Proceedings in Manufacturing Systems
Proceedings in Manufacturing Systems, Volume 20, Issue 1, 2025, pp. 133-144 ISSN 2067-9238

OPTIMISING MATERIAL FLOW THROUGH VIRTUAL PROTOTYPING: A DISCRETE-EVENT SIMULATION APPROACH

Andrei Daniel SCARLAT[1,*], Lidia Florentina PARPALA[2], Cicerone Laurentiu POPA[3], Radu Constantin PARPALA[3], Costel Emil COTET[4]

1) PhD Student, Robots and Manufacturing Systems Dep., National University of Science and Technology POLITEHNICA Bucharest, Romania
2) Lecturer, PhD, Robots and Production Systems Dep., National University of Science and Technology POLITEHNICA Bucharest, Romania
3) Assoc. Prof., PhD, Robots and Production Systems Dep., National University of Science and Technology POLITEHNICA Bucharest, Romania
4) Prof., PhD, Robots and Production Systems Dep., National University of Science and Technology POLITEHNICA Bucharest, Romania

Abstract: *The escalating demand for enhanced process efficiency and production adaptability in the manufacturing sector has catalysed the adoption of virtual prototyping and discrete-event simulation (DES) for optimising material flow prior to physical implementation. This paper delineates a simulation-centric methodology developed to analyse and improve the architecture of a beverage packaging line. The constructed virtual prototype accurately mirrors the entire production system, encompassing depalletising, filling, packaging, palletising, and wrapping, thereby serving as a digital testbed for evaluating various optimisation scenarios. A series of experiments was conducted to diagnose and investigate various optimisation scenarios based on cycle-time reduction, buffer expansion, and parallel machine configurations on overall system throughput. Findings reveal that a moderate enhancement at the bottleneck station—specifically, a 10% reduction in Modulfiller cycle time—resulted in a 7% increase in output. Conversely, excessive local acceleration or attempts to speed up downstream processes led to diminishing returns. These results underscore the efficacy of DES-based virtual prototyping in facilitating low-risk evaluations of process improvement strategies and establishing a robust framework for future Digital Twin integration.*

Key words: *Discrete-event simulation, Virtual prototyping, Material flow optimization, Bottleneck analysis, Witness Horizon, Smart manufacturing.*

1. INTRODUCTION

The increasing complexity of modern manufacturing systems, driven by globalization and the demand for higher product variability, has encouraged industries to adopt digital technologies for process analysis and optimization. Within the context of Industry 4.0, tools such as virtual prototyping, digital twins, and simulation based optimization enable companies to evaluate process performance, identify inefficiencies, and test improvements in a virtual environment before physical implementation. These digital technologies contribute to enhanced flexibility, reduced operational costs, and improved decision-making throughout the product lifecycle [1–3].

Among these, Discrete-Event Simulation (DES) has emerged as one of the most effective tools for modeling and optimizing manufacturing systems [4,5]. DES allows for the detailed representation of complex processes involving sequential, stochastic, and resource-dependent activities. Through DES, engineers can analyze material flow, machine utilization, waiting times, and bottleneck interactions, thereby supporting the design of more efficient production layouts [6]. In recent years, DES has been successfully applied across a wide range of industrial contexts, including assembly systems, food and beverage production, and logistics operations [7–9].

However, despite its widespread adoption, many studies in the literature remain limited to theoretical models or simplified case studies that do not fully integrate human–machine interactions, resource synchronization, and buffer dynamics [10, 11]. Moreover, few research efforts explicitly combine virtual prototyping – a digital representation of the physical system – with scenario-based simulation experiments that quantify the effect of process modifications on system performance. This gap highlights the need for integrated virtual models that can serve both as analytical tools and as precursors to Digital Twin implementations [12].

In this study, a virtual prototype of a beverage packaging line was developed using Witness Horizon, a professional DES platform, to investigate and optimize the material flow between interdependent production stations. The proposed model replicates the real structure of an industrial filling and packaging system, including depalletizing, filling, capping, packing, palletizing, and wrapping operations. The simulation experiments were

---

[*] Corresponding author: Splaiul Independenței 313, Sector 6, Bucharest, Romania,
Tel.: 0040 402 9420,
E-mail address: *scarlat.andrei.upb@gmail.com* (A.D. Scarlat)

designed to test six scenarios addressing cycle-time reduction, buffer expansion, and process parallelization.

The main objectives are:

- to identify the main bottlenecks within the production flow;
- to evaluate the quantitative impact of local improvements on global system performance; and
- to propose an optimization strategy based on simulation-driven decision-making.

The results demonstrate that moderate improvements at the bottleneck station lead to the most significant performance gains, whereas excessive or unbalanced parameter changes may shift the constraint downstream, generating new inefficiencies. The study contributes to current research by providing an empirical, data-driven framework for virtual prototyping and by demonstrating how discrete-event simulation supports evidence-based optimization in smart manufacturing environments.

2. MATERIALS AND METHODS

Digital transformation in manufacturing has accelerated the adoption of virtual prototyping and discrete-event simulation (DES) to evaluate and optimize production systems before physical implementation. Immersive visualization technologies have demonstrated added value in supporting engineering decisions by improving system understanding, collaboration, and validation accuracy. Oyekan et al. integrated a low-cost VR headset with WITNESS to create an “immersive digital factory,” showing that VR enhanced communication between design and planning teams and reduced design iteration time by enabling early identification of spatial conflicts and material-handling inefficiencies. Their experiment demonstrated that multi-disciplinary users could identify layout errors and routing conflicts up to 40% faster in immersive mode compared to traditional 2D simulation views, supporting the conclusion that VR-enhanced DES accelerates decision cycles and reduces rework risk [13].

Beyond visualization, recent research highlights the efficiency of aggregated simulation models for value-stream-level decision-making. Lidberg et al. applied DES combined with multi-objective optimization and machine learning to a full industrial factory, achieving improvements of −31% in inventory levels, −67% reduction in average lead time, and −50% reduction in batch size, while maintaining throughput performance [17].

These results illustrate that aggregated DES, when paired with systematic optimization, can meaningfully transform flow performance and enable data-driven re-engineering strategies. Importantly, the authors used clustering and decision tree techniques to extract interpretable scheduling rules from Pareto-optimal solutions, demonstrating how simulation can serve not only as an evaluation tool, but also as a decision-support engine for policy extraction in complex systems.

Complementing empirical work, Pedrielli et al. introduced the Discrete Event Optimization (DEO) framework, formally embedding DES logic into mathematical programming structures for production control problems [15].

Their experiments on buffer allocation and resource sharing highlighted the potential of hybrid DES-optimization models to achieve high-quality solutions in production scheduling while preserving system stochasticity. Although their work focuses on methodological rigor rather than industrial deployment, it reinforces the importance of structured decision models in simulation-based optimization workflows for manufacturing systems.

In practice-oriented environments, WITNESS has proven effective for the optimization of complex processing chains. Knapčíková et al. simulated a recycling line consisting of multiple processing and inspection stages, using DES to identify bottlenecks, evaluate buffer size policies and resource distributions, and propose system reconfiguration strategies [14].

Their results showed reduced waiting times and improved resource utilization after model-based re-balancing, validating the practical usefulness of DES for industrial system improvement, even in non-traditional manufacturing domains.

Finally, Turner et al. reviewed the role of virtual prototyping and VR-integrated simulation in cyber-physical manufacturing systems, emphasizing the emerging convergence of virtual design, simulation, and real-time data integration [16].

The authors note that although VR significantly enhances human-in-the-loop decision-making and training, widespread adoption is limited by technical barriers such as rendering latency, device ergonomics, and the absence of standardized integration frameworks between VR environments and DES platforms.

Taken together, these studies validate the strategic role of immersive and simulation-driven approaches in the design and optimization of production systems. They demonstrate significant quantitative benefits – lead time reductions up to 67%, batch size reductions up to 50%, and accelerated identification of design issues – while also highlighting the need for structured, scalable, and reproducible workflows that integrate virtual prototyping and DES for industrial material-flow improvement.

Although literature consistently reports substantial improvements in flow performance using DES and virtual prototyping, several limitations persist. First, studies tend to focus on either immersive design validation (VR + WITNESS) or optimization of factory-level flow (multi-objective DES), but none integrate both into a unified, evidence-driven workflow applicable to operational decision-making. Second, despite performance gains reported (e.g., −67% lead time, −50% batch size), few works investigate the relative contribution of layout redesign versus operational policy adjustments (buffer sizing, dispatching rules, batching strategies). Third, although VR has shown the ability to reduce error identification time by ~40%, the literature lacks quantitative frameworks for measuring VR’s effect on decision quality, engineering time savings, and stakeholder confidence. Finally, there is limited guidance on how immersive prototyping and DES can serve as a stepping-stone toward data-driven digital twins with continuous validation and feedback loops.

This study addresses these gaps by developing an integrated virtual-prototyping and DES framework in

WITNESS, supported by systematic model validation, multi-scenario experimentation, and quantification of both layout- and policy-driven improvements in material-flow performance.

3. METHODOLOGY

The research methodology followed a structured five-step approach, combining process observation, data collection, virtual prototyping, and discrete-event simulation (DES) analysis.

The methodology followed in this study is described below.

1. *System Analysis and Data Collection*
   The first stage consisted of observing the physical production process to identify the key operational stages, entity types, and resource interactions. Technical parameters such as machine nominal speeds, cycle times, and conveyor capacities were collected directly from the production line documentation and verified through on-site measurements. These data formed the quantitative basis for the simulation model.
2. *Conceptual Model Development*
   Based on the collected data, a conceptual model of the beverage packaging line was created, defining the material flow, process logic, and control rules between stations. The system included five main machines – Depalletizer, Modulfiller, Case Packer, Palletizer, and Wrapper – linked by three conveyors and supported by four buffers (for cans, caps, pallets, and layer pads). Human operators were integrated into the model as active resources associated with specific equipment groups.
3. *Discrete-Event Simulation and Model Implementation*
   The conceptual model was translated into a digital environment using Witness Horizon software. The simulation included predefined rules for entity flow, buffer management, and machine states (Busy, Idle, Blocked, Starved). Each machine's operating parameters – Cycle Time (CT), Cycles per Minute (CPM), and Nominal Speed – were implemented using the relations

   $$\mathrm{CPM} = \frac{\text{Nominal Speed}}{60} \quad \text{and} \quad \mathrm{CT} = \frac{3600}{\text{Nominal Speed}}. \quad (1, 2)$$

   The model was validated by comparing baseline simulation results with actual production rates observed in the factory.
4. *Scenario Design and Experimentation*
   After model validation, six simulation scenarios were designed to test the influence of process modifications on throughput and resource utilization. The scenarios included baseline replication, Modulfiller cycle-time reductions (–10% and –20%), dual Modulfiller configuration, increased buffer capacity (+50 cans), and a 30% reduction of the Case Packer cycle time. Each scenario was run for identical time horizons and evaluated using standardized Key Performance Indicators (KPIs), such as total output, resource utilization, idle and blocked time, and work-in-progress (WIP) levels.
5. *Result Analysis and Optimization Strategy*
   Simulation outputs were analyzed both quantitatively and qualitatively to identify the main bottlenecks and flow inefficiencies. Comparative evaluation across scenarios was performed to determine which modification produced the highest throughput with minimal side effects on flow balance. The findings were then synthesized into a structured optimization strategy for improving line performance under realistic industrial constraints.

4. CASE STUDY

The production line considered in this study is composed of several interacting subsystems that ensure the continuous transformation of raw cans into fully palletised finished goods. The proposed study focuses on the simulation and optimization of a beverage packaging line modeled through WITNESS Horizon. The production system follows a linear configuration that connects five main operational stations—Depalletizer, Modulfiller, Case Packer (Variopac), Palletizer, and Wrapper (Foil Winder)—through three conveyor systems (C1–C3). This configuration replicates a real industrial filling and packaging process, in which empty cans are depalletized, filled, sealed, grouped into cases, stacked on pallets, and finally wrapped for shipment.

The system includes four types of circulating entities: cans, caps, pallets, and layer pads. These entities are introduced into the system according to predefined feeding rules. The Depalletizer receives empty cans pushed from the *Buffer_Cans* every 30 minutes, while caps are introduced into the *Buffer_Caps* following the same arrival frequency. Similarly, pallets and layer pads are supplied to their respective magazines (*Buffer_pallets* and *Buffer_layer_pads*) at regular 30-minute intervals. All entities were modeled as *active*, initiating downstream processes and ensuring continuous flow through the system.

Material handling is performed through three conveyor segments with differentiated operational speeds and control logics. Conveyor C1 connects the Depalletizer to the Modulfiller, operating at a nominal speed of 10 m/s with both *input* and *output* conditions set to *wait*, maintaining synchronization between the two stations. Conveyor C2, linking the Modulfiller and Case Packer, operates at 15 m/s and follows a *push-to* output rule to sustain a consistent feeding rhythm. Conveyor C3, which transfers packed cases to the Palletizer, moves at 20 m/s, configured in *wait–wait* mode to prevent bottlenecks at the end of the line.

From an operational perspective, the process is supervised by a line supervisor responsible for the Depalletizer and Modulfiller, an operator at the Case Packer station, and another operator overseeing the Palletizer and Wrapper units. The synchronization of human resources and machine operation reflects typical real-world coordination patterns in automated packaging lines.

The nominal operating parameters of each machine are summarized in Table 1, which includes the nominal speed (units/hour), the corresponding cycles per minute (CPM), and the calculated cycle time (CT) per unit according to the relations:

$$CPM = \frac{\textbf{Nominal Speed}}{60}, \qquad (3)$$

$$CT = \frac{3600}{\textbf{Nominal Speed}} \qquad (4)$$

Using these expressions, Table 1 summarizes the nominal speed of each station together with the computed CPM and CT values, which served as baseline parameters for the Witness simulation model.

Table 1

Machine Technical Specifications and Nominal Operating Rates

Equipment Name	Nominal Speed	CPM (units/min)	Cycle Time (s/unit)
Depalletizer	10800	180	0.33
Modulfill	7200	120	0.5
Case Packer	8000	133.33	0.45
Palletizer	8500	141.66	0.42
Wrapper	8500	141.66	0.42

After collecting all relevant technical and operational data, a discrete-event simulation (DES) model of the production flow was developed in WITNESS Horizon. The objective of this model was to reproduce the dynamic behavior of the real packaging line and to evaluate its performance under different operating conditions. The simulation was structured as a virtual prototype of the system, replicating the physical layout, processing logic, and resource interactions observed on the shop floor.

The model (Fig. 1) includes all processing stations, conveyors, buffers, and control rules described previously, thus providing a comprehensive digital representation of the line. Through this virtual environment, various scenarios can be tested safely and efficiently, allowing the identification of bottlenecks, performance losses, and potential optimization strategies before implementation in the real system.

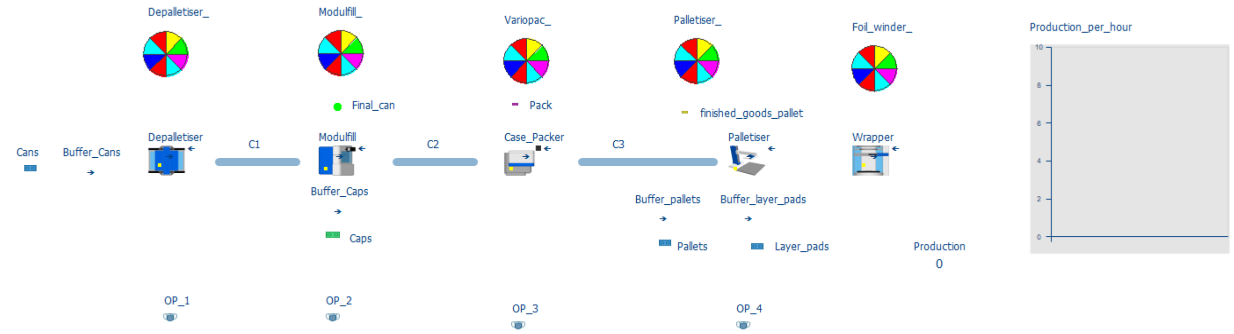


Fig. 1. The process flow chart.

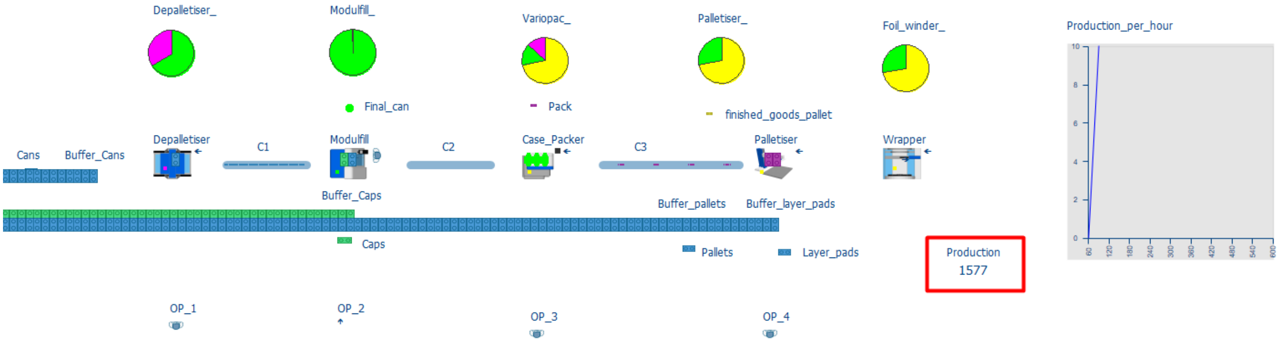
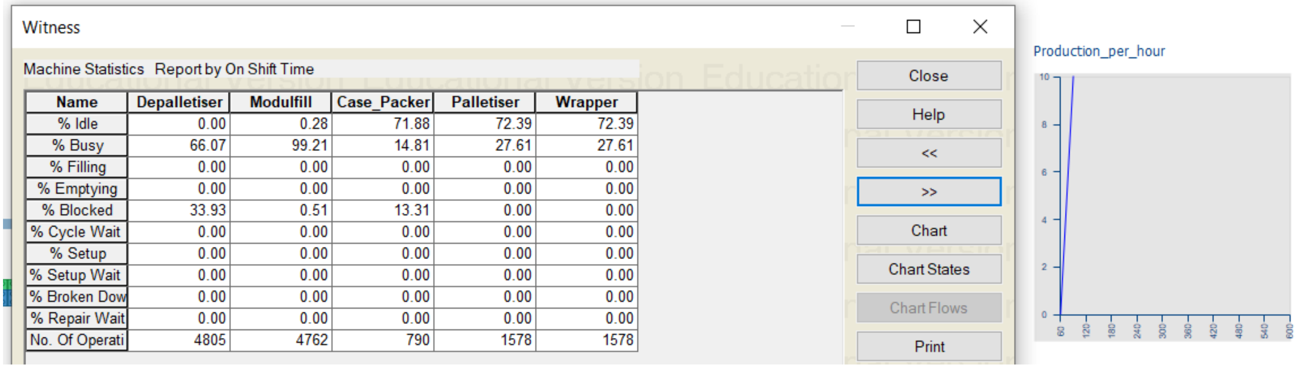


Fig. 2. Baseline (As-Is) Simulation Results for the Production Line.



Machine Statistics Report by On Shift Time

Name	Depalletiser	Modulfill	Case_Packer	Palletiser	Wrapper
% Idle	0.00	0.28	71.88	72.39	72.39
% Busy	66.07	99.21	14.81	27.61	27.61
% Filling	0.00	0.00	0.00	0.00	0.00
% Emptying	0.00	0.00	0.00	0.00	0.00
% Blocked	33.93	0.51	13.31	0.00	0.00
% Cycle Wait	0.00	0.00	0.00	0.00	0.00
% Setup	0.00	0.00	0.00	0.00	0.00
% Setup Wait	0.00	0.00	0.00	0.00	0.00
% Broken Dow	0.00	0.00	0.00	0.00	0.00
% Repair Wait	0.00	0.00	0.00	0.00	0.00
No. Of Operati	4805	4762	790	1578	1578

Fig. 3. Detailed Representation of the Process Flow Model Implemented in Witness Horizon.

Following the development of the virtual model, the As-Is simulation was executed to evaluate the baseline performance of the beverage packaging lineas as illustrated in Fig. 2. The simulation results, illustrated in Fig. 3, show the operational dynamics of each station, the utilization distribution, and the system throughput expressed as units produced per hour.

The Depalletizer exhibited an average utilization of 66.07%, indicating that its feeding rhythm is generally synchronized with the downstream process. The Modulfiller, representing the critical processing unit, operated at 99.21% utilization, confirming that it functions near its maximum capacity and constitutes the primary bottleneck of the production line. Downstream stations – namely the Case Packer, Palletizer, and Wrapper – recorded considerably lower activity levels, with busy times of 14.81%, 27.61%, and 27.61%, respectively. The high idle percentages (above 70%) observed for these units suggest that they are frequently waiting for input from the upstream Modulfiller, which limits their effective operation and overall line throughput.

In addition, the Depalletizer experienced 33.93% blocking time, caused by downstream buffers reaching capacity when the Modulfiller temporarily stops processing. This phenomenon demonstrates that the material flow is unbalanced: the upstream supply of cans exceeds the filling station's processing capability. The imbalance propagates through the line, generating underutilization of the packaging and palletizing units, and confirming the presence of starvation–blocking interactions typical for uncoordinated continuous production systems.

The throughput indicator (Production_per_hour chart) stabilizes around 9–10 finished units per hour, resulting in a total output of approximately 1577 units over the simulated horizon. This value provides the baseline against which future optimization scenarios will be compared. The steady but low production rate indicates that the system operates reliably yet far from its potential capacity, primarily constrained by the Modulfiller's limited processing rate and by the absence of adaptive synchronization between machines.

Overall, the initial simulation highlights three major findings:

1. The Modulfiller acts as the bottleneck, operating near 100% utilization.
2. Downstream stations (Case Packer, Palletizer, Wrapper) are underutilized due to supply starvation.
3. Buffer management and material release timing require adjustment to reduce blocking upstream and idle time downstream.

These results confirm that the As-Is model accurately reproduces real-world operational inefficiencies and provides a valid foundation for subsequent optimization scenarios, where conveyor speeds, buffer sizes, and control rules will be systematically varied to enhance throughput and balance machine utilization.

Based on the results obtained from the baseline (As-Is) simulation, several optimization scenarios were defined to evaluate the potential improvement of the line's performance through modifications in processing times and buffer capacities. The main objective of this phase is to increase the overall throughput and balance the utilization of equipment, while avoiding excessive work-in-progress (WIP) accumulation and blocking phenomena between stations.

The scenario design followed a stepwise logic, starting with local performance enhancements at the bottleneck station (Modulfiller) and progressively extending to structural adjustments of the production line. Each scenario was executed under identical simulation conditions – shift duration, entity arrival times, and control logic – to ensure comparability of the key performance indicators (KPIs).

The set of tested scenarios is summarized as follows:

Scenario 0 – Baseline (As-Is reference):

The current configuration of the production line serves as the control case, maintaining the nominal cycle times and buffer capacities. The results of this scenario represent the benchmark for all subsequent evaluations.

Scenario 1 – CT_Modulfiller –10%:

The cycle time of the Modulfiller is reduced by 10% to test the sensitivity of the system to moderate improvements in the bottleneck station. All other parameters remain unchanged.

Scenario 2 – CT_Modulfiller –20%:

The Modulfiller's cycle time is further reduced by 20% relative to the baseline, allowing for the assessment of nonlinear effects on throughput and potential propagation of starvation to downstream stations.

Scenario 3 – Parallel Modulfiller units (x2 configuration):

A duplicate Modulfiller unit is added in parallel, while maintaining identical operational logic and upstream feeding parameters. This configuration aims to evaluate the impact of process parallelization on overall production efficiency and downstream balance.

Scenario 4 – Increased Buffer Capacity (Buffer_Cans +50 units):

The buffer capacity between the Depalletizer and Modulfiller is increased by 50 units compared to the baseline. This test examines whether additional storage mitigates upstream blocking and stabilizes material flow.

Scenario 5 – CT_CasePacker –30% (conditional scenario):

This scenario is executed only if the previous tests indicate a shift of the bottleneck from the Modulfiller to the Case Packer. The cycle time of the Case Packer is reduced by 30% to restore system balance and ensure continuous downstream flow.

All scenarios are designed to preserve the same resource availability, inter-arrival rules, and shift duration, isolating the effects of cycle time and buffer modifications on the overall system performance. The outputs compared across scenarios include Throughput (units/hour), Machine Utilization (%), Average WIP, and Blocking/Idle time (%), which collectively describe the operational efficiency and stability of the production line.

In the baseline configuration, the cycle time (CT) of the Modulfiller was set to 0.5 seconds per unit, corresponding to a nominal speed of 120 units per minute.

For the optimization scenarios, the cycle time was adjusted according to the following relation:

$$CT_{new} = CT_{baseline}\ x\ \left(1 - \frac{\textbf{reduction percentage}}{\textbf{Nominal Speed}}\right). \quad (5)$$

Accordingly, in Scenario 1, a 10% reduction of the Modulfiller’s cycle time was applied, resulting in a new value of 0.45 s/unit (≈133.3 units/min) (Table 2).

In Scenario 2, the cycle time was reduced by 20%, yielding 0.40 s/unit (150 units/min).

These reductions simulate potential efficiency improvements in the filling process, such as increased automation speed or process tuning, and are intended to evaluate their effect on overall system throughput and resource utilization.

In Scenario 1, the cycle time of the Modulfiller was reduced by 10% (from 0.50 s/unit to 0.45 s/unit), while all other system parameters remained unchanged. The objective was to evaluate how a moderate performance improvement at the bottleneck station affects the overall line behavior.

The simulation results (Table 3) indicate a notable improvement in total output, with production increasing from 1577 units in the baseline to 1687 units, representing a 7% gain in throughput. The utilization of the Modulfiller slightly decreased from 99.21% to 95.56%, showing that the system became more stable and less saturated, as the faster processing rate reduced the accumulation of waiting time and blocking in the upstream Depalletizer.

Table 2

Modulfiller Cycle-Time Reduction Scenarios: Technical Parameters

Scenario	Cycle Time (s/unit)	Speed (units/min)	Change vs Baseline
Baseline	0.5	120	-
S1	0.45	133.3	–10%
S2	0.4	150	–20%

Table 3

Scenario 1 Results: Effect of Modulfiller CT –10% on System Performance

KPI	Baseline	Scenario 1	Change
Total Production (units)	1577	1687	+7%
Modulfiller Utilization	99.21%	95.56%	↓ slightly
Depalletizer Busy	66.07%	70.63%	↑
Case Packer Busy	14.81%	15.84%	↑
Case Packer Blocked	13.31% → 18.56%	↑	
Palletizer Busy	27.61%	29.54%	↑

Upstream, the Depalletizer recorded an increase in activity, with the busy percentage rising from 66.07% to 70.63%, and blocking slightly decreasing from 33.93% to 29.37%, indicating smoother feeding conditions and fewer buffer overloads. Downstream effects were also visible: both the Case Packer and Palletizer became more active, their busy percentages increasing from 14.81% and 27.61% to 15.84% and 29.54%, respectively. These changes confirm that the acceleration of the filling process allowed materials to flow more continuously through the system.

Nevertheless, the results also show that new signs of imbalance start to emerge. The Case Packer now registers a blocked percentage of 18.56%, suggesting that the modest speed increase at the Modulfiller begins to shift congestion downstream. The Palletizer and Wrapper still operate at around 29–30% utilization, meaning that the overall line is still limited by the filling stage and subsequent accumulation at the Case Packer.

In summary, Scenario 1 demonstrates that a 10% reduction in the Modulfiller cycle time yields a moderate improvement in throughput and flow stability, but does not eliminate the bottleneck entirely. The process remains constrained by downstream synchronization, particularly at the Case Packer, which begins to show blocking behavior as production flow increases.

A 10% reduction in Modulfiller cycle time improves line throughput by approximately 7%, but transfers the production constraint downstream, identifying the Case Packer as a potential secondary bottleneck to be addressed in subsequent scenarios (Fig. 4).

In Scenario 2, the cycle time of the Modulfiller was further reduced by 20% compared to the baseline configuration (from 0.50 s/unit to 0.40 s/unit), while all other parameters were maintained constant. This scenario aimed to assess whether a stronger acceleration of the bottleneck process could further enhance production performance and eliminate upstream blocking.

The results (Figs. 5 and 6, Table 4) show that the system achieved a total output of 1659 units, which represents a 5% increase compared to the baseline and a slight decrease compared to Scenario 1 (1687 units). This counterintuitive outcome indicates that while the Modulfiller’s capacity improved, the rest of the system was unable to absorb the higher production rate, leading to new downstream inefficiencies.

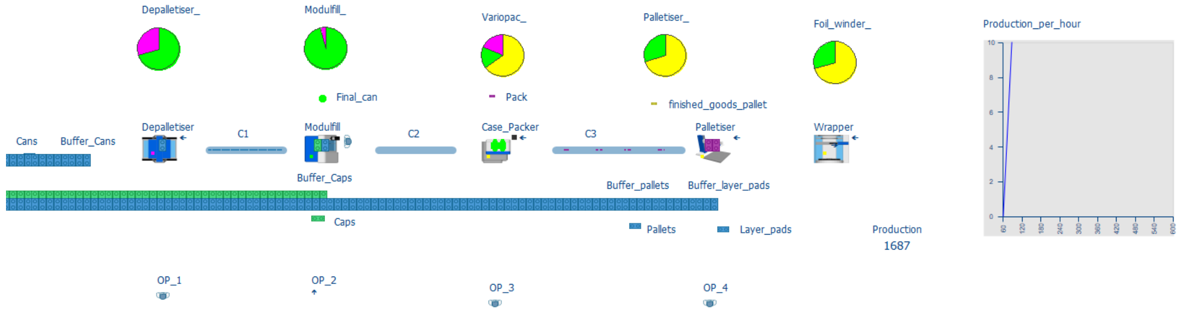


Fig. 4. Modulfiller Cycle-Time Reduction Scenarios (−10% and −20%) – Conceptual Overview.

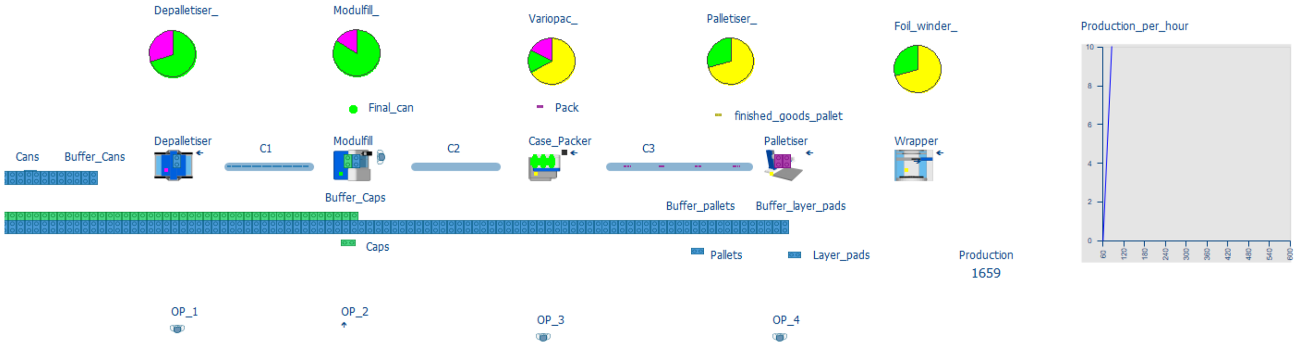
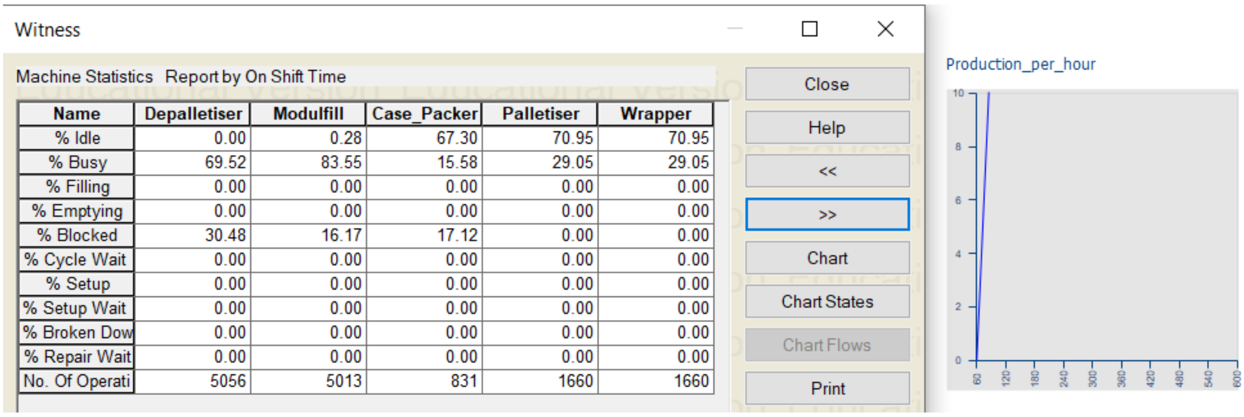


Fig. 5. Simulation Outputs for Scenario 2 (Modulfiller CT –20%).



Machine Statistics Report by On Shift Time

Name	Depalletiser	Modulfill	Case_Packer	Palletiser	Wrapper
% Idle	0.00	0.28	67.30	70.95	70.95
% Busy	69.52	83.55	15.58	29.05	29.05
% Filling	0.00	0.00	0.00	0.00	0.00
% Emptying	0.00	0.00	0.00	0.00	0.00
% Blocked	30.48	16.17	17.12	0.00	0.00
% Cycle Wait	0.00	0.00	0.00	0.00	0.00
% Setup	0.00	0.00	0.00	0.00	0.00
% Setup Wait	0.00	0.00	0.00	0.00	0.00
% Broken Dow	0.00	0.00	0.00	0.00	0.00
% Repair Wait	0.00	0.00	0.00	0.00	0.00
No. Of Operati	5056	5013	831	1660	1660

Fig. 6. System Behavior Under Modulfiller Cycle-Time Reduction – Comparative Visualization.

Table 4

Scenario 2 Results: Effect of Modulfiller CT –20% on System Performance

KPI	Baseline	Scenario 1	Scenario 2
Total Production (units)	1577	1687	1659
Modulfiller Utilization	99.21%	95.56%	93.57%
Depalletizer Busy	66.07%	70.63%	70.46%
Case Packer Busy	14.81%	15.84%	17.83%
Case Packer Blocked	13.31%	18.56%	23.71%
Palletizer Busy	27.61%	29.54%	29.54%

The Modulfiller operated at 93.57% utilization, a further reduction from Scenario 1, suggesting that although its internal process is faster, it now experiences waiting times due to downstream congestion. The Depalletizer remained highly active, with 70.46% busy time, but recorded a similar level of blocking (29.54%), showing that upstream conditions did not significantly improve beyond those observed in Scenario 1.

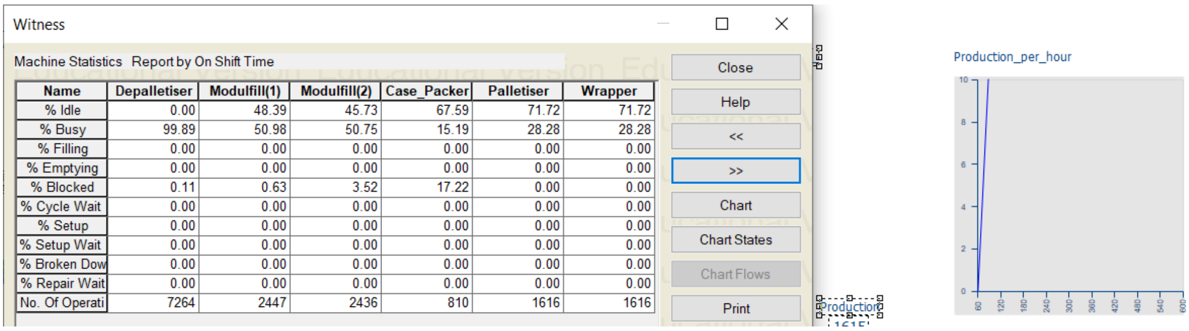
The most notable changes occurred in the downstream stations. The Case Packer again became the most constrained element, with busy time rising to 17.83% but blocking increasing sharply to 23.71%, confirming its role as the secondary bottleneck of the system. Both the Palletizer and Wrapper maintained activity levels around 29–30% utilization, with minimal gains compared to the previous scenario, indicating that throughput limitation persists upstream.

These results demonstrate that the 20% reduction in the Modulfiller cycle time did not translate into proportional improvements in system throughput. Instead, the excessive acceleration of the filling stage introduced flow imbalance, overloading the Case Packer and saturating its input buffer. Consequently, the production system exhibits the classical behavior of bottleneck shifting: once the primary constraint (Modulfiller) is partially relieved, the restriction moves downstream to the next processing station.

Reducing the Modulfiller's cycle time by 20% produced diminishing returns in throughput and caused congestion at the Case Packer. The results highlight the importance of system-wide balancing rather than isolated performance improvements, as bottleneck shifts can offset potential efficiency gains.

In Scenario 3, a second Modulfiller unit was added in parallel to the original filling station while keeping the same cycle time of 0.5 s/unit. The goal was to evaluate whether process parallelization could reduce the bottleneck effect identified in previous scenarios and increase the overall system throughput without altering the processing speed of individual machines.

The simulation results (Fig. 7, Table 5) show that, although the addition of a second Modulfiller successfully balanced the workload between the two filling stations—each operating at approximately 50 % utilization – the overall system throughput increased only marginally, reaching 1615 finished units, which is slightly above the baseline value (1577 units) but below



Machine Statistics Report by On Shift Time

Name	Depalletiser	Modulfill(1)	Modulfill(2)	Case_Packer	Palletiser	Wrapper
% Idle	0.00	48.39	45.73	67.59	71.72	71.72
% Busy	99.89	50.98	50.75	15.19	28.28	28.28
% Filling	0.00	0.00	0.00	0.00	0.00	0.00
% Emptying	0.00	0.00	0.00	0.00	0.00	0.00
% Blocked	0.11	0.63	3.52	17.22	0.00	0.00
% Cycle Wait	0.00	0.00	0.00	0.00	0.00	0.00
% Setup	0.00	0.00	0.00	0.00	0.00	0.00
% Setup Wait	0.00	0.00	0.00	0.00	0.00	0.00
% Broken Dow	0.00	0.00	0.00	0.00	0.00	0.00
% Repair Wait	0.00	0.00	0.00	0.00	0.00	0.00
No. Of Operati	7264	2447	2436	810	1616	1616

Fig. 7. Parallel Modulfiller Configuration (Scenario 3) – Flow Distribution Representation.

Table 5

Scenario 3 Results:
Dual Modulfiller Configuration Performance Indicators

KPI	Baseline	Scenario 1	Scenario 3
Total Production (units)	1577	1687	1615
Modulfiller Utilization	99.21%	95.56%	51 % (each)
Depalletizer Busy	66.07%	70.63%	99.89 %
Case Packer Busy	14.81%	15.84%	15.19 %
Case Packer Blocked	13.31%	18.56%	17.22 %
Palletizer Busy	27.61%	29.54%	28.28 %

the result obtained in Scenario 1 (1687 units). This indicates that simply duplicating the filling station did not proportionally enhance production efficiency.

The Depalletizer operated almost continuously, with 99.89 % busy time, confirming that the upstream feeding capacity was fully utilized to supply both fillers. However, the Case Packer remained the main downstream constraint, with only 15.19 % busy time and a blocking rate of 17.22 %, showing that the combined output from the two Modulfiller units could not be effectively processed further down the line. Consequently, the downstream flow (Palletizer and Wrapper, each ~28 % busy) did not benefit from the parallelization, as the Case Packer acted as a throughput limiter.

In terms of system dynamics, the introduction of two Modulfiller stations redistributed the internal workload but did not alleviate the global bottleneck. Instead, the restriction shifted entirely to the Case Packer, which lacks sufficient capacity to absorb the doubled filling rate. The presence of partial blocking (3–4 %) at the Modulfiller outputs also suggests intermittent congestion at the merging point of material flow.

While the duplication of the Modulfiller station reduced its individual utilization and eliminated the primary bottleneck, the expected throughput improvement was not achieved. The constraint migrated downstream to the Case Packer, which now governs line performance. These findings confirm that structural balancing across all stages is required—particularly an enhancement of the Case Packer capacity or control logic—to achieve significant productivity gains.

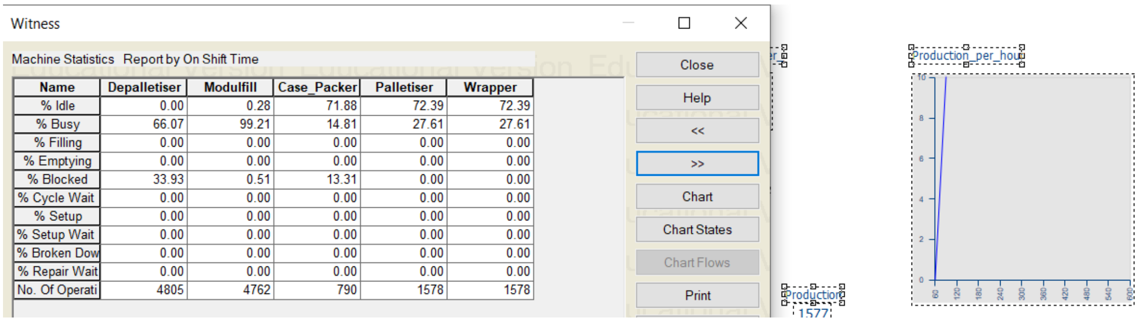
In Scenario 4, the production line maintained its original single Modulfiller configuration, while the buffer capacity between the Depalletizer and the Modulfiller was increased by 50 additional cans compared with the baseline model. The aim of this scenario was to assess the extent to which a larger intermediate buffer could reduce blocking at the Depalletizer and improve line stability.

The simulation results show that the overall system performance remained almost identical to the baseline, with total production reaching 1577 units, equal to the reference case. The Depalletizer remained active 66.07% of the time and blocked 33.93%, while the Modulfiller continued to operate at nearly full utilization (99.21%). Downstream stations – the Case Packer (14.81% busy), Palletizer (27.61%), and Wrapper (27.61%) – recorded the same performance levels as in the initial scenario.

This outcome indicates that increasing buffer capacity alone did not produce measurable improvements, as the bottleneck remains intrinsic to the Modulfiller's processing speed. Although a larger buffer theoretically enhances flow resilience, the filling stage continues to constrain the system throughput, limiting the Depalletizer's ability to offload cans faster. The unchanged blocking percentage at the Depalletizer confirms that the buffer does not accumulate additional material because the Modulfiller cannot process it more rapidly.

From a systemic perspective, Scenario 4 highlights that buffer expansion without addressing the process rate of the bottleneck has minimal impact on productivity (Fig. 8). The line remains stable but inefficiently synchronized, confirming that effective optimization must focus on cycle-time reduction or downstream capacity balancing rather than storage expansion.

The results (Table 6) confirm that increasing the upstream buffer capacity does not improve throughput when the bottleneck process remains unchanged. The Modulfiller continues to limit production performance, and further optimization should therefore target either cycle-time reduction or increased packing capacity to achieve meaningful gains.


Witness

Machine Statistics Report by On Shift Time

Name	Depalletiser	Modulfill	Case_Packer	Palletiser	Wrapper
% Idle	0.00	0.28	71.88	72.39	72.39
% Busy	66.07	99.21	14.81	27.61	27.61
% Filling	0.00	0.00	0.00	0.00	0.00
% Emptying	0.00	0.00	0.00	0.00	0.00
% Blocked	33.93	0.51	13.31	0.00	0.00
% Cycle Wait	0.00	0.00	0.00	0.00	0.00
% Setup	0.00	0.00	0.00	0.00	0.00
% Setup Wait	0.00	0.00	0.00	0.00	0.00
% Broken Dow	0.00	0.00	0.00	0.00	0.00
% Repair Wait	0.00	0.00	0.00	0.00	0.00
No. Of Operati	4805	4762	790	1578	1578

Fig. 8. Simulation Results for Increased Buffer Capacity Scenario (Scenario 4).

Table 6

Scenario 4 Results: Impact of Increased Buffer Capacity

KPI	Baseline	Scenario 4	Change
Total Production (units)	1577	1577	-
Modulfiller Utilization	99.21%	99.21%	-
Depalletizer Busy	66.07%	66.07%	-
Case Packer Busy	14.81%	14.81%	-
Palletizer Busy	27.61%	27.61%	-

Table 1

Machine Technical Specifications and Nominal Operating Rates

Parameter	Baseline	Scenario 5 (–30%)	Change
CT (s/unit)	0.45	0.315	–30 %
Speed (units/min)	133.33	190.48	+43 %

In Scenario 5 (Table 1), the cycle time of the Case Packer was reduced by 30 % (from 0.45 s/unit to 0.315 s/unit) to evaluate whether downstream acceleration could relieve the flow congestion previously observed when the filling station was improved.

The simulation results (Fig. 9, Table 7) indicate that total production remained practically unchanged, at 1576 units, identical to the baseline level (1577 units). The Case Packer, despite its enhanced speed, exhibited only 10.37 % busy time and 16.31 % blocked time, revealing that its activity is still limited by the upstream Modulfiller rather than by its own processing capacity. The Modulfiller maintained 99.17 % utilization, confirming that it remains the dominant bottleneck of the line.

Upstream, the Depalletizer showed 66.04 % busy time and 33.96 % blocked, values nearly identical to the baseline, while the Palletizer and Wrapper operated at about 27.6 % utilization, also without significant did not change. These results confirm that speeding up the Case Packer did not propagate improvements along the production line because the Modulfiller's processing rate still constrains the overall flow.

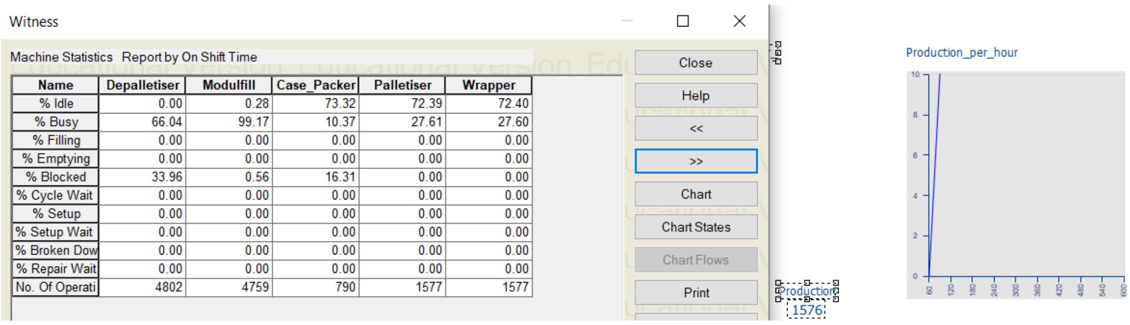
Table 7

Scenario 5 Results: Effect of Case Packer CT –30%

KPI	Baseline	Scenario 5
Total Production (units)	1577	1576
Modulfiller Utilization	99.21%	66.04%
Depalletizer Busy	66.07%	99.17%
Case Packer Busy	14.81%	10.37%
Case Packer Blocked	13.31%	16.31%
Palletizer Busy	27.61%	27.61%

From a system-level perspective, this experiment highlights that optimizing a non-bottleneck station yields negligible impact on throughput. The extra capacity added downstream remains under-utilized while upstream machines continue to dictate production rhythm. Therefore, performance improvements in this configuration must target the Modulfiller's cycle time or the coordination between filling and packing stages rather than isolated speed adjustments.

Reducing the Case Packer's cycle time by 30 % had no measurable effect on throughput, as the Modulfiller continues to govern the line's performance. This confirms the principle that downstream acceleration is ineffective unless the primary bottleneck is first relieved.


Witness

Machine Statistics Report by On Shift Time

Name	Depalletiser	Modulfill	Case_Packer	Palletiser	Wrapper
% Idle	0.00	0.28	73.32	72.39	72.40
% Busy	66.04	99.17	10.37	27.61	27.60
% Filling	0.00	0.00	0.00	0.00	0.00
% Emptying	0.00	0.00	0.00	0.00	0.00
% Blocked	33.96	0.56	16.31	0.00	0.00
% Cycle Wait	0.00	0.00	0.00	0.00	0.00
% Setup	0.00	0.00	0.00	0.00	0.00
% Setup Wait	0.00	0.00	0.00	0.00	0.00
% Broken Dow	0.00	0.00	0.00	0.00	0.00
% Repair Wait	0.00	0.00	0.00	0.00	0.00
No. Of Operati	4802	4759	790	1577	1577

Fig. 9. Case Packer Cycle-Time Reduction Scenario (Scenario 5) – Simulation Output.

Comparative Analysis of All Scenarios

To systematically evaluate the influence of different optimization strategies on material flow and production efficiency, six scenarios were analyzed using discrete-event simulation in Witness Horizon.

Each scenario modified a specific system parameter, while all other model characteristics remained constant.

The comparative results (Table 8) reveal that isolated adjustments – such as increasing buffer capacity or accelerating downstream machines – do not lead to significant gains when the main bottleneck remains unresolved.

Among all tested configurations, Scenario 1 (Modulfiller –10%) provided the best balance between stability and throughput improvement, yielding a 7% production increase with minimal flow disruption. Further acceleration of the same process (Scenario 2) produced smaller gains and introduced systemic imbalance, confirming that over-optimization at one stage can propagate inefficiencies downstream.

The parallel configuration (Scenario 3) demonstrated that capacity duplication does not proportionally increase throughput unless downstream synchronization is improved.

Finally, Scenarios 4 and 5 confirmed that non-bottleneck optimizations—buffer expansion or downstream speed increase—produce negligible or even counterproductive results.

Overall, the experiments emphasize the importance of a systemic approach to optimization rather than local efficiency improvements. A holistic analysis of process interdependencies is essential to ensure that gains at one station translate effectively into global performance improvements.

The comparative results reveal that isolated adjustments – such as increasing buffer capacity or accelerating downstream machines – do not lead to significant gains when the main bottleneck remains unresolved.

Among all tested configurations, Scenario 1 (Modulfiller –10%) provided the best balance between stability and throughput improvement, yielding a 7% production increase with minimal flow disruption.

Further acceleration of the same process (Scenario 2) produced smaller gains and introduced systemic imbalance, confirming that over-optimization at one stage can propagate inefficiencies downstream.

The parallel configuration (Scenario 3) demonstrated that capacity duplication does not proportionally increase throughput unless downstream synchronization is improved.

Finally, Scenarios 4 and 5 confirmed that non-bottleneck optimizations – buffer expansion or downstream speed increase – produce negligible or even counterproductive results.

Overall, the experiments emphasize the importance of a systemic approach to optimization rather than local efficiency improvements. A holistic analysis of process interdependencies is essential to ensure that gains at one station translate effectively into global performance improvements.

The simulation-based comparative study highlights the critical role of bottleneck management in flow optimization. The Modulfiller consistently constrained the system's performance, while local adjustments in buffering or packing speed did not enhance output. These results validate the discrete-event simulation approach as an effective tool for testing and prioritizing process-improvement strategies before real implementation.

5. LIMITATIONS AND FUTURE WORK

5.1. Study Limitations

While the discrete-event simulation used in this paper provides a detailed representation of material flow within the production line, it is important to recognise several methodological and practical limitations.

Firstly, the model operates under the assumption of ideal conditions, omitting critical factors such as unplanned downtime, mechanical failures, and variability in operator performance. These stochastic elements, commonly encountered in real industrial settings, can substantially impact machine utilisation and the stability of throughput.

Secondly, the simulation is confined to a single production line configuration characterised by fixed cycle times and deterministic routing. In practice, production schedules, shift patterns, and product mixes fluctuate dynamically, resulting in far more complex system interactions than those captured in this model. As a result, while the findings may serve as a basis for comparative scenario analysis, extrapolation beyond the specific operational parameters employed requires further parametric adaptation (Table 8).

Thirdly, the current model excludes key metrics such as energy consumption, maintenance schedules, and cost considerations, all of which are significant and should be included for a holistic approach to production optimisation. The analysis has primarily concentrated on throughput and resource utilisation. A more robust model would integrate additional performance indicators to effectively balance efficiency, cost, and sustainability.

Lastly, although the Witness simulation environment excels in discrete-event modelling, it abstracts certain physical constraints, including conveyor accumulation dynamics, real-time control logic, and feedback mechanisms. These simplifications can lead to discrepancies between simulated outcomes and actual system behaviour, particularly under high load or unbalanced conditions.

5.2. Future Work

Future research will address current limitations and broaden the scope of digital analysis in manufacturing systems. A promising avenue is the integration of discrete-event simulation with Digital Twin technology, facilitating real-time data interchange between virtual models and their corresponding physical production systems. This integration allows for continuous performance monitoring, predictive maintenance, and automated decision-making driven by live sensor data.

To refine the optimisation processes, leveraging multi-objective algorithms, such as genetic algorithms and simulated annealing, could help identify optimal trade-offs among production throughput, resource utilisation, and energy efficiency. By implementing these methods within Witness or coupling them with Python-

Table 8

Comparative Summary of All Optimization Scenarios

Scenario	Description	Total Output (units)	Δ vs. Baseline	Main Bottleneck	Observed Effects
Baseline	Reference configuration	1577	–	Modulfiller	Stable line, Modulfiller saturated (99%), blocking upstream
S1	Modulfiller CT –10% (0.45 s/unit)	1687	7%	Case Packer	Increased throughput; new blocking at Case Packer (18.6%)
S2	Modulfiller CT –20% (0.40 s/unit)	1659	5%	Case Packer	Diminishing returns; flow imbalance and downstream congestion
S3	Two parallel Modulfiller stations (0.5 s/unit each)	1615	2.40%	Case Packer	Load redistribution; bottleneck shift to Case Packer; Depalletizer saturated
S4	+50 units in Buffer_Cans	1577	0%	Modulfiller	No impact; same blocking pattern; buffer underutilized
S5	Case Packer CT –30% (0.315 s/unit)	1576	0%	Modulfiller	No improvement; downstream optimization ineffective

based optimisation frameworks, we can gain deeper insights into process resilience.

Another critical area of exploration is the introduction of stochastic variability to more accurately represent real-world uncertainties – such as machine failures, material delays, and workforce changes – to evaluate system robustness in non-ideal scenarios.

Extending the simulation to encompass a network of interconnected production lines enables assessment of inter-line dependencies and the propagation of bottlenecks throughout an entire manufacturing plant. Lastly, we aim to explore the implementation of AI-driven predictive control mechanisms to dynamically adjust cycle times and balance workloads in smart manufacturing environments. These advancements will pivot the simulation model from a traditional analytical tool into a continuously adaptive decision-support system, aligning with the principles of Industry 5.0.

In conclusion, while the current study effectively showcases the utility of discrete-event simulation for process optimisation, future efforts will centre on enhancing model realism, integrating real-time feedback mechanisms, and embedding intelligent optimisation strategies to support data-driven, adaptive manufacturing practices.

6. CONCLUSIONS

This research focused on optimising material flow within a beverage production line through the application of virtual prototyping and discrete-event simulation in a Witness Horizon environment. The primary objective was to assess the effects of specific optimisation approaches to process parameters – including cycle times, buffer capacities, and equipment configurations – on the overall performance metrics, throughput, and resource utilisation of the production system.

The findings indicate that discrete-event simulation serves as an effective decision-support tool for pinpointing bottlenecks and evaluating potential enhancements in a controlled environment. The Modulfiller station consistently emerged as the primary constraint across all scenarios, dictating production rates and affecting both upstream and downstream processes.

A comparative analysis of various optimisation scenarios led to several critical insights:

1. Bottleneck Improvement Efficiency: Modest improvements in the bottleneck process yield significant efficiency gains.
2. Cycle Time Reduction Effectiveness: A 10% decrease in the Modulfiller's cycle time (Scenario 1) resulted in an approximate 7% increase in total throughput with negligible disruption to overall system balance.
3. Local vs. total Optimisation: Over-optimising locally can lead to system instability.
4. Diminishing Returns with Excessive Cycle Time Reduction: A 20% reduction in cycle time (Scenario 2) yielded diminishing returns, as it caused increased blocking downstream – a clear demonstration of bottleneck shifting.
5. Inefficacy of Parallelisation Without Synchronisation: Introducing a second Modulfiller (Scenario 3) redistributed the workload but did not significantly boost total output, since the Case Packer emerged as the new limiting factor.
6. Limitations of Buffer Expansion: Expanding the can buffer by 50 units (Scenario 4) showed no measurable performance improvements, as the core process constraint remained unaddressed.
7. Downstream Acceleration Impact: Reducing the Case Packer's cycle time by 30% (Scenario 5) revealed that downstream enhancements have marginal benefits if the primary bottleneck continues to exist.

These findings emphasise that production optimisation should adopt a holistic perspective rather than focusing on isolated components, taking into account the interdependencies throughout the entire process chain. The experiments underscore the necessity of a well-balanced strategy that enhances bottleneck performance in tandem with synchronised adjustments across connected operations. Moreover, this study validates the efficacy of virtual prototyping as a low-risk, high-precision method for conducting "what-if" analyses prior to real-world implementation. By facilitating quantitative evaluations of design alternatives, discrete-event simulation fosters data-driven decision-making and aligns with the overarching vision of Digital Twin-enabled smart manufacturing.

In conclusion, the approach outlined herein establishes a replicable framework for modelling, analysing, and optimising production systems through digital simulation. The insights derived from this research lay a foundational groundwork for future investigations into real-time adaptive manufacturing and the integration of fully realised Digital Twin architectures.

Author contributions: A.D Scarlat: methodology, writing-original draft preparation, data analysis, the creation of the digital model and its functional redesign; C.L. Popa: writing-preparation of the original version, data analysis, supervision; C.E. Cotet, L. Parpala and R. Parpala: conceptualization, methodology, supervision; all authors had approved the final version.

REFERENCES

[1] Wang, S., Wan, J., Li, D., & Zhang, C. (2016). Implementing Smart Factory of Industrie 4.0: An Outlook. *International Journal of Distributed Sensor Networks*, 12(1), 3159805.

[2] Tao, F., Zhang, M., Cheng, J., & Qi, Q. (2019). Digital Twin Workshop: A New Paradigm for Future Smart Manufacturing. *Computers in Industry*, 112, 103372.

[3] Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin Concept in Manufacturing: A Literature Review and Research Agenda. *Procedia CIRP*, 67, 101–107.

[4] Banks, J., Carson, J., Nelson, B., & Nicol, D. (2010). *Discrete-Event System Simulation*. Pearson Education.

[5] Turner, C.J., Hutabarat, W., Oyekan, J., Tiwari, A. (2016). Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends. *IEEE Transactions on Human-Machine Systems*, 46(6), 882–894.

[6] Lidberg, S., & Ng, A. H. C. (2020). A Framework for Simulation-Based Optimization of Manufacturing Systems. *Procedia Manufacturing*, 51, 1171–1178.

[7] Oyekan, J., et al. (2020). Applying Virtual Prototyping and Simulation to Improve Industrial Automation Efficiency. *Journal of Manufacturing Systems*, 54, 200–212.

[8] Pedrielli, G., Ng, A., & Tiwari, A. (2020). Digital Twin-driven Optimization for Smart Manufacturing. *Simulation Modelling Practice and Theory*, 102, 102060.

[9] Turner, C., et al. (2018). Simulation for Manufacturing System Design and Decision Making. *Procedia CIRP*, 72, 1133–1138.

[10] Negahban, A., & Smith, J. S. (2014). Simulation for Manufacturing System Design and Operation: Literature Review and Analysis. *Journal of Manufacturing Systems*, 33(2), 241–261.

[11] Qamar, A., et al. (2021). Virtual Prototyping and Model-Based Systems Engineering for Smart Manufacturing. *Journal of Industrial Information Integration*, 25, 100256.

[12] Tao, F., & Qi, Q. (2019). Make More Digital Twins. *Nature*, 573(7775), 490–491.

[13] Oyekan, J.; Hutabarat, W.; Turner, C.; Tiwari, A.; Prajapat, N.; Ince, N.; Gan, X.-P.; Waller, T. A 3D immersive Discrete Event Simulator for enabling prototyping of factory layouts. Procedia CIRP 2015, 38, 63–67.

[14] Knapčíková, L.; Behúnová, A.; Behún, M. Using a discrete event simulation as an effective method applied in the production of recycled material. Advances in Production Engineering & Management 2020, 15(4), 431–440.

[15] Pedrielli, G.; Matta, A.; Alfieri, A.; Zhang, M.Design and control of manufacturing systems: A discrete event optimisation methodology. International Journal of Production Research 2018, 56(1–2), 543–564.

[16] Turner, C.J.; Hutabarat, W.; Oyekan, J.; Tiwari, A. Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends. IEEE Transactions on Human-Machine Systems 2016, 46(6), 882–894.

[17] Lidberg, S.; Aslam, T.; Pehrsson, L.; Ng, A.H.C. Optimizing real-world factory flows using aggregated discrete event simulation modelling: Creating decision-support through simulation-based optimization and knowledge-extraction. Flexible Services and Manufacturing Journal 2019, 32, 888–9.