Assignment 02: Discrete-rate simulation (DRS) and Discrete-event simulation (DES) with ExtendSim

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Abstract—This project presents the modeling and simulation of a cookie production factory using a hybrid approach that integrates both Discrete Rate Simulation (DRS) and Discrete Event Simulation (DES) techniques. The simulation aims to evaluate the performance of the production system over a two-week period, with particular focus on identifying bottlenecks and estimating total output. A conceptual model was first developed to define the process flow and system parameters, followed by a rough throughput calculation. Subsequently, a simulation model was implemented in ExtendSim to mirror the real-world dynamics of the cookie factory. Flow rates for DRS processes were derived from time-based production intervals, while DES was employed for discrete operations. The simulation results provided insight into total cookie production over 14 days and revealed process bottlenecks that impact system efficiency. The findings were compared against analytical calculations, and the validity of simulation as a decision-support tool in production planning was evaluated.

Contents

1. Introduction

Simulation is a valuable tool in production system analysis, especially when multiple interconnected processes operate under varying time constraints and capacities. This report focuses on simulating a cookie factory to estimate the number of cookies that can be produced in two weeks, to identify bottlenecks in the production system, and to count the number of cartons arriving at the shipping area.

To effectively model the process, a combination of Discrete Rate Simulation (DRS) and Discrete Event Simulation (DES) is used, depending on the nature of each process. Flow rates are derived analytically and then applied in the simulation model which is built using ExtendSim. The simulation is run for a period of 14 days, and the results are compared with rough calculations from the conceptual model to validate accuracy.

The following tasks are addressed in this report:

- Developing a conceptual model of the cookie factory with a rough output estimate.
- Determining which processes are best suited for DRS and which for DES.
- Calculating flow rates for DRS processes.
- Building a hybrid simulation model in ExtendSim.
- Running the simulation for two weeks to evaluate cookie output and bottlenecks.
- Comparison of simulation results with analytical expectations.
- Evaluating whether the use of simulation is appropriate for this scenario.

The following sections provide a detailed explanation of the modeling assumptions, the steps taken to implement them, and the insights gained from the simulation results. The simulation model used is also presented alongside this report.

2. Conceptual Model of the Cookie Factory

This section presents the conceptual model of the cookie production system. It describes the main stages involved in the production line and provides a basis for the simulation model. The conceptual model also includes a preliminary calculation to estimate expected output over a two-week production period.

2.1. Process Flow Diagram and Parameters

Figure 1 provides a graphical representation of the entire cookie production system. It illustrates the sequential process steps from cookie production to shipping, along with the relevant processing times, transport durations, and decision points within the system.

2.2. Preliminary Output Estimation

A rough output calculation has been performed on the basis of the time parameters defined in the conceptual model. This estimate helps predict the approximate number of cookies and cartons expected to be produced during a 14-day simulation period, serving as a reference for comparison with simulation results.

2.2.1. Assumptions

Key Assumptions

- 24 hour/day operation, 14 consecutive days, no downtime.
- Fixed cycle times and yields based on process specifications.
- Conveyors introduce only transit delays and do not limit capacity.

2.2.2. System Parameters

Cookie Production Line: Table 1 summarizes the operations and cycle times involved in the cookie production process.

Carton Production Line: Table 2 outlines the parameters of the carton line, including stamping, packing, sealing, and labeling.

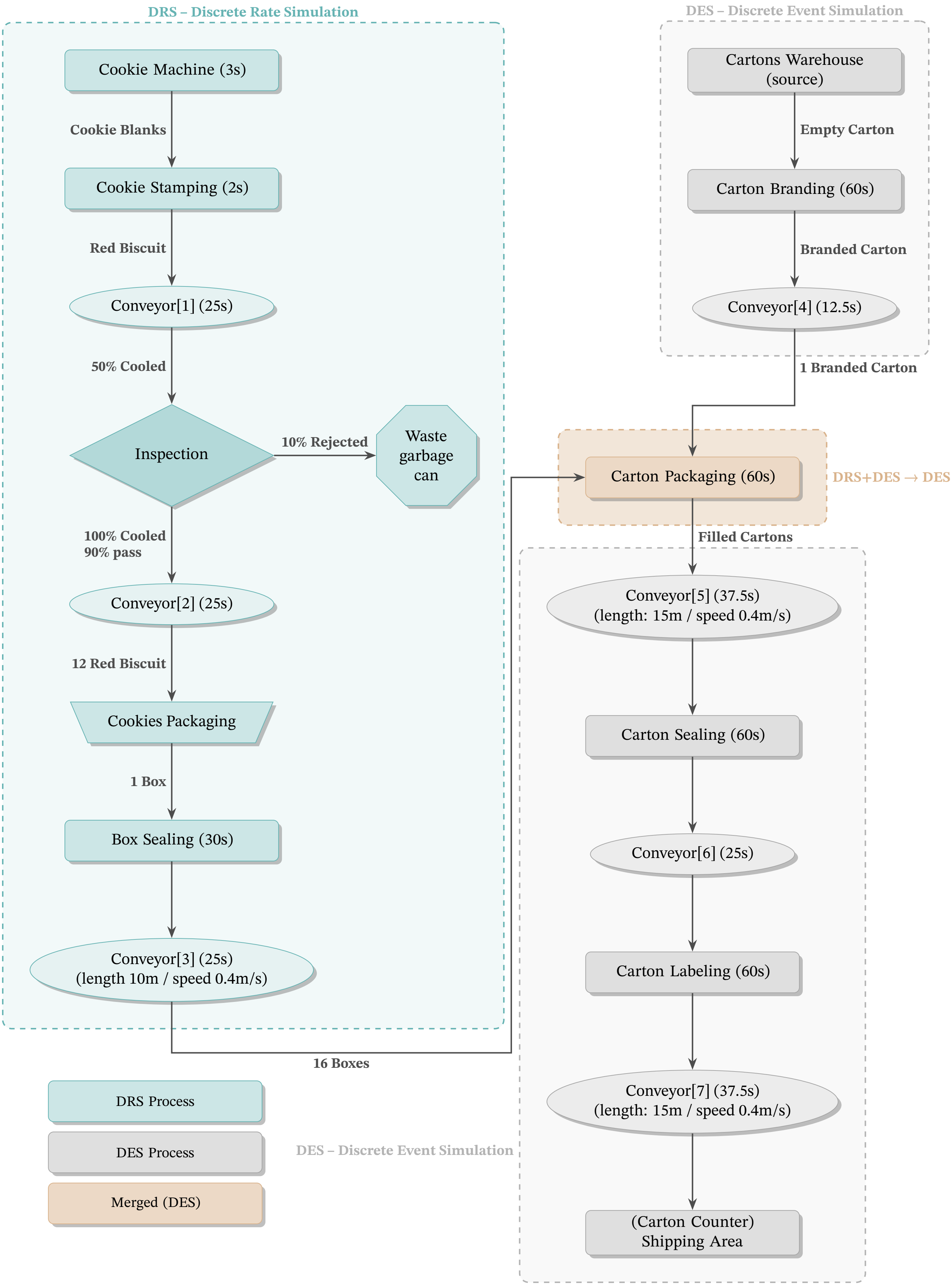

Figure 1. Cookie production flow chart

Operation	Cycle time
Cookie machine	3 s/cookie
Cookie stamping	2 s/cookie
Conveying (1)	25 s transit
Inspection	90% pass, 10% reject
Conveying (2)	25 s transit
Cookie packaging	30 s/box (12 cookies/box)
Sealing (box)	30 s/box
Conveying (3)	25 s transit (10 m at 0.4 m/s)

Table 1. Cookie Production Line Parameters

Operation	Cycle time
Carton stamping	60 s/carton
Conveying (1)	12.5 s transit
Packaging	60 s/carton
Conveying (2)	37.5 s transit (15 m at 0.4 m/s)
Sealing	60 s/carton
Conveying (3)	25 s transit
Labeling	60 s/carton
Conveying (4)	37.5 s transit (15 m at 0.4 m/s)

Table 2. Carton Production Line Parameters

2.2.3. Steady-State Throughput

The following calculations are based on continuous operation for 24 hours a day.

2.2.4. Cookie-Level Output

- Total seconds per day: $T_{\text{day}} = 24 \times 60 \times 60 = 86{,}400$ s
- Raw cookies/day $= \frac{1}{3} \times 86{,}400 = 28{,}800$
- Good cookies/day $= 28{,}800 \times 0.9 = 25{,}920$
- Boxes/day $= \frac{25{,}920}{12} = 2{,}160$
- Cartons/day $= \frac{2{,}160}{16} = 135$

2.2.5. Fourteen-Day Forecast

Metric	Per day	14 days
Raw cookies	28,800	403,200
Good cookies	25,920	362,880
Scrap cookies	2,880	40,320
Boxes	2,160	30,240
Cartons	135	1,890

Table 3. 14-Day Forecast Based on Steady-State

2.2.6. Bottleneck Analysis (Analytical)

Cookie Line: The cycle time for each stage is calculated and compared to determine the bottleneck. The rates are shown both per second and per minute for clarity:

- **Cookie machine:**

$$\begin{aligned} \text{1 cookie every 3 seconds} &= \frac{1}{3}\ \text{cookie/s} \\ &= 20\ \text{cookies/min} \end{aligned}$$

- **Stamping:**

$$\begin{aligned} \text{1 cookie every 2 seconds} &= \frac{1}{2}\ \text{cookie/s} \\ &= 30\ \text{cookies/min} \end{aligned}$$

- **Packaging:**

$$\begin{aligned} \text{12 cookies every 30 seconds} &= \frac{2}{5}\ \text{cookie/s} \\ &= 24\ \text{cookies/min} \end{aligned}$$

Since the cookie machine has the lowest output rate (20 cookies/min), it is identified as the **bottleneck**. It determines the maximum cookie production rate for the entire cookie line.

Carton Line: While all downstream processes in the carton line (branding, sealing, labeling, and transport) operate at a rate of $\frac{1}{60}$ carton / s (that is, 1 carton / minute), the true bottleneck lies at the entry stage to the carton packaging stage. Each carton must wait until 16 sealed boxes are available before packaging can begin. This delay is caused by the upstream box sealing process, which limits the supply rate of boxes. As a result, the carton line is not fully balanced and is instead constrained by the arrival rate of sealed, making this the effective bottleneck of the carton line (see Section 2.2.7).

2.2.7. Start-up Delay (relevant for carton calculation)

To compute when the first carton will be ready, the total time required for **16 boxes** to arrive at the carton packaging station must be considered. This includes the initial delays due to cookie production, inspection, and sequential packaging of boxes. Each step contributes to cumulative delay due to processing and conveyor transport times. The breakdown of this timeline is detailed in Table 4.

Description	Time (s)	Notes
Initial cookie processing	5	Cookie machine + stamping
Conveying to inspection	25	Conveyor 1
Conveying to box packaging	25	Conveyor 2
Box fill (first box)	30	12 cookies per box
Conveyor to carton station	25	Conveyor 3
Remaining 15 boxes	540	15×36 s (at bottleneck rate)
Total waiting time	**650**	≈10.8 minutes

Table 4. Start-up Delay Calculation for First Carton (16 Boxes)

2.2.8. Summary of Calculated Conveyor Belt Systems and Transport Parameters Used in Simulation

This section provides a detailed summary of all conveyor systems involved in the production process, including their respective durations, lengths, and speeds. For cases where the original length was not provided, it has been calculated based on a constant conveyor speed of 0.4 m/s. In the simulation, time is represented in minutes to ensure whole-number values instead of fractional seconds. The breakdown of this is detailed in Table 5.

Conveyor No.	Duration (s)	Length (m)	Speed (m/s)	Speed (m/min)
Conveyor[1]	25.0	10.0*	0.4*	24.0*
Conveyor[2]	25.0	10.0*	0.4*	24.0*
Conveyor[3]	25.0*	10.0	0.4	24.0*
Conveyor[4]	12.5	5.0*	0.4*	24.0*
Conveyor[5]	37.5	15.0	0.4	24.0*
Conveyor[6]	25.0	10.0*	0.4*	24.0*
Conveyor[7]	37.5	15.0	0.4	24.0*

Table 5. Summary of Conveyor Systems with Speeds and Lengths
Note: Values marked with * are calculated values.

#	Process	Duration/Details	Method	Rationale
1	Cookie Machine	(3 s/cookie)	DRS	Fixed cycle time; continuous high-volume process.
2	Cookie Stamping	(2 s/cookie)	DRS	Deterministic timing; no event-based logic.
3	Conveyor[1]	(25 s transit)	DRS	Pure delay stage; modeled as deterministic flow.
4	Inspection	(90% Pass & 10% rejected)	DRS	Rate-based rejection; modeled as proportional flow split.
5	Waste_Garbage_Can	(10% rejected)	DRS	Represents rejected cookies removed via proportional flow split.
6	Conveyor[2]	(25 s transit)	DRS	Cooling continues as fixed-delay process.
7	Cookies Packaging	(30 s/box, 12 cookies)	DRS	Deterministic batch process; bulk flow.
8	Box Sealing	(30 s/box)	DRS	Fixed sealing duration; no item-based variation.
9	Conveyor[3]	(25 s transit, 10m / 0.4m/s)	DRS	Based on length/speed; no events required.
10	Carton Warehouse	(source)	DES	Generates discrete cartons on demand.
11	Carton Branding	(60 s/carton)	DES	Operates on each carton separately.
12	Conveyor[4]	(12.5 s transit)	DES	Transporting identifiable cartons.
13	Carton Packaging	(60 s/carton, 16 boxes)	DES	Merges flow from DRS (boxes) and DES (cartons).
14	Conveyor[5]	(37.5 s transit, 15m / 0.4m/s)	DES	Moves discrete packed cartons.
15	Carton Sealing	(60 s/carton)	DES	Item-level operation with known time.
16	Conveyor[6]	(25 s transit)	DES	Intermediate delay modeled per carton.
17	Carton Labeling	(60 s/carton)	DES	Discrete labeling step.
18	Conveyor[7]	(37.5 s transit, 15m / 0.4m/s)	DES	Final transport for discrete units.
19	Shipping Area (Carton Counter)	(sink)	DES	Explicit count of arriving cartons required at destination.

Table 6. Process modeling choices based on simulation requirements and logic.

3. Process List and Modeling Paradigm

Simulation methods for each process stage are listed in Table 6. This decision is made based on the modeling requirements described in the task. Discrete Rate Simulation (DRS) is applied for continuous, deterministic processes where the focus is on throughput, while Discrete Event Simulation (DES) is used for discrete, item-level operations that require tracking or counting individual entities.

3.1. Rationale Summary

The simulation methods for each process were chosen based on the nature of the production logic and the specific analysis requested in the task. Discrete Rate Simulation (DRS) is used for the cookie production process, which operates in a continuous, high-throughput, and deterministic manner. The task requires calculating how many cookies can be produced in two weeks, which is aligned well with a flow-based modeling approach without tracking individual cookies. Even the inspection step, despite involving rejection, is implemented in a rate-based manner since individual cookie tracking is unnecessary.

In contrast, Discrete Event Simulation (DES) is used for the carton stream. The task explicitly requires counting the number of cartons arriving in the shipping area. Since this involves item-level tracking and discrete routing of cartons through packing, sealing, labeling, and final counting, DES is the most suitable modeling choice. This hybrid modeling approach effectively balances simulation accuracy and performance, applying DRS where flow is homogeneous and DES where item identity and tracking are required.

4. Flow Rate Calculation for DRS Processes

This section describes how the flow rates used as input for the Discrete Rate Simulation (DRS) processes are calculated and implemented in the simulation model. As an example, cookie machine operations are considered.

The production process defines that a cookie machine produces one identical cookie blank every 3 seconds. These event-based timings are converted to rate-based values for use in DRS.

Example: Cookie Machine (DRS)

Step 1: Event-Based Timing

- A cookie machine produces: $\frac{1}{3}$ cookie/second.
- Converted to per minute: $\frac{60}{3} = 20$ cookies/minute.

Step 2: Configuration in ExtendSim for DRS

- The `Tank` block (Ref Fig. 2) is set to have infinite capacity, acting as a continuous source of cookies.
- The `Valve` block (Ref Fig. 3), placed after the tank, limits the flow to **20 cookies/minute**, thereby enforcing the event-based rate.

Although the tank provides infinite flow, the valve regulates the actual flow to match the desired production rate. This setup ensures that the continuous flow model in DRS accurately reflects the discrete event logic, where a cookie is produced every 3 seconds.

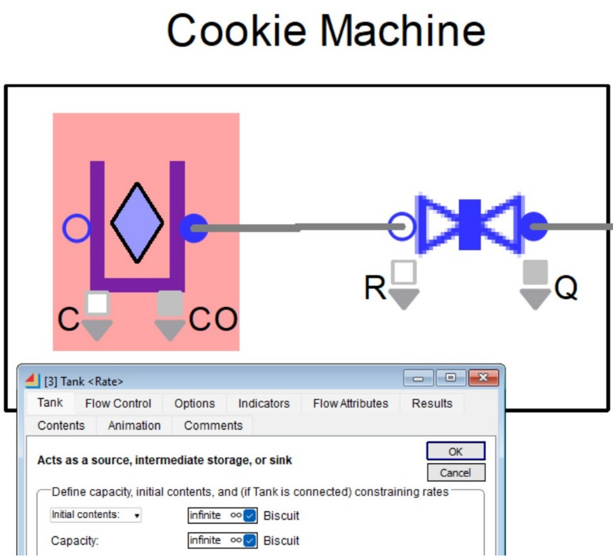

Figure 2. Tank block configuration in ExtendSim, representing an infinite cookie source.

5. Simulation Model Overview

The simulation model, **Assignment_02_Siddharthan _Somasundaram**, was executed for a continuous 14-day period, which is equivalent to **20,160 minutes** of operation. The simulation produced a total of **403,200** cookies. Of these, **362,872.50**

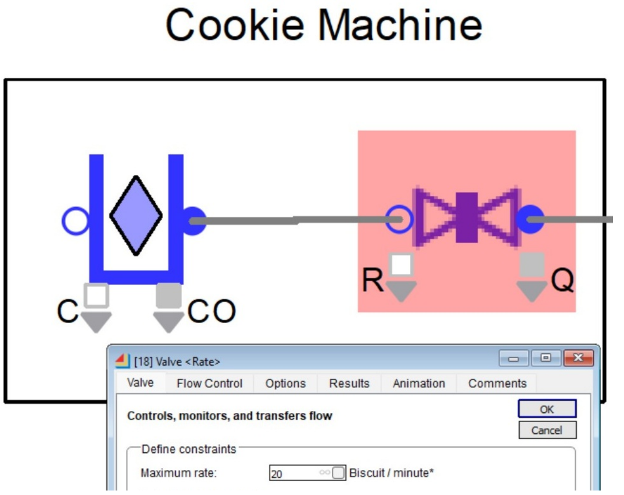

Figure 3. Valve block settings in ExtendSim, controlling the flow to 20 cookies/minute.

cookies were saleable, while **40,319.17** were rejected due to quality control. These saleable cookies were packed into **30,238.75** boxes, resulting in **1,889** cartons shipped to the shipping area.

The output values were obtained from the simulation results as shown in Fig. 4. Additionally, the average waiting time for the arrival of **16 boxes** at the carton packaging section was recorded as **10.66668 minutes**, indicating the average delay before a carton could begin packing.

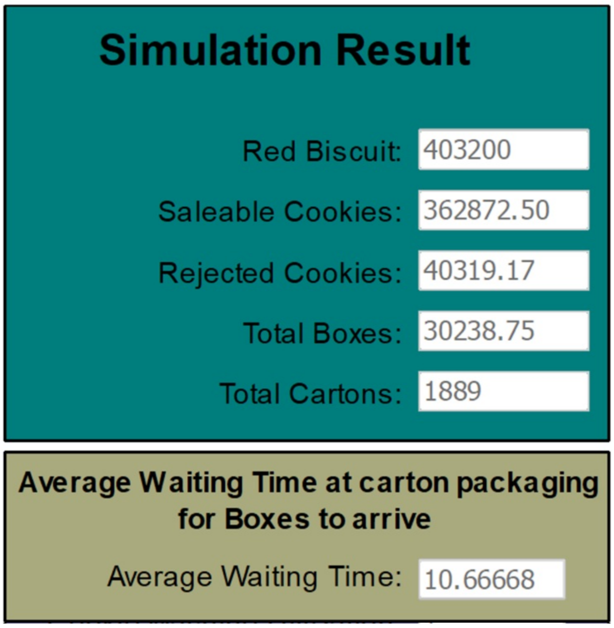

Figure 4. Simulation Result for 14 days

5.1. Bottleneck Analysis

5.1.1. Methodology

Bottleneck identification was carried out by analyzing the **utilization levels of key machines and stages** throughout the production line. A high utilization value (close to 1) indicates a fully utilized resource and a potential bottleneck, while low utilization reflects idle capacity.

The utilization of the production line components is illustrated in Fig. 5, which helps highlight the most strained areas in the system.

5.1.2. Primary Bottleneck: Cookie Production Line

The **cookie machine** operated at full capacity with a utilization of **1.00**, identifying it as the primary bottleneck of the system. In comparison, the downstream stages **cookie stamping** and **box sealing** had moderate utilization levels of **0.67** and **0.75**, respectively. This under use confirms that the cookie production rate is the limiting factor in the line. Increasing the capacity of the cookie machine or adding a parallel unit would potentially increase the system's total throughput.

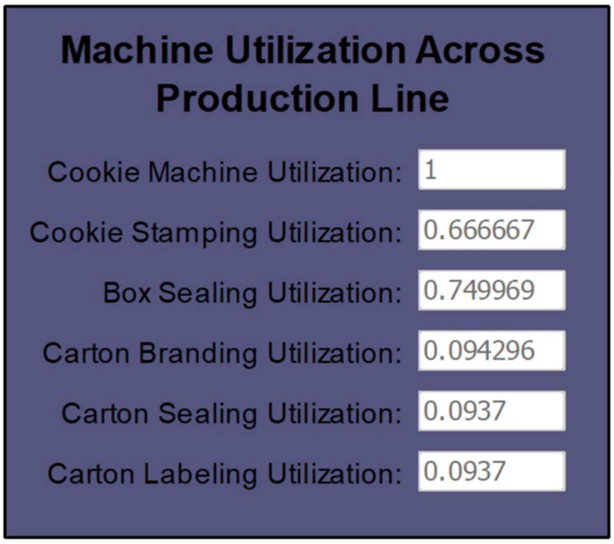

Figure 5. Utilization levels of key resources in the production line

This observation aligns with the **analytical bottleneck evaluation** presented in Section 2.2.6, which identified the cookie machine as the slowest stage (20 cookies/min) and the primary constraint of the cookie line.

5.1.3. Secondary Bottleneck: Carton Packaging Delay

At the **carton packaging stage**, the simulation recorded an **average waiting time of 10.67 minutes** as shown in Fig. 4 for the 16 sealed boxes to arrive. Although the actual carton packaging operation takes only 60 seconds, the process is delayed because the boxes are not available enough quickly.

This finding corresponds with the analytical conclusion in Section 2.2.6, where the delay in the carton packaging stage was attributed to the box sealing production rate rather than to limitations in the carton processing stages themselves.

5.1.4. Impact of Rejection Rate

The cause of the delay in the carton packaging stage is in part due to the **10% cookie rejection rate** at inspection. For every 100 cookies produced, only 90 are considered saleable. This means that to fill one box (12 saleable cookies), approximately 13.3 raw cookies must be produced. Consequently, to fill one carton (16 boxes), around **213 cookies** are required instead of 192, further slowing down the arrival of boxes at the carton packaging stage.

5.1.5. Link Between Primary and Secondary Bottlenecks

The secondary bottleneck in the carton packaging station is directly related to the primary bottleneck in the cookie production line. Because the cookie machine is the slowest fully utilized component and cookie rejects reduce the number of saleable units, the box output rate is limited. This, in turn, delays the carton packaging, which must wait for the sealed boxes to accumulate. The low utilization values for **carton branding, sealing, and labeling** (all around **0.09**) confirm that these processes have spare capacity and do not cause any delays.

5.1.6. Conveyor Consideration

According to the assumptions of the model, **conveyors are considered to introduce only transit delays and do not limit the capacity of the system**.

6. Comparison of Simulation Results vs. Conceptual Model Forecast

6.1. Overview

A detailed comparison was conducted between the output of the simulation model and the conceptual forecast based on steady-state assumptions. The simulation results Fig. 4 align with the rough calculation model Table 3, and the key findings are summarized below and compared in Table 7.

6.2. Key Comparisons

Metric	Conceptual Forecast	Simulation Result	Difference (%)
Red Cookies	403,200	403,200.00	0.00%
Saleable Cookies	362,880	362,872.50	-0.002%
Rejected Cookies	40,320	40,319.17	-0.002%
Boxes	30,240	30,238.75	-0.004%
Cartons	1,890	1,889	-0.053%

Table 7. Comparison Between Conceptual Forecast and Simulation Output

6.2.1. Explanation of Similarities

The simulation results are highly consistent with the conceptual forecast. In particular, the raw cookie output is exactly the same in both cases (403,200), confirming that the cookie machine operates precisely at the expected rate of 28,800 cookies/day for 14 days. This validates the integrity of both the forecast assumptions and the simulation logic in the upstream production stages.

6.2.2. Explanation of Minor Differences

The small deviations in the remaining metrics can be attributed to the following factors:

- **In-Process Units at Simulation End:** At the end of the 14-day simulation, some cookies, boxes, or cartons are still in transit or undergoing processing. These units are not included in the final output counts, unlike in the idealized forecast, which assumes that all items produced during the period are fully processed and counted. This is visible in the conveyor system flow data refer Fig. 6, where minor discrepancies between inflow and outflow suggest the presence of items still within the system at termination.

6.2.3. Forecast vs. Simulation

The conceptual forecast assumes a perfectly balanced production system with uninterrupted, steady-state flow across all stages. It calculates total output by multiplying the per-day rates by the total number of days (14), assuming that all units processed are fully completed and counted by the simulation end time. However, this analytical approach does not account for the actual travel time of items between stages — particularly the time spent on conveyors — which leads to minor discrepancies.

In contrast, the simulation model includes realistic conveyor behavior and transport times. As a result, while the flow remains constant, some items are still in transit on conveyors when the simulation ends at 20,160 minutes. These in-transit units are not yet processed and therefore do not appear in the simulation's reported output.

For example, as shown in Table 7, the carton count in the conceptual forecast is 1,890, but the simulation records only 1,889 cartons — a difference of one carton or -0.053%. This discrepancy arises because the final carton could not be fully formed or sealed before the simulation cut-off, due to delays introduced by upstream conveyor travel time.

This is further evidenced by the conveyor system flow data shown in Fig. 6, where slight mismatches between inflow and outflow are visible for conveyors 1–3.

- **Conveyor[1]** shows an inflow of 403,200 cookies and an outflow of 403,191.67, resulting in a shortfall of **8.33 cookies** or approximately **0.002%**.
- **Conveyor[2]** shows an inflow of 362,872.50 cookies and an outflow of 362,865.00, indicating **7.5 cookies** still in transit — a difference of **0.002%**.
- **Conveyor[3]** carries boxes and shows a difference of **0.63 boxes** (30,238.75 in vs. 30,238.12 out), which equates to approximately **0.002%**.

These small differences confirm that material was still moving between stages when the simulation concluded. The 0.002% discrepancy at Conveyor[3] accounts for part of the 0.004% difference observed between the fore casted and simulated total box counts (see Table 7). The remaining 0.002% deviation is caused by upstream shortfalls in Conveyor[1] and Conveyor[2], which limit the number of cookies available for packaging into complete boxes.

While each individual delta is minimal, these delays accumulate downstream — ultimately resulting in one fewer carton being completed and recorded within the simulation time frame.

These discrepancies accumulate downstream: delays at early conveyors cause a cascading effect, ultimately leading to one fewer carton being packed and recorded. Although this difference is minor in a 14-day run, it emphasizes the need to account for physical transport delays when evaluating simulation output against idealized forecasts.

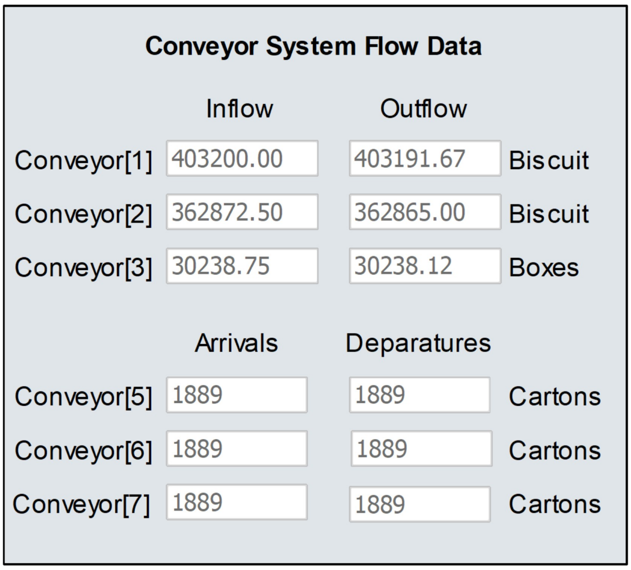

Figure 6. Conveyor system flow data showing small discrepancies between inflow and outflow at simulation end, indicating in-transit items.

7. Simulation Worthiness Assessment

Is this a simulation-worthy task? Yes.

Simulation is highly justified and effective for this task for the following reasons:

Core Justifications

- **Complex system dynamics:** The cookie production line encompasses multiple interdependent processes including cookie stamping, inspection, box sealing, and carton packaging. These stages exhibit different cycle times, rejection rates, and resource dependencies, creating a system too complex for accurate analysis using static calculations alone.
- **Critical bottleneck identification:** The simulation successfully identified key bottlenecks that were not immediately evident through conceptual analysis. Specifically, the cookie machine operates at maximum utilization (100%), while the carton

packaging station experiences average delays exceeding 10 minutes due to waiting for sealed boxes. These insights are critical for performance optimization and were only discoverable through dynamic simulation modeling.
- **Transient behavior analysis:** The simulation captured the system's start-up delay of 650 seconds (10.8 minutes) before the first carton could be processed. This initial non-productive period and its cascading impact through downstream processes are typically overlooked in static, steady-state analyses but significantly affect real-world performance metrics.
- **Comprehensive resource utilization insights:** Simulation provided detailed machine-level utilization metrics throughout the entire system, ranging from 9.37% (carton labeling) to 100% (cookie machine). These granular operational insights cannot be captured through manual calculations and are essential for identifying improvement opportunities.

Additional Benefits

- **Model validation and verification:** The simulation results closely aligned with the conceptual forecast, validating the analytical approach while revealing minor differences attributable to real-time flow dynamics and startup effects. This dual validation strengthens confidence in both the simulation model and the underlying assumptions.
- **Risk-free scenario evaluation:** Simulation enables virtual experimentation with production improvements, such as adding a second cookie machine, modifying packaging logic, or implementing buffer strategies, without disrupting actual operations. This provides a cost-effective method for evaluating proposed changes before capital investment.
- **Stochastic variability accommodation:** While current results emphasize deterministic behavior, real manufacturing systems incorporate randomness in arrival patterns, processing times, equipment failures, and quality variations. Simulation naturally accommodates these stochastic elements, unlike static calculations which assume constant operating conditions.
- **Scalability and sensitivity analysis:** The simulation framework can easily accommodate "what-if" scenarios, demand variations, and capacity changes, providing management with quantitative decision support for strategic planning.

For production planning tasks involving throughput estimation, bottleneck analysis, resource utilization optimization, and system performance evaluation, simulation offers essential insights that analytical or static approaches cannot provide. The ability to capture system dynamics, transient behaviors, and complex inter-dependencies makes this unquestionably a simulation-worthy task with significant practical value for operational decision-making.

8. Final Conclusion

This simulation study demonstrated the value of a hybrid modeling approach to analyze a complex cookie production system. By integrating Discrete Rate Simulation (DRS) for high-volume flow and Discrete Event Simulation (DES) for item-level tracking, we gained insights into system dynamics that would be difficult to obtain analytically.

Key Findings

Over 14 days, the system produced 403,200 cookies, of which 362,872 were saleable, yielding 30,238 boxes and 1,889 cartons. The deviation from the forecast (1,890 cartons) was just 0.053%, attributable to realistic conveyor delays and in-transit material at the simulation cut-off.

The primary bottleneck was the cookie machine, operating at 100% utilization. A secondary delay was observed at carton packaging, where an average wait of 10.67 minutes was needed to accumulate 16 boxes—reflecting the upstream bottleneck's ripple effect.

Value of the Hybrid Simulation Approach

The hybrid DRS-DES model proved both efficient and detailed. DRS allowed scalable modeling of bulk cookie flow, while DES captured granular tracking of boxes and cartons. Unlike static forecasts, the simulation realistically modeled conveyor travel times and in-transit inventory at simulation end—providing a more accurate representation of system performance.

Key insights included:

- Accurate machine utilization and flow dynamics
- Interaction between stages and delay propagation
- Realistic conveyor delays resulting in small in-transit inventories (e.g., 8.33 cookies, 0.63 boxes)
- Cumulative upstream delays leading to downstream output loss

Practical Implications

The model provides clear guidance for optimization:

1. Prioritize cookie machine upgrades to improve throughput
2. Reallocate resources from underutilized carton processing
3. Account for transport delays when comparing simulation vs. forecast
4. Recognize how minor upstream delays can impact downstream output

Model Validation and Accuracy

The close match between simulation and forecast validates the model, while minor discrepancies (0.002–0.053%) highlight its ability to capture physical realities that analytical models omit. The shortfall of one carton was due to small upstream delays accumulating—confirming the simulation's accuracy and the importance of modeling time-based behavior.

In conclusion, this analysis confirms our assessment that the cookie factory study is indeed a simulation-worthy task, with the benefits of simulation substantially outweighing the investment in model development and execution. The methodology successfully demonstrated that even minor physical realities—such as conveyor transport delays—can influence system performance in measurable ways that analytical approaches cannot capture. The insights gained provide a solid foundation for both operational improvements and future simulation studies of similar manufacturing systems, with the added confidence that the model accurately represents real-world system behavior.