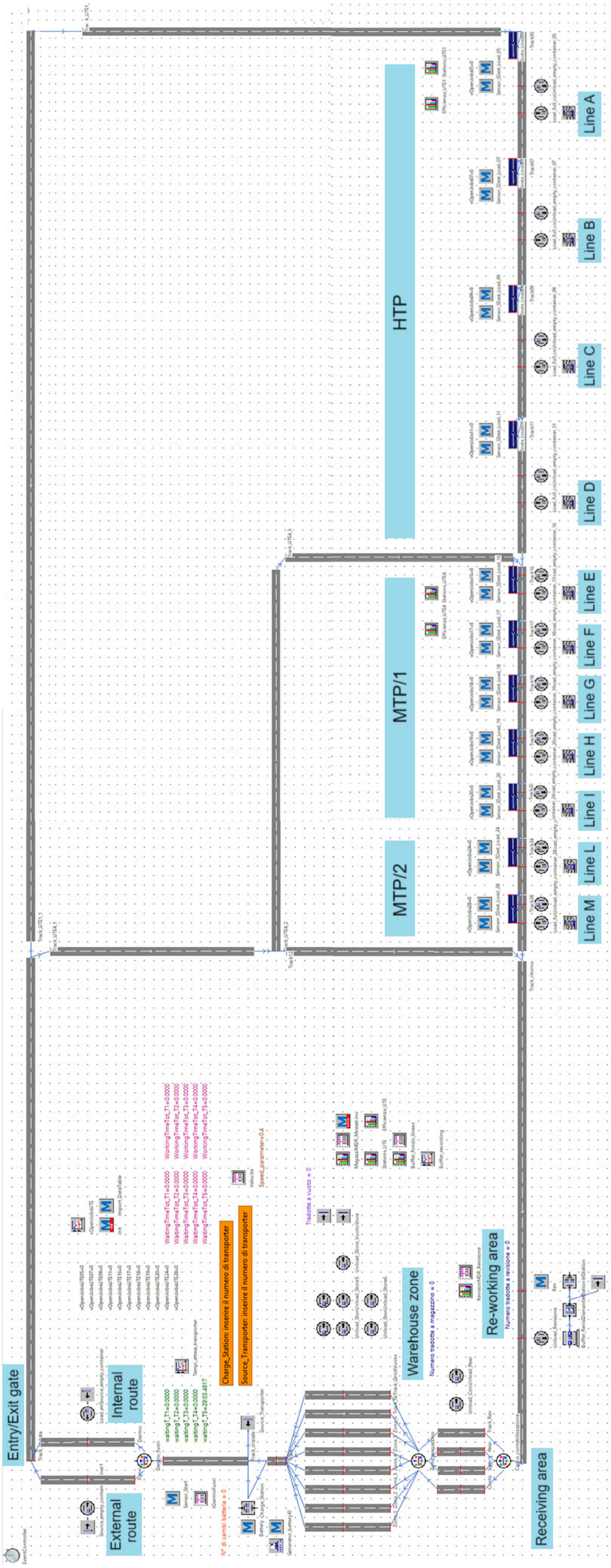
Warehouse zone	Distance [m]
Zone 1	170
Zone 2	160
Zone 3	150
Zone 4	200
Zone 5	60
Zone 6	200

Table A.3: Distances to the finished component warehouse zones

Task	Average time
Loading empty unit loads on trolleys (in the empty unit load storage area)	144 s/train
Uncoupling trolleys with empty unit loads	9 s/train
Coupling trolleys with full unit loads	12 s/train
Loading/unloading unit loads on/from trolleys in the end-of-line buffer area	70 s/unit load
FCW: Counting full unit loads	22 s/unit load
FCW: Reading full unit load barcodes	27 s/unit load
FCW: Weighing full unit loads	22 s/unit load
FCW: Unloading full unit loads	116 s/unit load
Battery swapping	15 min/tractor

Table A.4: Average time of main tasks (FCW: finished component warehouse)

Appendix B. SIMULATION MODEL OVERVIEW



Appendix C. FOCUS ON MAIN SUB-MODELS

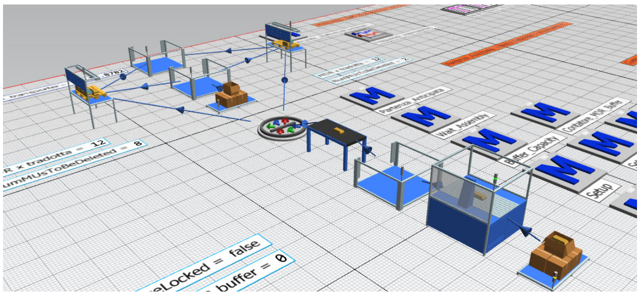


Figure C.1: Press line

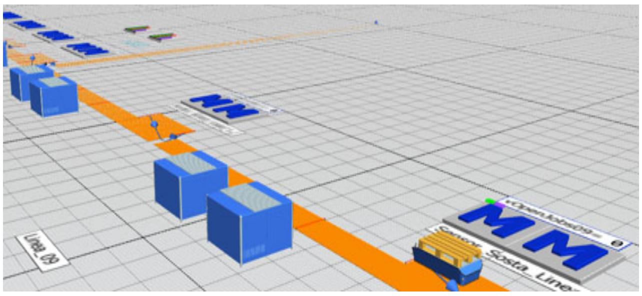


Figure C.2: Train parking area

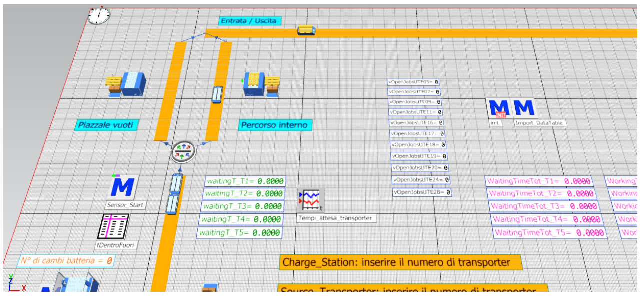


Figure C.3: Empty unit load storage area

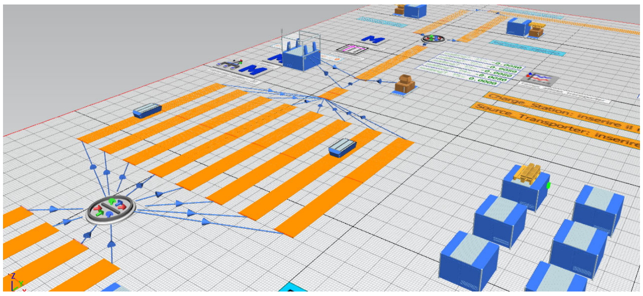


Figure C.4: Finished component warehouse

Appendix D. RESULTS

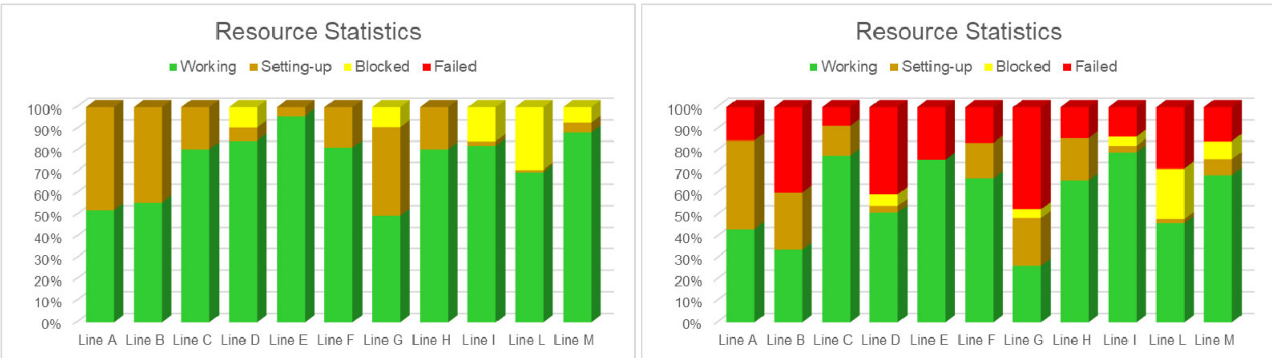


Figure D.1: Press lines states without (left) and with (right) failures – 4 tractors