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# Enhancing Operational Resilience Through the Simulation of Automated Material Handling in the Food Industry

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**Abstract**

Operating within a complex and dynamic global ecosystem, organizations are subject to continual evolution in response to shifting market demands. Adaptability has long been a crucial attribute of modern organizations. However, in recent years, resilience has become equally essential, shaping the future trajectory of their development. The aim of this study is to contribute empirically by proposing simulation as a method for enhancing operational resilience. Designing workflows within this context necessitates a multifaceted approach. While a comprehensive understanding of the individual process steps is essential, it is equally crucial to consider the broader system context and the factors that influence the successful execution and desired outcomes. This paper presents simulation research as a tool for performance improvement, and investment decisions. Crucially, simulation modelling facilitates a forward-looking approach, enabling organizations to not only withstand and recover from challenges but to emerge strengthened and transformed, rather than merely reverting to pre-crisis conditions. The article emphasizes the strategic value of simulation modelling in enhancing an organization's operational resilience.

**Keywords**

operational resilience, simulation, production, logistics, organizational improvement, organizational resilience.

## Introduction

The simultaneous impact of the effects of the pandemic crisis (Schleper et al., 2021), Russian aggression against Ukraine (Srai et al., 2023), trade wars, as well as the intensification of EU activities aimed at creating a modern, resource-efficient and competitive economy mean that a requirement for modern enterprises is "to have the fundamental competence to respond efficiently to significant changes that disrupt the achievement of adopted plans without falling into long crisis periods" (Banaszyk, 2022). This competence is resilience.

The concept of resilience has been investigated across three principal branches of the social sciences: sociology, psychology, and economics. To date, research has explored organizational resilience from multiple perspectives. (Hepfer and Lawrence (2022) identify three primary conceptualizations: absorption and recovery, anticipation, coping, and adaptation, as well as bouncing back and bouncing forward.

The first emphasizes continued operation in the face of adversity without necessarily reverting to a previous state or progressing to a new one. The second highlights reactive and adaptive behaviors. The third differentiates between returning to an original position ("bouncing back") and positive development ("bouncing forward") following a setback.

Resilience is understood in this study as the adaptive ability to reduce the probability of sudden disruptions of an endo- or exogenous nature, to prepare for these disruptions, to respond quickly to them, to prevent the spread of disruptions, to rebuild after them and finally to return to the original situation or to a new, more desirable state (Marinus et al., 2016; Maryniak et al., 2021; Ocicka et al., 2022; Szymczak, 2015).

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A recent study by Hepfer and Lawrence (2022) identified three distinct dimensions of organizational resilience. Strategic resilience pertains to an organization's capacity to anticipate and counteract threats to its overarching strategy, particularly those endangering its long-term objectives. Operational resilience refers to an organization's ability to respond positively to adverse circumstances affecting the entire entity, which may compromise its ongoing operations. Finally, functional resilience concentrates on a particular organizational unit or process, with the majority of research dedicated to isolated disruptions within supply chain and information systems contexts. The concept of resilience in supply chain management (SCRES) emerged relatively recently, with Rice and Caniato (2003) being among the early contributors to the field. A significant step forward was made by Christopher and Peck (2004), who developed an initial framework for supply chain resilience (SCRES). They defined SCRES as 'the ability of a system to return to its original state or move to a new, more desirable state after being disturbed' (Schleper et al., 2021), providing a foundational definition for subsequent research. As stated by Hohenstein et al. (2015) supply chain resilience is 'the supply chain's ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state'. It is noteworthy that both disruption in general and the specific case of the COVID-19 pandemic have stimulated increased academic and practical interest in supply chain resilience as a means of achieving competitive advantage (Irfan et al., 2022).

Of the three forms of organizational resilience, operational resilience has been least explored within the realms of management and organizational research (Holgado et al., 2024). Essuman et al. (2020) contend that scholarly understanding of operational resilience is limited, as the majority of research concentrates on the firm and supply chain levels.

Simulation is becoming increasingly important in building operational resilience (Lewandowska-Ciszek, 2025; Lewandowska-Ciszek et al., 2024). Designing business workflows in a shifting environment is challenging. Beyond a deep grasp of the workflow itself, it's crucial to consider the bigger picture it's a part of and the requirements for it to function as intended and deliver the anticipated outcome. Managing operations in times of turbulence becomes a serious challenge. It is necessary to consider a large number of action options. Simulations, allowing to understand the consequences of possible decisions before they are made, enable the planning of the material flow process in a way that ensures its efficiency maximization while taking into account the requirements of individual production environments. Within this activity, it is possible to plan actions in such a way as to enable their implementation in the face of unforeseen situations.

This paper aims to analyze the role of simulation in strengthening operational resilience, particularly in the context of organizations operating under turbulent and uncertain conditions.

One central research question is addressed: How does simulation support enhancing operational resilience? A case study methodology is applied to enable a contextual understanding of simulation use in resilience-building. Data are collected from three primary sources: simulation models, project documentation, and records of project meetings.

## The essence of simulation

While direct experimentation can be a powerful tool for studying social and economic systems, its application is often limited. Such experiments can be prohibitively expensive and logistically cumbersome, or even entirely infeasible (Winkowski, 1974). Therefore, to circumvent the limitations of direct experimentation on real-world systems, researchers and entrepreneurs can create models for investigation. This approach allows for safe and cost-effective research without compromising the integrity of the original system (Burduk et al., 2021).

A mathematical model is one of the types of models that describes the examined reality through symbols and the relationships between them. Once it is created, ways of adapting it to various conditions, using it and methods of interpreting the results should be determined. Analytical solutions can be used in this case. But what about systems for which analytical methods turn out to be helpless and for which they cannot provide solutions (Fishman, 1981)? What about highly complex systems, where trying to map them in an overly simplified model will reduce the cognitive value and credibility of the analyzed case (Mielczarek, 2009)?

When dealing with complex realities, simulations offer a compelling alternative to direct experimentation (Fig. 1). These simulations involve conducting experiments on encoded computer programs represent-

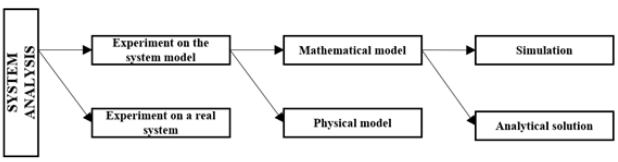


Fig. 1. Methods of analyzing economic and social systems

ing mathematical models of the system under study. This approach provides a safe and controlled environment that mirrors the real world, potentially bypassing the need for direct manipulation of the actual object (Mielczarek, 2009). Therefore, simulation is possible to implement thanks to a mathematical model, i.e. an object manipulated during simulation research.

In combination with other quantitative techniques supporting decision-making processes, simulation enables experimentation on the model by performing multiple iterations of the computational process, continuously monitoring the system, and interpreting the results obtained.

The term 'simulation' has its origins in Latin (simulo, similis, similo, similar, simulacrum) and means: to pretend, to represent, to imitate, to imitate, similar, likeness. It can be considered in various contexts.

Previous scientific research, as documented in the literature (Diakun, 2023), has considered this issue within the following contexts:

- research methodology: this refers to the use of simulation as a research method.
- technical and organizational projects: this includes simulation studies and simulation projects.
- computational processes: this encompasses individual simulation runs.

Fishman (2001) defines simulation as collection of techniques that, when applied to the study of a discrete-event dynamical system, generates sequences called sample paths that characterize its behavior. According to Robinson (2004) simulation is an experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better under-standing and/or improving that system. Banks, Carson II, Nelson, Nicol (2010) state that simulation is the imitation of the operation of a real-world process or system over time (Banks et al., 2010). Nowadays, its tool is usually a computer program.

Considering the above, it can be concluded that computer simulation is a numerical technique and a form of experimentation carried out on dynamic models that reflect real systems, allowing for a better understanding of how these systems behave over time (Łatuszyńska, 2011; Mielczarek, 2009).

Simulation stages in the context of a simulation study are usually presented in the pertinent scholarly literature in the form of steps, as well as in the form of a block diagram. The following stages of the simulation study are distinguished, as presented in Fig. 2 (Banks et al., 2010; Burduk, 2013; Diakun, 2023; Mielczarek, 2009):

- defining the problem,
- setting a goal,
- determining the scope of the study and the level of detail of the model,
- collection and analysis of input data,
- construction of a simulation model,
- model verification,
- model validation,
- planning a simulation experiment,
- conducting a simulation experiment,
- data analysis,
- preparation of documentation,
- implementation of simulation results.

Simulation is an attractive analysis tool because of its many advantages (Fishman, 1981). By anticipating potential issues, facilitating modifications, and accelerating cost and benefit estimation, it empowers organizations to concentrate on high-return, low-cost scenarios. Risks associated with delays are mitigated through optimized resource allocation, infrastructure refinement, and inventory management. Moreover, sim-

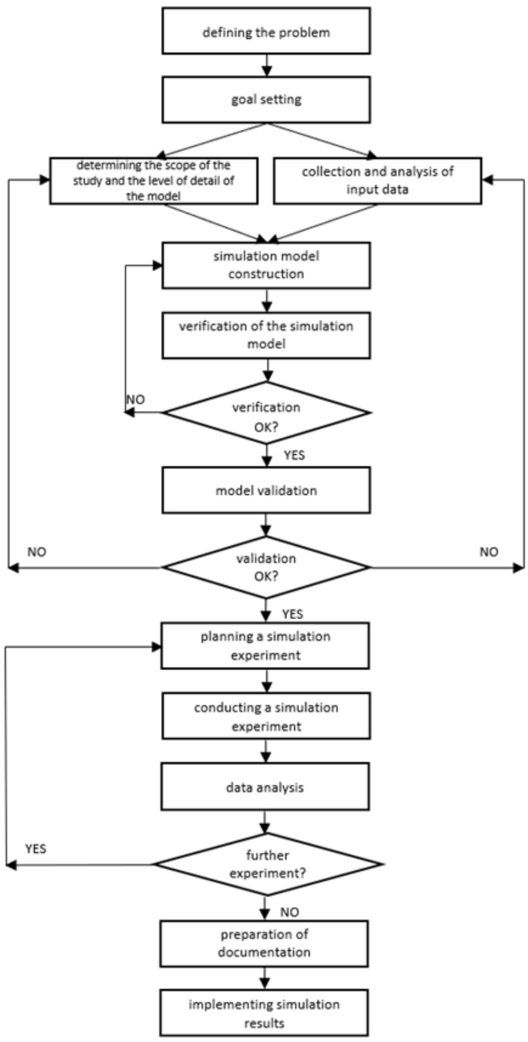


Fig. 2. Stages of the simulation study

ulation enables the reuse of models across multiple design iterations, ensuring consistency and reducing errors. Accelerated testing, particularly in resource-constrained environments, contributes to optimal operational planning and swift implementation. Business process simulation is a valuable tool for problem-solving and investment justification. The required level of model complexity varies depending on specific objectives, such as production optimization or economic analysis (Eberle, 2020). Simulation studies can be applied to highly complex processes or those that do not yet exist. They may also concern hazardous processes or involve resources that are currently unavailable. Furthermore, simulation can be used for real systems where analytical methods are insufficient to provide viable solutions. Simulation facilitates a better understanding of how real systems function by revealing interdependencies within the system. It supports decision-making by simplifying the analysis of specific system components and motivates users to systematize their knowledge about the processes being studied. By utilizing time control mechanisms, users can define the ratio of simulation time units to real-time seconds. This feature allows for both accelerated simulations (known as "time condensing") and decelerated simulations ("time extension"), depending on the analytical needs.

## Research methodology

This study adopts a single in-depth case study approach, a well-established method in research on logistics operations for examining complex, real-world systems and uncovering underlying mechanisms (Aastrup & Halldórsson, 2008). It integrates qualitative and quantitative elements, making it effective for theory development and validation (Dinwoodie & Xu, 2008; Hakkinen & Hilmola, 2005), while offering strong construct validity and the potential to reveal new variables or hypotheses (Bennett, 2004). Particularly effective in industrial manufacturing contexts, the approach is supported by tools such as workplace visualization (Dulina et al., 2024), value stream mapping, and lean performance indicators (Domingo et al., 2007). Material flow is analyzed at both micro and macro levels (Kósi & Torma, 2005), using techniques like time studies, SMED, and 5-Why analysis to detect inefficiencies (Halim et al., 2013). The methodology typically involves assessing the current state, developing logistics programs, and identifying optimization opportunities (Królczyk et al., 2014), with production flow analysis contributing to improved layouts and material handling (Modrák, 2009).

The case study in this research explores the contribution of simulation to building operational resilience, with a focus on organizations functioning in dynamic and unpredictable conditions.

Data sources include simulation models, project documentation, and records from project-related meetings supporting investment decision-making. The analysis was conducted iteratively, focusing on the evaluation and comparison of alternative workflow scenarios within the single case. This enabled the identification of performance patterns, resource utilization dynamics, and resilience-enhancing factors relevant to strategic planning and operational improvement.

A simulation model was developed to present a novel investment concept and its implementation strategy to potential investors. Built using the FlexSim material flow simulation software, the model served to visualize and evaluate the proposed operational design in a dynamic and data-driven manner. Since the model was theoretical in nature and intended to support investment decision-making prior to implementation, traditional validation against real-world operational data was not feasible.

To ensure the model's technical soundness, verification was carried out through internal logic testing and step-by-step analysis of the simulation flow within the FlexSim environment. Each model component and rule was individually examined to ensure consistency with the intended process logic and underlying conceptual assumptions.

Regarding validation, a conceptual validation approach was applied. The model's structure, input parameters, and expected outcomes were reviewed in collaboration with experts and project stakeholders. Their feedback confirmed that the model adequately reflected the envisioned system and fulfilled the requirements of the investment analysis. At this stage, validation focused on ensuring that the model was a credible and reasonable representation of the proposed solution, aligned with the early-stage project constraints.

FlexSim software was chosen for its ability to combine powerful analytical capabilities with intuitive visual representation. It supports the creation of dynamic 3D models using a variety of pre-built components, including robots, human workers, conveyor systems, and processing units (Luscinski & Ivanov, 2020). Each component can be customized to reflect real operational behavior. Once the model was complete, various scenarios were tested to assess their impact on system performance. The simulation accurately mirrored the company's production facility layout, incorporating the precise arrangement of machinery and storage areas based on the actual floor plan. Input data used to calculate performance metrics and evaluate average production rates are presented in Fig. 4. The FlexSim environment allowed for real-time experimentation with operational parameters, and automatically generated visual reports provided valuable insights into key performance indicators. The decision to adopt this simulation tool was driven by its capacity to support multiple stages of the investment project, including feasibility assessment, cost analysis, detailed design, and verification of existing operational processes (Kaczmar & Banyai, 2024).

## Description of the problem

The expansion process of the production system, outlined below, pertains to a leading company within the food and beverage supply chain.

The entity is identified as the leading participant in the chain, as its activities enable the final products to achieve acceptable market competitiveness through the entity's core competencies and distinctive capabilities.

The development plans of the entity under analysis, as a pivotal link in the supply chain, directly impact the operations of other businesses within the supply chain and simultaneously set a benchmark for their future development.

The existing system is to be upgraded and expanded with the addition of an internal transport system and a palletizing station.

The output data of the existing production system, including the performance of individual packaging lines, has been used as input data for the newly designed internal transport system.

The production system under analysis consists of two packaging lines (Fig. 3) PL4 and PL1, which is divided into two sections: PL11 and PL12.

Lines PL4, PL11 and PL12 consist of a series of machines, including a packaging machine for packing individual items and a cartoning machine for putting items into boxes. Automated equipment begins the packaging process by inserting the finished product into single-unit packaging. The individually packaged product is then conveyed to a packaging station where it is placed into a bulk pack, configured according to a pre-determined pattern. This pattern is selected based on the product type and its intended destination. The PL1 line comprises two sub-lines, PL11 and PL12. Both handle the same product but with different unit packaging to meet specific end-customer requirements. While production line PL11 uses generic packaging featuring the manufacturer's branding, line PL12 is dedicated to producing the same product but in packaging tailored exclusively to the supermarket's own brand. At the end of each production line, there is a designated area where pallet load units are formed according to a pre-determined pattern, dependent on the product type and the destination country. This area is staffed by five workers on PL4, four workers on PL11, and four workers on PL12.

The PL lines are situated in various, discrete sections of the production hall, which spans a total area of 2500 m$^2$ (Fig. 3). Due to the significant distances separating the individual lines and their respective output levels, it is not feasible for a single team of operators to manage all three stations.

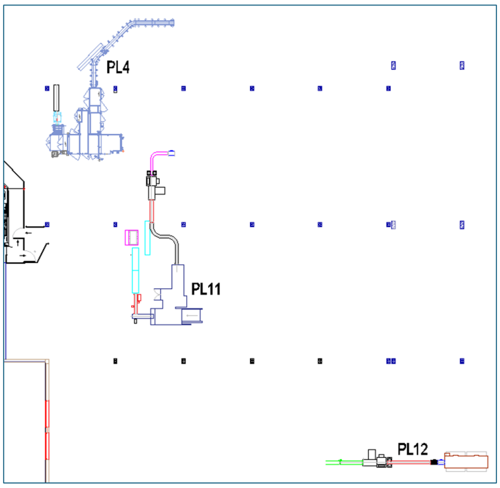


Fig. 3. Location of two packaging lines within the production system under study

At the end of each packaging machine, there is a conveyor that acts as a buffer zone for finished products. From this point, operators retrieve the packages and place them onto empty pallets according to a predetermined pattern. The line must be continuously supplied with empty pallets. These are supplied by an operator using a forklift truck, in stacks of 15. The same operator collects the pallets with the formed pallet load unit and deposits them in a designated storage area within the production hall. Each line is serviced by a single forklift driver. In addition to the employees tasked with transporting pallets along the lines, there are individuals responsible for configuring pallets according to specific patterns. To ensure a continuous flow of materials exiting the lines and minimize downtime, the following labor resources have been allocated to support these lines. Specifically, line PL4 is staffed with 4 employees per shift, while lines PL11 and PL12 each have 3 employees per shift. The total number of employees servicing these line segments is 13 per shift.

According to data collected from the enterprise under investigation, there are currently 19 packaging patterns for 13 product types (Fig. 4). A proportion of products are palletized on either EU or UK pallets. Line efficiencies vary depending on the product variant, ranging from 4.6 to 10 pallets per hour. A detailed breakdown is provided in the table below (Fig. 4).

| No | Case | Boxes production rate per minute | Takt time | Boxes production rate per hour | Number of finished pallets per hour | Pallet type | Number of boxes per layer | Number of layers |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 14 | 4.29 | 840 | 5.71 | EU | 21 | 7 |
| 2 | 2 | 14 | 4.29 | 840 | 6.67 | EU | 21 | 6 |
| 3 | 3 | 14 | 4.29 | 840 | 7.50 | EU | 16 | 7 |
| 4 | 3 | 14 | 4.29 | 840 | 5.71 | UK | 21 | 7 |
| 5 | 4 | 14 | 4.29 | 840 | 8.75 | EU | 16 | 6 |
| 6 | 4 | 14 | 4.29 | 840 | 6.67 | UK | 21 | 6 |
| 7 | 5 | 7 | 8.57 | 420 | 6.67 | EU | 9 | 7 |
| 8 | 6 | 7 | 8.57 | 420 | 7.78 | EU | 9 | 6 |
| 9 | 7 | 14 | 4.29 | 840 | 9.88 | EU | 17 | 5 |
| 10 | 7 | 14 | 4.29 | 840 | 6.67 | UK | 21 | 6 |
| 11 | 8 | 6 | 10.00 | 360 | 10.00 | EU | 6 | 6 |
| 12 | 9 | 55 | 1.09 | 3300 | 8.25 | EU | 40 | 10 |
| 13 | 10 | 55 | 1.09 | 3300 | 8.68 | EU | 38 | 10 |
| 14 | 11 | 42 | 1.43 | 2520 | 7.33 | EU | 43 | 8 |
| 15 | 11 | 42 | 1.43 | 2520 | 5.83 | UK | 54 | 8 |
| 16 | 12 | 28 | 2.14 | 1680 | 5.60 | EU | 30 | 10 |
| 17 | 12 | 28 | 2.14 | 1680 | 4.91 | UK | 38 | 9 |
| 18 | 13 | 21 | 2.86 | 1260 | 7.50 | EU | 21 | 8 |
| 19 | 13 | 21 | 2.86 | 1260 | 4.67 | UK | 27 | 10 |

Fig. 4. Input parameters

The manual process of constructing a pallet unit load (PUL) begins with an operator retrieving an empty pallet from a stack. Depending on the specific loading pattern being implemented, there are two methods for securing the stacked layers of products:

- Yellow cardboard separators are placed directly onto the pallet beneath the first layer and on top of the final layer. The stacked layers between the separators are placed one on top of the other (Fig. 5) without any additional securing.

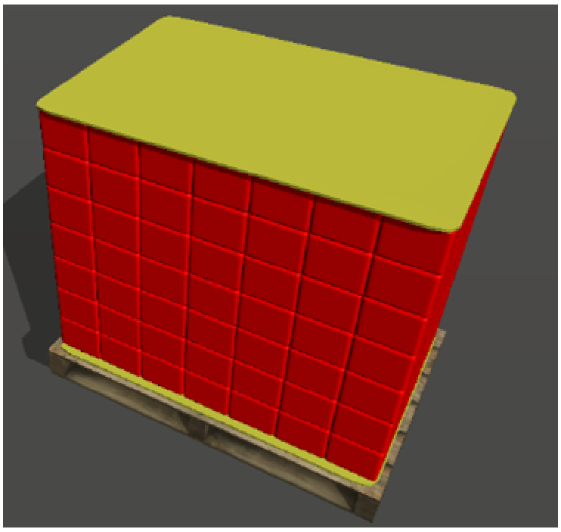

Fig. 5. First method for securing stacked product layers

- Prior to each product layer, a black cardboard tray is positioned. A yellow cardboard divider is then situated atop the final layer (as depicted in Fig. 6)

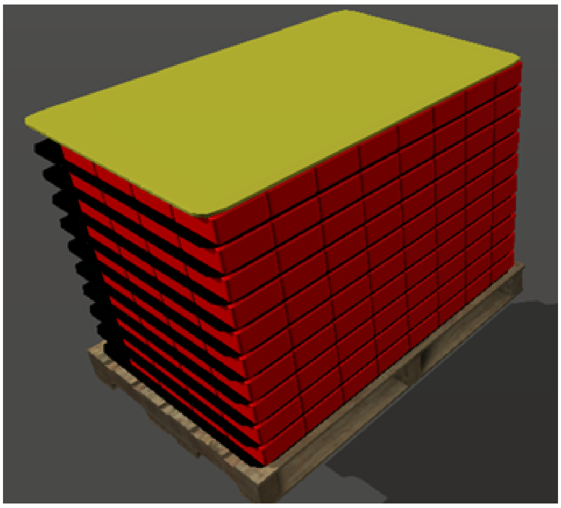

Fig. 6. Second method for securing stacked product layers

Individual units undergo a process of being picked singly by operators and layered onto pallets.

The investor's order encompassed an expansion of the existing End-of-Line (EOL) area. A key component of this project was the development of an internal transport concept, including a palletizer. Once palletized, the unit loads were to be directed to a designated storage area within the hall, from where they would be transported to the finished goods warehouse.

Several critical factors were considered during the project:

- Dynamic process parameters: Specifically, the performance requirements of individual lines were a priority.
- Available space: The limited space within the EOL area was carefully assessed.
- Palletization points: The location of pallet drop-off points near packaging lines was optimized.
- Finished goods storage: The optimal placement of finished goods pallet storage areas was determined.
- Potential bottlenecks: Potential issues such as the intersection of supply routes for packaging lines and finished goods removal routes were identified and addressed.
- Return on investment: The focus was on scenarios that maximized return on investment while minimizing capital costs.
- Investment costs: The length of conveyors was a significant factor in determining overall investment costs.

The objective was therefore to minimize losses and establish a continuous flow at the process level. Sources of waste could include: any disruptions causing downtime, unnecessary waiting times within the flow, and any process irregularities.

## The simulation of automated material flow processes

The convergence of digitalization, robotics, and automation is driving the evolution of Industry 4.0 production and logistics. By increasing efficiency, accuracy, and safety, while simultaneously decreasing costs, robotics and automation technologies have revolutionized the field of operations management.

### The first proposed solution

Considering the first proposed solution, a conveyor can be installed behind the cartoning machines. From this conveyor, product packages will be routed to a central consolidation area within the hall (Fig. 7). Here, operators will build pallet-sized unit loads. Once completed, these pallets will be transported to the finished goods warehouse using a forklift. In this scenario, empty pallets are delivered to a centralized location. They are stacked 15 high on the floor and subsequently retrieved manually by operators to construct unit loads. This solution enables a reduction in the number of forklift truck operators from three per shift to two per shift. The number of operators responsible for forming load units will remain unchanged due to the efficiency of individual lines. A proposed materials flow diagram incorporating a conveyor system is presented below.

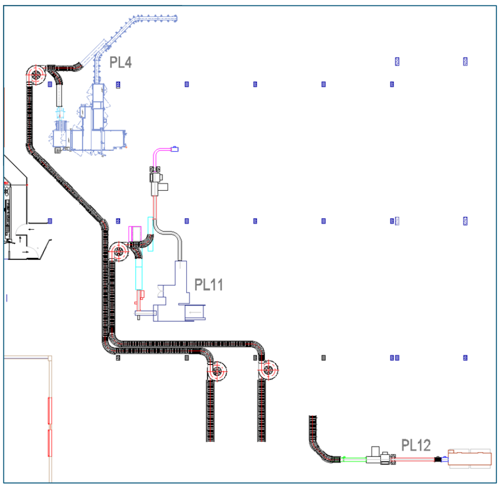


Fig. 7. Conveyor system located downstream of cartoning machines

### The second proposed solution

The second solution proposes supplementing the previously suggested solution with two additional pallet destackers, each capable of holding 15 pallets. A roller conveyor is installed after the destackers to transport empty pallets to pallet unit build-up locations according to a predetermined pattern (Fig. 8). This solution reduces the production cycle time by eliminating the time spent by operators traveling to collect empty pallets for loading. Consequently, the number of operators required to form pallet units can be reduced from 10 to 9 per shift.

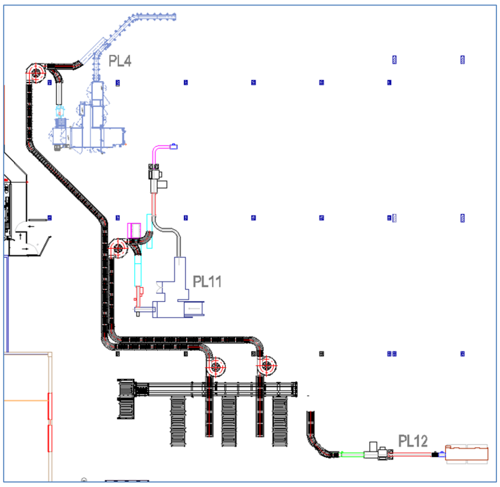


Fig. 8. Conveyor system installed downstream of cartoning machines with dual pallet destackers

### The third proposed solution – simulating a fully automated pallet load preparation process with three robots

The client's requirement included the development of an internal transport concept in the EOL area that would ensure continuous flow at the process level without downtime, disruptions or inhibitions, reduction of losses, balancing of workstation loads, minimization of process irregularities, and shortening of customer order fulfilment time.

To support this, a simulation model was created using material flow simulation software to present a novel investment concept and its implementation plan to stakeholders.

This study aims to investigate the feasibility of reducing the number of operators required to form palletized unit loads on lines PL4, PL11, and PL12. To achieve this, it is proposed to automate the process by deploying three palletizing robots. These robots will be positioned near the collection points for bulk packaging, replacing the operators who were previously stationed at these locations.

The automated process of building a pallet unit commences with an empty pallet being conveyed from a destacker. Two methods may be employed to secure product layers, analogous to those used in the manual construction of a pallet unit load (Fig. 9, Fig. 10).

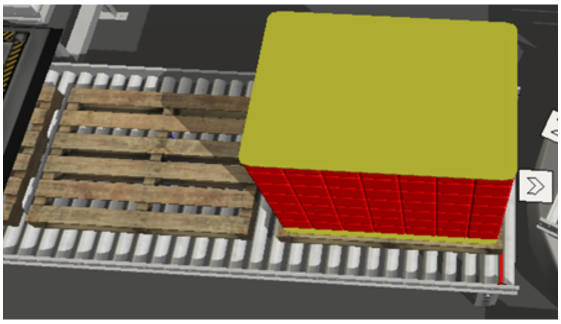

Fig. 9. First method for securing stacked product layers

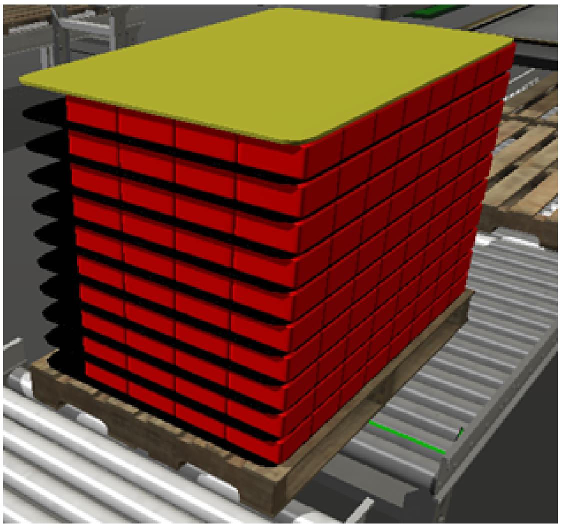

Fig. 10. Second method for securing stacked product layers

Individual units are conveyed via conveyors from packaging machines to a designated pick point. The number of packages per layer is defined based on the product type. Each layer is constructed from one, two, or three complete sections. Subsequent sections are formed at the pick point using a layerer and then picked by a robot using a gripper and placed onto a pallet. This process is repeated until the formation of palletized unit loads is complete.

The third solution proposes automating the palletizing process with the deployment of three robots. These robots would be positioned close to the bulk product packaging collection points, eliminating the need for manual labor at these stations (Fig. 11, Fig. 12).

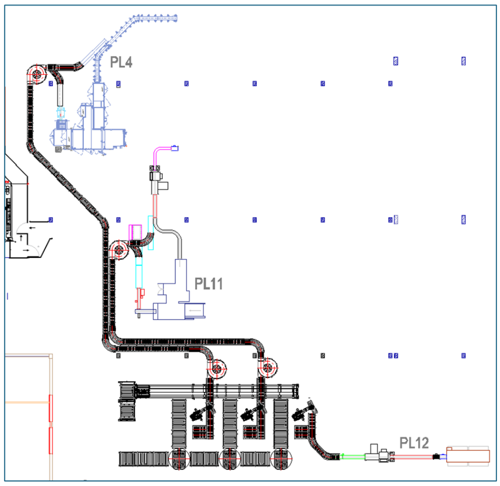


Fig. 11. Automated palletizing system employing three robots

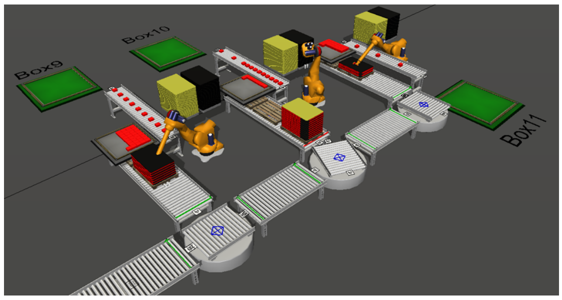


Fig. 12. The third investment solution

To enable a structured comparison of the proposed investment scenarios, a set of dynamic process parameters was defined at the beginning of the simulation study. These parameters served as assessment measures for evaluating each variant's performance. The selected measures reflect the operational efficiency and system behavior under different automation configurations and include:

- Robot workload [%] – indicating the utilization level of robotic resources,
- Average number of unit packages in buffer [units],
- Number of individual units remaining in the buffer after an 8-hour shift [units] – measuring backlog and flow constraints,
- Number of finished pallets per hour [pallets/h] – representing system throughput.

The same assessment measures were applied consistently across all four simulated solutions to ensure comparability. Each solution was evaluated using these criteria to provide a clear basis for comparison and decision-making.

The following statistics pertain to the operational schedule of robotic systems engaged in the most time-consuming configuration of palletized unit loads. The dynamic process parameters resulting from the simulation are presented in Fig. 13 to 16.

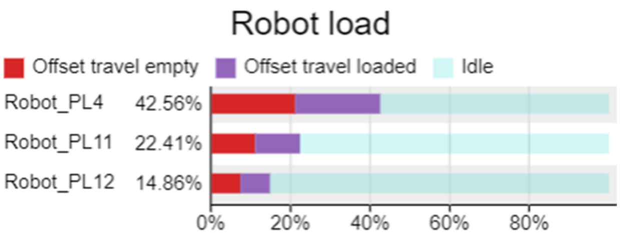


Fig. 13. Dynamic process parameters of the third proposed solution – robot load

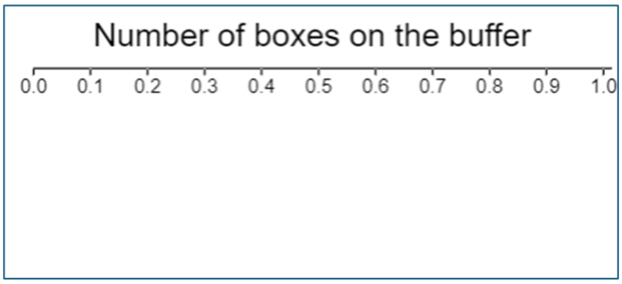


Fig. 14. Dynamic process of the third proposed solution – number of individual units in the buffer after an 8-hour shift – outstanding orders

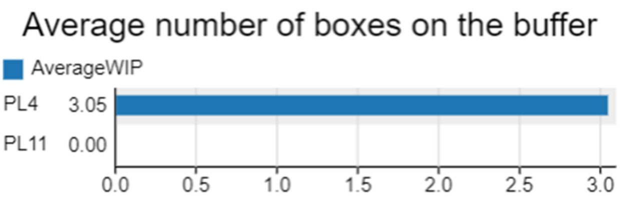


Fig. 15. Dynamic process parameters of the third proposed solution – average number of unit packages per buffer

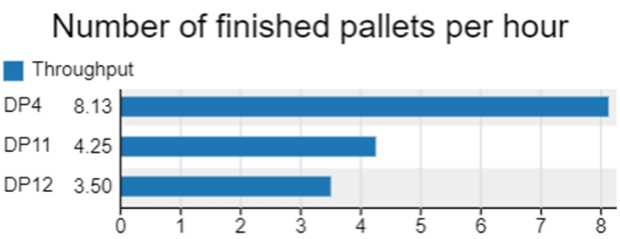


Fig. 16. Dynamic process parameters of the third proposed solution – number of finished pallets per hour

Analysis of the idle time percentage of palletizing robots reveals underutilization, indicating potential for increased throughput of the entire system in future iterations. This scenario exhibits perfect synchronization between the inflow of bulk packages from packing machines and their retrieval by palletizing robots stationed in robotic cells. No product buffering is implemented.

**The fourth proposed solution – simulating a fully automated pallet load preparation process with two robots**

In light of the preceding, a simulation of the palletizing process was undertaken using two robots (Fig. 17). The statistical results of this solution, including the key dynamic process parameters, are shown in Fig. 18 to 21.

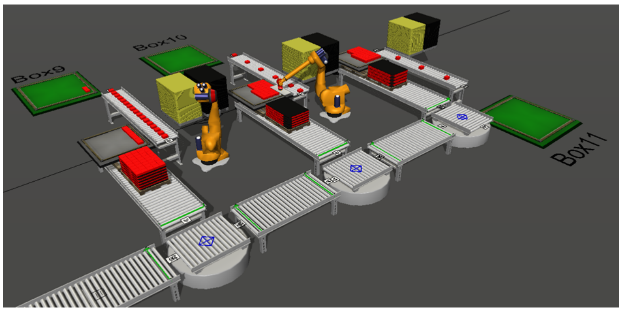


Fig. 17. The fourth investment solution

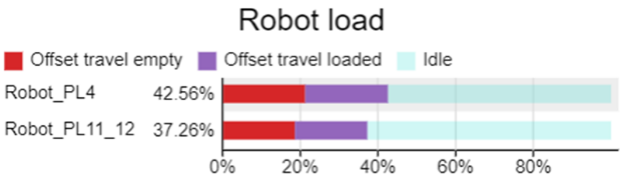


Fig. 18. Dynamic process parameters of the fourth proposed solution – robot load

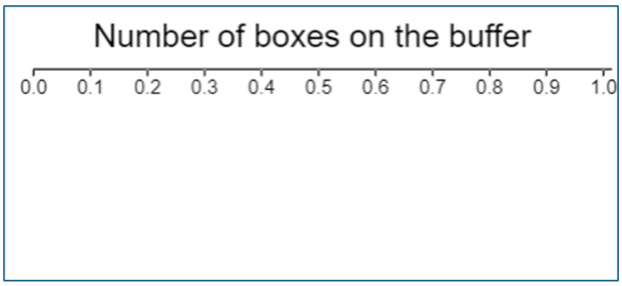


Fig. 19. Dynamic process parameters of the fourth proposed solution – number of individual units in the buffer after an 8-hour shift – outstanding orders

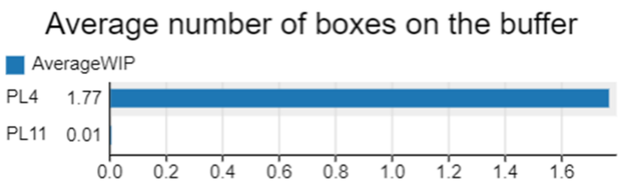


Fig. 20. Dynamic process parameters of the fourth proposed solution – average number of unit packages per buffer

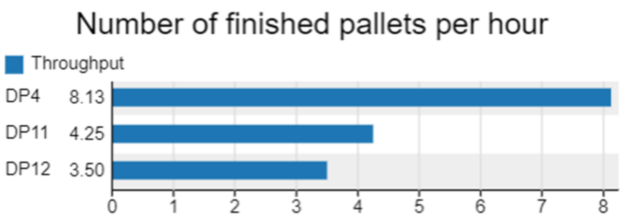


Fig. 21. Dynamic process parameters of the fourth proposed solution – number of finished pallets per hour

In this configuration, the idle time percentage of the palletizing robots is lower than in the three-robot variant but remains at a safe level, ensuring uninterrupted flow. Full synchronization is observed between the inflow of bulk packages from the packaging machines and their retrieval by the palletizing robots located in the robotic cells. No product buffering is required. In conclusion, the designed solution does not reduce the throughput of the existing production system. Moreover, the possibility of increasing the overall system throughput in the future is retained, albeit at a level lower than in the variant with 3 palletizing robots.

### The fifth proposed solution – simulating automated palletizing with one robot - robot stopping in front of each pallet-forming area

The latest variant analyzed involved a single robot with a seventh linear axis (Fig. 22). This was the only configuration capable of servicing three pick points using a single robot. The robot's tasks included linear movement and stopping at each pick point to retrieve a product layer and deposit it onto the appropriate pallet. However, this variant was only feasible under very specific assumptions. The statistics presented below, illustrated in Fig. 23 to 26, refer to a robot work schedule that excludes the most time-consuming configuration of forming pallet unit loads. Given the system's limitations, a bottleneck work schedule must be developed to ensure a continuous flow through the bottleneck and maximize its utilization. The initial robot movement program stipulated that the robot would come to a complete stop prior to each pallet formation area.

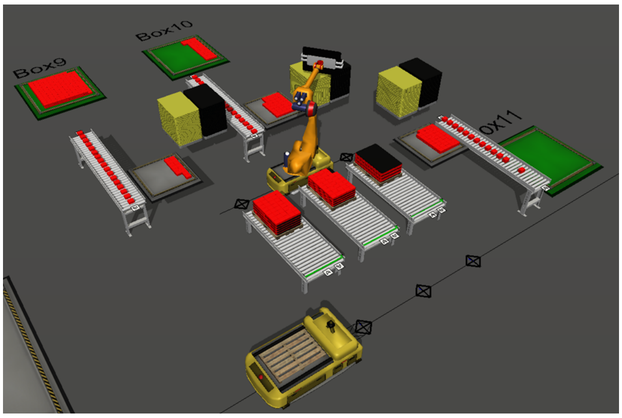


Fig. 22. The fifth investment solution

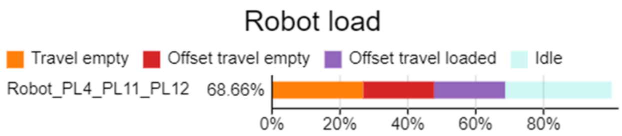


Fig. 23. Dynamic process of the fifth proposed solution – robot load

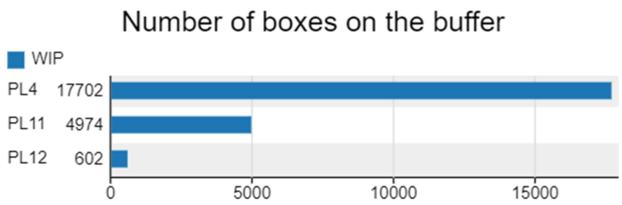


Fig. 24. Dynamic process parameters of the fifth proposed solution – number of individual units in the buffer after an 8-hour shift – outstanding orders

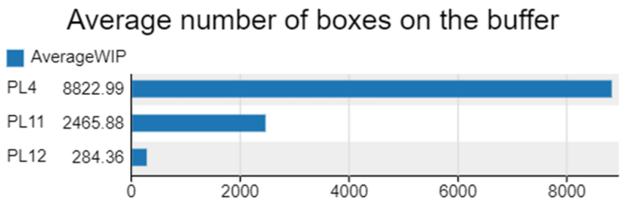


Fig. 25. Dynamic process parameters of the fifth proposed solution – average number of unit packages per buffer

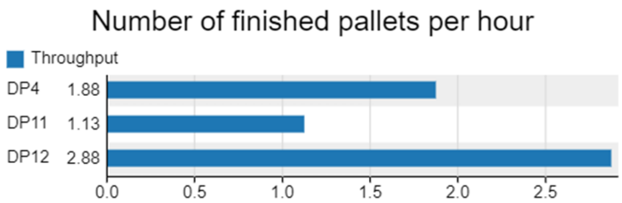


Fig. 26. Dynamic process parameters of the fifth proposed solution – number of finished pallets per hour

### The sixth proposed solution imulating automated palletizing with one robot – robot stopping between the first and second, and the second and third pallet formation areas

To elevate the bottleneck, the robot's linear movement was modified. Two extreme robot positions were identified, located between the first and second, and the second and third pallet formation areas (Fig. 27). This reduced the robot's travel time between drop-off points, increasing overall process efficiency, as shown in Fig. 28 to 31.

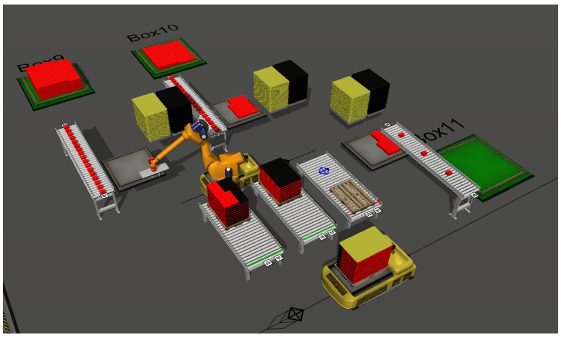


Fig. 27. The sixth investment solution

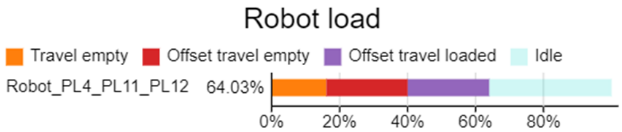


Fig. 28. Dynamic process parameters of the sixth proposed solution – robot load

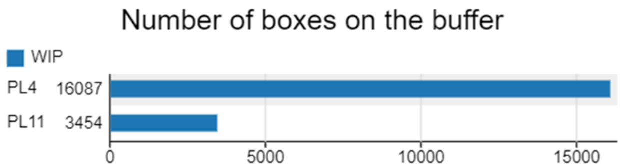


Fig. 29. Dynamic process parameters of the sixth proposed solution – number of individual units in the buffer after an 8-hour shift – outstanding orders

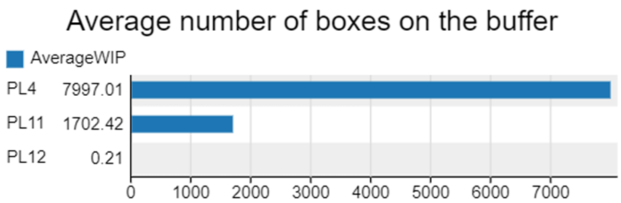


Fig. 30. Dynamic process parameters of the sixth proposed solution – average number of unit packages per buffer

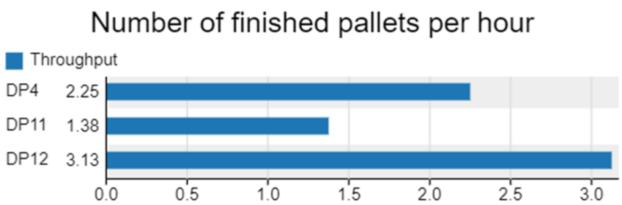


Fig. 31. Dynamic process parameters of the sixth proposed solution – number of finished pallets per hour

## Discussion

The decision to develop a solution using the simulation software FlexSim was motivated by the categories of benefits expected to support various stages of the business project implementation, including the feasibility stage, cost avoidance, detailed design, and the verification of current processes and operations (Beaverstock et al., 2017).

Business process simulation studies can effectively solve problems and support investment decisions (Gołda et al., 2018). Depending on the specific task, such as production simulation, production process optimization, or solving economic problems, models of varying accuracy are required (Eberle, 2020; Lidberg et al., 2020).

The solution presented to the investor was aimed at creating a continuous process flow without downtime, disruptions, or bottlenecks, while simultaneously reducing losses, balancing workstation loads, minimizing process irregularities, and shortening the processing time of customer orders.

Given the above assumptions, it was necessary to take a holistic look at the entire system and create scenarios of events and relationships that could occur in the analyzed system. The system should not be viewed as a collection of independent subsystems, but rather as a unified whole (Goldratt & Cox, 2016). A holistic approach allows for a comprehensive understanding of how related elements contribute to determining the strength of the entire chain (Hamrol et al., 2015). The ultimate goal of every organization is to achieve success. However, in any business, constraints can prevent the system from reaching its full potential. These constraints act as bottlenecks, limiting system throughput. The Theory of Constraints (TOC) recognizes the interconnectedness of various elements in a system, similar to the chain network theory (Moore & Scheinkopf, 1998), where the strength of the entire network is determined by the weakest link (Hamrol et al., 2015). TOC focuses on identifying and managing these constraints, ensuring that the flow of materials, products, information and human resources is consistent with the capabilities of the system. This approach allows organizations to maximize their effectiveness, ultimately paving the way to lasting success.

## Conclusions

Based on the analysis of the simulated automated pallet load preparation processes, several key conclusions can be drawn:

Reducing the number of palletizing robots to two presents a viable strategy for optimizing resource utilization without negatively impacting throughput. This two-robot configuration results in a lower percentage of idle time compared to the three-robot setup, while still ensuring a continuous flow of goods. Importantly, this approach maintains the current production system's throughput and preserves the potential for future capacity expansion.

Achieving full synchronization between the packaging and palletizing stages eliminates the need for product buffering, streamlining the overall process and potentially reducing space requirements. This synchronization is consistently highlighted across the proposed solutions.

Implementing a single robot equipped with a linear axis to service multiple pick points presents a technically feasible solution under specific operational assumptions. However, the initial single-robot configuration might face limitations in broader applicability.

Modifying the linear movement of a single robot to strategically position it between pallet formation areas can significantly improve efficiency by reducing travel time between pick-up and drop-off points. This optimization demonstrates the potential for enhancing the performance of a single-robot system.

The proposed automated solutions, particularly the two-robot system and the optimized single-robot system, not only maintain the existing production system's throughput but also offer the potential for future increases in overall system efficiency. This suggests that automation can be implemented without hindering current production levels while paving the way for future scalability.

The findings of this study are specific to the analyzed production setup, product types, and time parameters. Consequently, the results may not be directly applicable to other production environments without further validation. Moreover, the simulation assumes ideal, uninterrupted process execution, which does not fully capture the variability and complexity of real-world operations. This includes the assumption of perfect synchronization between robotic movements and pallet-forming activities, which in practice may be affected by minor delays, queuing, or system lag. The model also relies on fixed transport paths and a static layout, excluding potential layout reconfigurations or temporary blockages. Additionally, the simulation does not consider random disruptions such as equipment failures, maintenance downtime, or fluctuations in supply delivery. Finally, while performance metrics are analyzed, the model does not incorporate economic evaluations such as cost-efficiency, investment return, or trade-offs between automation levels and operational flexibility.

To further enhance the system, future work might examine the use of adaptive scheduling methods and machine learning to intelligently adjust robot movements and resource distribution as production data changes in real time.

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