

MODELING OF A PULL-FLOW PRODUCTION SYSTEM WITH DYNAMIC BUFFER STOCK CONTROL

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Abstract. In modern industrial logistics, efficient production relies on synchronizing raw material supply with real-time demand to minimize waste and improve performance. This paper proposes a modelling approach for production systems based on a pull flow strategy, which controls the replenishment of raw materials in response to real-time demand. The production system is represented in Simulink as a discrete manufacturing unit supported by a buffer stock. A feedback control loop governs the flow of materials from the warehouse to the buffer, using demand-driven trigger points to prevent shortages and maintain stable machine throughput. The objective is to ensure uninterrupted production while optimizing stock levels. Simulation results highlight the effectiveness of the proposed approach in synchronizing supply with consumption, enhancing overall system responsiveness and operational efficiency.

Keywords: pull flow, production system, modeling, replenishment control

MODELOWANIE SYSTEMU PRODUKCYJNEGO TYPU PULL-FLOW Z DYNAMICZNYM STEROWANIEM ZAPASAMI BUFOROWYMI

Streszczenie. We współczesnej logistyce przemysłowej wydajna produkcja opiera się na synchronizacji dostaw surowców z popytem w czasie rzeczywistym, co pozwala zminimalizować marnotrawstwo i poprawić wydajność. W niniejszym artykule zaproponowano podejście modelowe do systemów produkcyjnych oparte na strategii przepływu typu "pull", która steruje uzupełnianiem zapasów surowców w odpowiedzi na popyt w czasie rzeczywistym. System produkcyjny jest przedstawiony w programie Simulink jako dyskretna jednostka produkcyjna wspierana przez zapas buforowy. Pętla sterowania sprzężeniem zwrotnym reguluje przepływ materiałów z magazynu do bufora, wykorzystując punkty wyzwalające oparte na popycie, aby zapobiegać niedoborom i utrzymać stabilną wydajność maszyn. Celem jest zapewnienie nieprzerwanej produkcji przy jednoczesnej optymalizacji poziomów zapasów. Wyniki symulacji podkreślają skuteczność proponowanego podejścia w synchronizacji dostaw z zużyciem, zwiększając ogólną responsywność systemu i wydajność operacyjną.

Słowa kluczowe: przepływ wyciągania, system produkcyjny, modelowanie, sterowanie uzupełnianiem zapasów

Introduction

Logistics has shifted into a strategic domain, driven by the integration of advanced technologies to manage increasingly complex supply chains [13]. At the heart of this are production processes, which significantly influence both operational costs and product quality [4, 9, 11]. Ensuring efficient production requires tight coordination with replenishment activities to maintain continuity and minimize expenses [9]. Incorporating control policies and real-time data exchange enhances this coordination, enabling faster decision-making and better alignment between production output and inventory levels.

This study explores the improvement of pull-based, demand-driven production systems, where manufacturing is initiated only in response to actual demand. A mathematical model of the production machine is developed based on its functional logic, and integrated into a simulated production scenario that includes buffer stock and replenishment processes. The system is designed as a closed-loop control structure, where material supplies from the warehouse is continuously triggered based on the machine's actual consumption, ensuring stable operation and avoiding shortages.

The evolution of production systems has been driven by the need to convert raw materials into finished goods efficiently, while responding dynamically to fluctuating demand. Early modeling approaches, such as the two-machine-one-buffer (2M1B) system, provided valuable insight into production dynamics under constrained conditions [10]. However, these models lacked the adaptability required for real-time decision-making in modern, volatile environments. As manufacturing paradigms transitioned from push- to pull-based strategies, frameworks such as Kanban and CONWIP emerged, emphasizing demand-driven control and minimal work-in-process inventory [12]. Simulation-based approaches have played a critical role in enhancing the understanding and implementation of such pull systems [14].

To support demand-driven production, replenishment has become a crucial mechanism for maintaining inventory

balance and preventing both shortages and overstocking. Unlike static inventory models, dynamic replenishment systems rely on real-time information to adapt supply rates based on current and forecasted demand. Modeling these systems using control theory has proven effective in capturing system delays, feedback effects, and sensitivity to disturbances [1, 7]. For instance, sensitivity analysis in order-picking processes can improve throughput and resource allocation under uncertainty [1], while parametric models such as ARX, ARMAX, and Box-Jenkins (BJ) structures offer robust tools for forecasting and control [7].

Several recent studies emphasize the integration of inventory and replenishment control to achieve more resilient and efficient production systems. Valery Lukinskiy & Vladislav Lukinskiy [11] highlight the impact of logistic operations' reliability on overall supply chain costs, reinforcing the need for precise control strategies. Elbaraka et al. [6] explore the synchronization between buffer stock supply and machine-level replenishment control through simulation, demonstrating how these interactions influence production continuity and responsiveness.

Recent advancements in the modeling of pull-flow production systems have increasingly emphasized the role of dynamic buffer stock control in improving system responsiveness and throughput. The integration of adaptive buffer management mechanisms allows production systems to maintain flow stability despite demand variability and process disturbances. Alekseev et al. [3] contribute to this body of research by investigating flow stabilization in sugar production processes. Their study focuses on hydrodynamic modes within diffusion apparatuses, proposing control system designs that respond dynamically to operational variations – an essential aspect of effective buffer control in continuous manufacturing systems.

In a parallel domain, Cavana et al. [5] examine buffer management within the context of smart gas distribution networks. By modeling linepack – the storage capability of pressurized gas pipelines – as a transient buffer stock, they enable real-time estimation of network capacity in response to fluctuating production and consumption levels. This fluid-dynamic modeling approach not only enhances flow stability but also mirrors key principles found in manufacturing systems, particularly

the strategic use of buffers to absorb variability and regulate throughput.

The goal is to analyze and optimize the interaction between production and inventory through automation and control strategies. This work provides new insights into smart manufacturing, and a foundation for advanced modelling and simulation in future industrial application.

Following the problem definition presented in the first chapter, the paper proceeds to describe the structure and architecture of the proposed production system. The subsequent chapter is dedicated to the mathematical modeling of the production machine, forming the basis for the complete block diagram representation of the system. The model is then implemented and simulated using Simulink, allowing for dynamic analysis of system parameters over time. Finally, the paper concludes with a presentation of simulation results, along with interpretation and discussion of the system's performance and behavior.

1. Problem statement

The efficient transformation of raw materials into finished products depends critically on the coordination between production processes, replenishment mechanisms, and ever-changing customer demand. A persistent challenge in this context is maintaining a continuous and uninterrupted flow of raw materials to the production machine, while dynamically adjusting this input based on real-time demand fluctuations [1, 4].

Traditional push-based production models, which operate according to fixed schedules and predetermined supply rates, often fail to meet this requirement. These systems typically do not account for demand variability, resulting in common inefficiencies such as excess inventory, raw material shortages, or production delays [6]. In environments where demand is uncertain or volatile, these limitations can lead to significant disruptions in production continuity and negatively impact overall system performance.

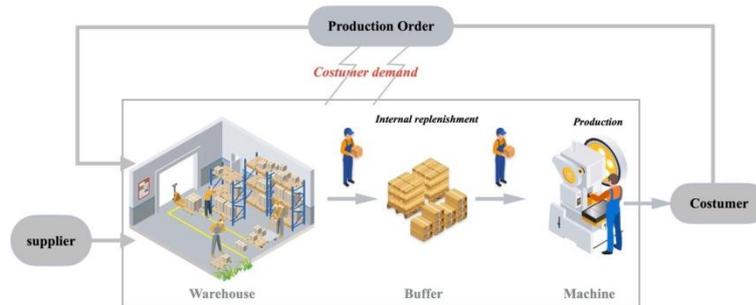


Fig. 1. Demand-driven production process

3. Modeling of the production system

3.1. Production machine

The analogy between manufacturing systems and electrical circuits offers a useful perspective for understanding material flow. By treating product flow like electric current and buffer levels like electrical charge, this approach helps simplify and structure system behavior. This modeling perspective, previously explored [7], serves as a foundation for the current study. Here, it is adapted to develop a mathematical model of a single production machine operating in a pull flow context [2, 12] integrating control logic, inventory levels, and physical constraints to support efficient and responsive system performance [7, 10].

One considers a machine capable of processing up to k units simultaneously. The time required to process a single unit is denoted by t_e in minutes ref, for a realistic operating mode, the system operates in discrete time, with time steps $t \in \mathbb{N}$ [7], where production decisions are made at regular intervals defined by a reference time $T_{ref} \in \mathbb{N}$. Production is triggered only when the following conditions are simultaneously met:

To respond effectively to these challenges, it is necessary to develop a dynamic control system capable of real-time monitoring and adjustment. Such a system should regulate both the replenishment of input materials and the operation of the production machine based on current demand conditions. By doing so, it can minimize waste, reduce the risk of stockouts, and improve the overall responsiveness and efficiency of the production process in demand-driven environments.

2. Main concepts

Understanding the architecture of a production system is crucial for analyzing its behavior and developing effective regulation and optimization strategies.

Production systems are inherently complex networks, where disruptions or inefficiencies in one segment can propagate and significantly affect overall system performance [4, 8, 11]. Therefore, Fig. 1 clearly identify and define the system's fundamental components and their definition in Table 1, their interdependencies, and the nature of their interactions. Establishing a structured analytical framework alongside explicit modeling assumptions enables a comprehensive understanding of the system's behavior. This foundational clarity is critical for developing control strategies and improvements across the production network.

Table 1. Definitions

Component	Definition
Production System	An interconnected network where each element affects overall performance and outcomes.
Demand-Driven Approach	Triggers production based on real-time demand; reduces waste and increases flexibility.
Buffer stock	Maintains steady material flow to the machine; replenished based on actual consumption.
Replenishment Process	Supplies materials in real time based on buffer usage; avoids overstock and shortages.

- A customer order is pending, $G_{(t)}$ (order gap), meaning that the machine has not yet produced the required quantity to fulfill the demand.
- The buffer stock level $S_{(t)}$ is sufficient to ensure that the machine does not experience a shortage during its production cycle.
- The machine is only allowed to produce at instants that are multiples of the reference time T_{ref}

The machine can produce at a maximum rate of $C_{max} = \frac{k}{t_e}$ (units per minute), so the actual production rate at time t is defined as:

$$R_{(t)} = \min\left(\frac{k}{t_e}, E_{(t)}\right) \quad (1)$$

This means that the machine cannot exceed its maximum production capacity of k/t_e and the work-in-progress level $E_{(t)}$. Therefore, the machine is constrained by two physical limits: its production capacity and available resources.

In a pull-flow production system, the decision to produce depends on several logical conditions that must be met simultaneously. To formally represent this logic in a way that

can be used for simulation or analysis, we introduce the concept of indicator functions. We consider three necessary conditions for the machine to operate at a given time $t \in \mathbb{N}$:

Time-based condition

The machine can only produce at every T_{ref} time units, according to a fixed production cycle. This defines the set:

$$A_1 = \{t \in \mathbb{N} \mid \text{mod}(t, T_{ref}) = 0\} \tag{2}$$

Presence of an order

There must be an unsatisfied demand, represented by an order gap $G(t)$, such that:

$$A_2 = \{t \in \mathbb{N} \mid G(t) > 0\} \tag{3}$$

Sufficiency of buffer stock

The machine can only operate if the input stock $S(t)$ is greater than or equal to the possible production rate $R(t)$. Thus:

$$A_3 = \{t \in \mathbb{N} \mid S(t) \geq R(t)\} \tag{4}$$

Each of these conditions is represented by an indicator function associated with the set A_i denoted by $1_{A_i}(t)$. These functions take the value 1 when the condition is satisfied, and 0 otherwise:

$$1_{A_i}(t) = \begin{cases} 1 & \text{si } t \in A_i \\ 0 & \text{sinon} \end{cases} \rightarrow MC(t) = R(t) \cdot 1_{A_1 \cap A_2 \cap A_3}(t) \tag{5}$$

- $\delta(t) = 1$ if $\text{mod}(t, T_{ref}) = 0$, else 0
- $\gamma(t) = 1$ if $G(t) > 0$, else 0
- $\sigma(S, R) = 1$ if $S(t) \geq R(t)$, else 0

The consumption equation is expressed as:

$$MC(t) = \delta(t) \cdot \gamma(t) \cdot \sigma(S, R(t)) \tag{6}$$

Equivalently, using piecewise notation:

$$MC(t) = \begin{cases} \min\left(\frac{k}{t_e}, E(t)\right) & \text{if } \text{mod}(t, T_{ref}) = 0, G(t) > 0, S(t) \geq R(t) \\ 0 & \text{else} \end{cases} \tag{7}$$

Table 2. Definitions

$R(t)$	effective production rate
k	maximum number of units that can be processed simultaneously (machine capacity)
t_e	time required to process one unit (in minutes)
$E(t)$	work-in-progress level at time t (amount of material or products to be processed)
$G(t)$	order gap (indicates whether there are pending orders)
$S(t)$	stock level
T_{ref}	reference time (period during which the machine can potentially operate)
t	current simulation time

3.2. Representation of the buffer system

To illustrate buffer stock dynamics, one developed a simplified visual model inspired by the "Two-Machine-One-Buffer Continuous Model" [10]. This version includes a warehouse supplying materials to a buffer, which in turn feeds a single production machine. The buffer is modeled as a subsystem with two key flows: inflow from the warehouse (replenishment) and outflow to the machine (consumption) [6].

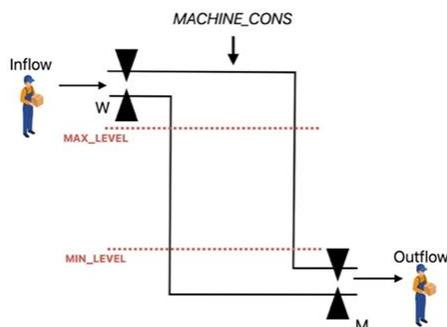


Fig. 2. Illustration of the Inflow/outflow, MIN/MAX Levels, and machine consumption disruption

As represented in Fig. 2 the buffer stock subsystem operates within two key limits: MAX_LEVEL to prevent overstocking and MIN_LEVEL to trigger replenishment and avoid stockouts [6, 10]. As we can notice in Fig. 3, the machine consumes materials $R(t)$, it steadily reduces the buffer level, creating the need for timely replenishment.

3.3. Modelling assumptions

To isolate and analyze the core dynamics between buffer stock, material replenishment, and the production machine, the following simplifying assumptions are adopted.

Demand-driven pull flow

The production process is initiated strictly in response to actual demand. Once the required quantity is fulfilled, both production and supply activities are suspended to prevent overproduction and unnecessary inventory buildup [6].

Unlimited warehouse capacity

The system assumes an infinite availability of raw materials, implying that the upstream warehouse always has sufficient stock to meet replenishment needs without delay [6].

These assumptions allow the study to concentrate on the internal behavior of the production system without external supply constraints. The optimal management of such systems requires a clear understanding of the dynamic interactions between production, replenishment flows, and fluctuating demand [1, 6, 10]. In this context, modeling and simulation provide a structured and effective approach for capturing, analyzing, and optimizing these interdependencies, ultimately supporting the design of more responsive and efficient control strategies.

3.4. Modelling of the buffer stock system and replenishment control

The proposed model describes a closed-loop production system designed to regulate buffer stock through the dynamic interaction of material inflow (replenishment) and outflow (consumption by the production machine). It is structured around three core components: the production machine, the replenishment policy, and the buffer stock [6, 10]. Central to the model is a feedback-based control mechanism, in which replenishment is activated whenever the stock level drops below a predefined threshold. A control loop continuously monitors the buffer status and adjusts the inflow rate in real time to maintain system stability.

In parallel, the production machine withdraws materials from the buffer to fulfill production requirements, creating a dynamic outflow that reflects operational demand. This bidirectional flow – replenishment in, consumption out – is managed to ensure a continuous balance between supply and demand. A monitoring unit compares actual production output with real-time consumption levels, allowing for constant evaluation of system performance. The model thus ensures that production objectives are achieved while maintaining optimal buffer levels, minimizing both the risk of stockouts and the inefficiencies of overstocking.

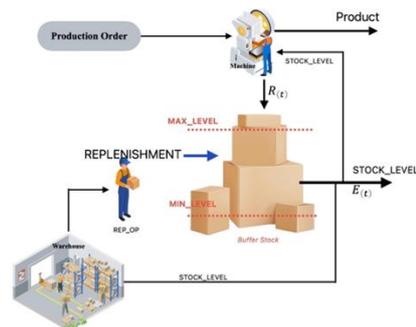


Fig. 3. Buffer stock in the production system

Fig. 4 represents the block diagram modeling a pull-based production system structured around three core subsystems: the production machine, the replenishment policy, and the buffer stock. Governed by key parameters such as MACHINE_RATE, TIME, TIME_REF, ORDER_GAP, STOCK_LVL, TRIGGER_POINT, MAX_OUTPUT that we described in Table 3, the system operates based on demand signals and real-time inventory status. Material consumption by the machine occurs only when three conditions are simultaneously met: the current time is a multiple of the reference interval (TIME_REF), a production gap exists (ORDER_GAP > 0), and sufficient stock is available (STOCK_LVL ≥ MACHINE_RATE). This logic ensures production aligns with actual demand, avoiding overproduction and maintaining resource efficiency. The consumed input undergoes a processing delay, is scaled according to a conversion rate, and accumulated to compute total finished goods. When the buffer stock level drops below a predefined threshold (TRIGGER_POINT), the replenishment control activates, and the replenishment operation delivers materials based on the available accumulation (REP_OP), without exceeding the operator's maximum output capacity (MAX_OUTPUT). The actual replenished amount is tracked (y), while any remaining unmet need is held in a buffer (buff) for future cycles. The buffer stock dynamically updates its level based on the net difference between inflow (replenishment) and outflow (machine consumption), ensuring the system remains stable, responsive, and synchronized with demand.

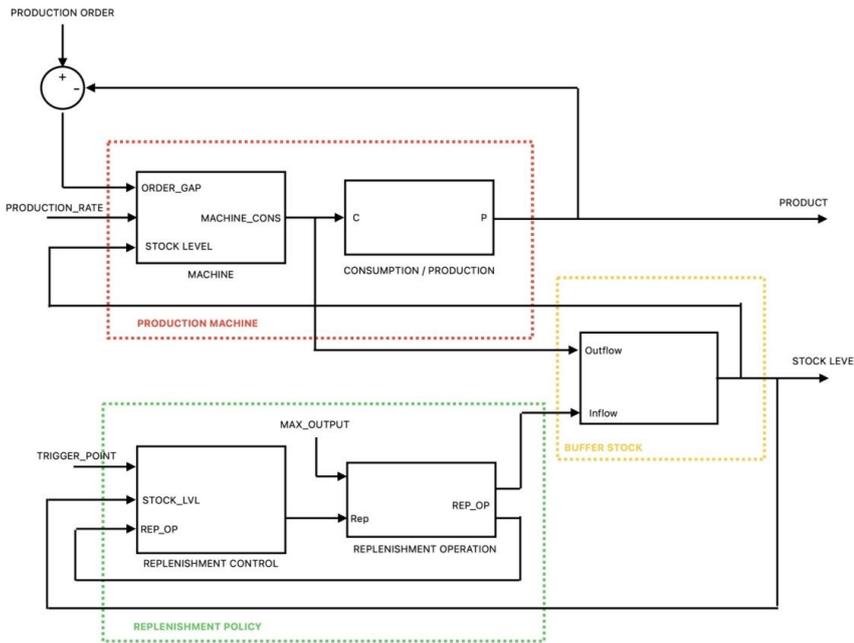


Fig. 4. Block diagram modelling of the buffer stock replenishment control in Simulink

We managed to integrate a manual replenishment according to a real manufacturing scenario which is the REPLENISHMENT OPERATION block following the MATLAB script – Fig. 6.

MAX_OUTPUT represents the maximum amount the operator can hold. The function accumulates replenishment quantities (REP) in REP_OP and checks if it meets or exceeds MAX_OUTPUT. If so, it replenishes MAX_OUTPUT and adjusts REP_OP accordingly. If not enough is available, it replenishes what is in REP_OP. The output 'y' shows the actual replenished amount, and 'buff' tracks the remaining replenishment needs for future cycles.

Once replenished, the buffer stock becomes available to support the production machine's consumption. Designed as a closed-loop system, this model dynamically regulates buffer stock levels to avoid shortages and sustain continuous production flow. In this demand-driven concept, the system prioritizes production orders as a central element influencing material consumption. This framework highlights the role of replenishment

The system is controlled by two other Simulink blocks, REPLENISHMENT CONTROL and REPLENISHMENT OP that constitutes the replenishment policy. The feedback loop operates as follows: When the buffer stock level falls below a predefined minimum threshold (STOCK_LEVEL ≤ TRIGGER_POINT), the replenishment order is triggered. The replenishment quantity is determined by a MATLAB script – Fig. 5.

Table 3. Definitions

MIN_LEVEL	minimum capacity of the buffer stock also used as a trigger point (TRIGGER_POINT)
STOCK_LVL	real time quantity in the buffer stock
MACHINE_CONS	consumption rate of materials by the production machine.
MACHINE_RATE	machine production rate quantities
MAX_OUTPUT	maximum quantity that that one operator can supply

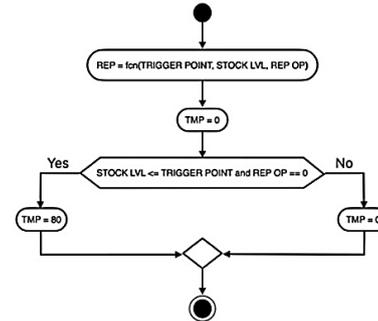


Fig. 5. Replenishment quantities graph

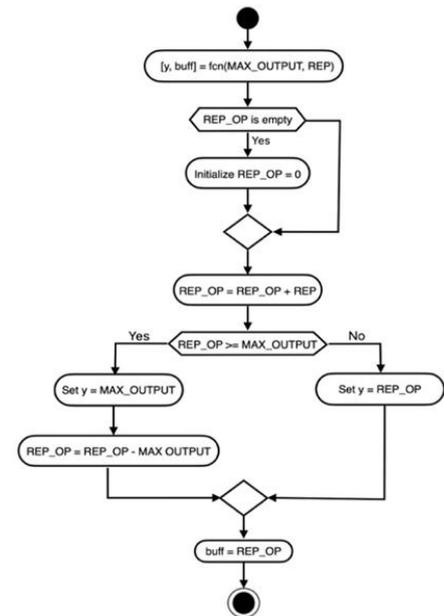


Fig. 6. Replenishment operation graph

control mechanisms in aligning stock levels with actual production requirements, effectively reducing disruptions and enhancing overall operational efficiency.

Given the complexity of these processes, simulation becomes a vital tool for analyzing the behavior of such systems under varying operational scenarios. It offers a precise way to replicate the behavior of the production system under real-world conditions and enables the analysis of the replenishment operations and the impact of machine consumption on overall performance. This approach is crucial for exploring control strategies and adjusting system parameters effectively. In the next chapter, we will delve into the simulation results, providing detailed insights into system behavior and performance.

Given the complexity of these interactions, simulation is essential for analyzing this production scenario, assessing replenishment strategies, and optimizing control [14]. The next chapter presents key results and insights on our system.

4. Simulation and results analysis

To evaluate the behavior and performance of the proposed pull-based production model, a simulation was developed using Simulink. In this study, the simulation was deliberately conducted for a single-product, multi-stage production line in order to clearly analyze the system's response to consumption demands and replenishment triggers under defined constraints.

By modelling real-time interactions between machine consumption, buffer stock levels, and replenishment logic, the simulation provides insights into the system's ability to maintain stock stability, prevent production halts, and fulfill orders efficiently.

The buffer stock subsystem was regulated within two critical thresholds: a maximum capacity level (MAX_LEVEL) to avoid overstocking and a minimum threshold (MIN_LEVEL) to prevent material shortages [6, 7]. A key feature of the model is the implementation of a replenishment trigger point, defined at 20% of the buffer's maximum capacity. Once the buffer stock level $S(t)$ falls to or below this 20% threshold, the system automatically activates the replenishment mechanism. This point functions as a control signal within the feedback loop, ensuring timely inflow adjustments to restore material availability before production is interrupted. As the machine consumes materials $MC(t)$ over time, the buffer stock gradually depletes, and approaching the trigger threshold prompts an incremental replenishment process.

Fig. 8 is demonstrating how replenishment quantities are governed by the real-time buffer stock level and a clearly defined replenishment policy. The system continuously monitors the buffer stock, and replenishment is triggered when this level falls below a fixed threshold, specifically set at 20% of the buffer's maximum capacity. This trigger point initiates the inflow of materials to prevent the risk of stockout and ensure uninterrupted production.

Rather than replenishing the entire deficit at once, the simulation applies a gradual replenishment approach, where inflow is delivered in fixed, discrete quantities. Each replenishment increment corresponds to 80% of the buffer's maximum capacity. This step-based logic allows the buffer to recover progressively, smoothing out fluctuations and avoiding sudden inflow spikes that could lead to inefficiencies or overstocking.

The replenishment operation is designed to reflect the practical constraints of supply execution, notably through the incorporation of an operator-controlled mechanism. Once the buffer stock level falls below the defined trigger point – set at 20% of the buffer's maximum capacity – the replenishment control logic activates, initiating material inflow.

However, the quantity of replenishment delivered at each time step is not unlimited. It is determined by the operator's capacity, which is represented in the model by two parameters:

- REP: the fixed replenishment increment (e.g., 5% of maximum buffer capacity)
- REP_OP: the number of increments the operator can supply per control cycle
- MAX_OUTPUT: the maximum replenishment quantity allowed in one cycle

The operator block effectively acts as a rate limiter within the replenishment loop, enforcing a delay or throttling mechanism that introduces realism into the simulation. This behavior prevents oversupply and models typical operational bottlenecks found in manufacturing or logistics chains.

Production was governed by a pull-based logic, where manufacturing was directly driven by the actual demand represented by a fixed production order of 500 units. This target reflects the quantity that the system must fulfill to meet customer requirements, derived from the product's bill of materials (BOM). Production in the Fig. 10 continues incrementally until the cumulative output satisfies this order, at which point

it automatically terminates to prevent overproduction. This approach ensures that production quantities are precisely aligned with demand, enhancing efficiency and minimizing waste. Future work may involve varying this demand to evaluate the system's adaptability under different order sizes or fluctuating market conditions.



Fig. 7. Buffer stock

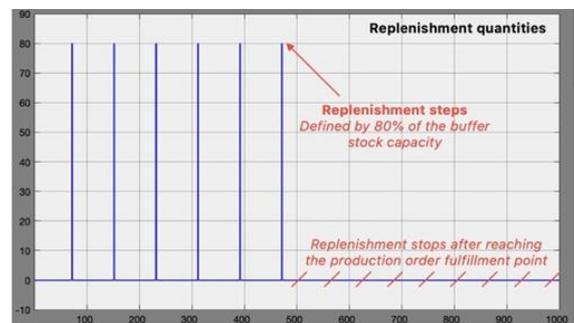


Fig. 8. Replenishment quantities

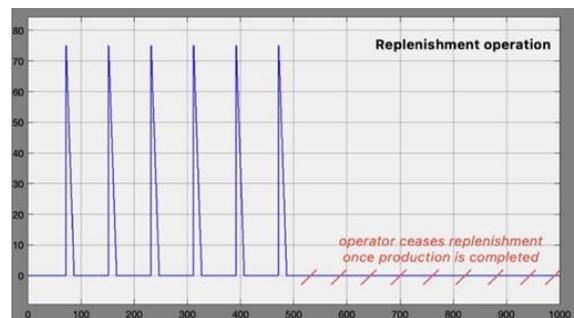


Fig. 9. Replenishment operation

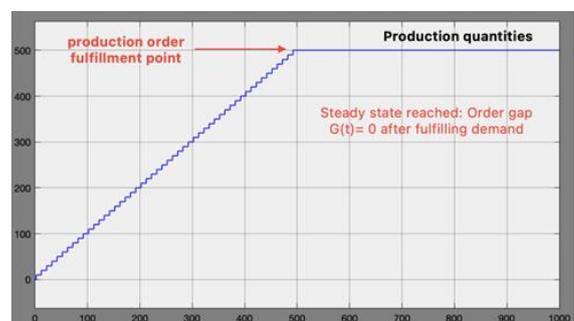


Fig. 10. Production quantities and demand fulfillment

5. Conclusion and research perspective

This study establishes a foundational model for simulating a demand-driven production system using a closed-loop framework that integrates a discrete-time machine block, buffer stock dynamics, and a responsive replenishment policy. The machine subsystem, operating under pull-flow logic, demonstrated effective alignment between material consumption and actual production needs, ensuring that operations proceed only when demand is present and stock conditions are met.

The simulation results confirm that this approach maintains buffer levels within designated thresholds, activates replenishment at appropriate moments, and halts production upon fulfilling demand target reflecting real production behavior. While the system performed reliably within the simulated environment, its current formulation assumes ideal conditions, such as immediate replenishment and constant consumption rates. These assumptions, while simplifying the analysis, limit the model's applicability to more complex industrial settings.

To enhance realism and broaden applicability, future research will extend the proposed framework by incorporating processing and transport time delays, imperfect yields, and variable processing capacities in multi-machine production lines. Such extensions would enable a more faithful representation of shop-floor dynamics, capturing interactions such as blocking, starvation, and quality-related losses, and thereby improving the predictive capability of the model. Furthermore, the integration of adaptive control strategies and smart manufacturing technologies constitutes a promising direction for further improving system responsiveness and operational efficiency.

In sum, this work offers a scalable and flexible platform for exploring pull-based production control strategies. It paves the way for more comprehensive digital models capable of supporting decision-making and automation in modern industrial logistics.

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