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B. Sc. Final Year Project

Optimization of Production Scheduling in a Multi-Product Powdered Mix Factory

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July – 2025

DECLARATION

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Optimization of Production Scheduling in a Multi-Product Powdered Mix Factory

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ABSTRACT

Scheduling is a critical component of manufacturing operations, especially in factories producing a wide range of products. It involves assigning tasks or products to machines, workers, and resources over time to ensure an efficient workflow. Effective scheduling is essential for minimizing downtime, maximizing machine utilization, and meeting production goals. However, in factories where different products are made on the same machines, scheduling becomes more complex. Balancing production demands, machine capacities, and operational constraints can be challenging, especially when dealing with frequent changeovers and bottlenecks.

This project focuses on a factory that manufactures powdered mix products such as jelly, cake mix, juice mix, and ice cream. The factory faces significant challenges related to bottlenecks and changeovers, which are further complicated by the recent addition of a new machine to the production line. Bottlenecks occur when certain machines or processes become overloaded, limiting the flow of production. Changeovers, involving the adjustment of machines for different products, often lead to extended downtime. The new machine, while intended to increase capacity, has introduced additional disruptions, highlighting inefficiencies in the existing workflow and scheduling.

The primary goal of this project is to improve production efficiency by addressing key operational challenges. The focus lies in optimizing product allocation to machines and refining scheduling practices to reduce idle times and enhance workflow. Special attention is given to effectively integrating the new machine into the production line. To assess potential improvements, a simulation model was developed to test different production sequences for the six product types. The scenarios were evaluated using key performance metrics, including average cycle time and total units produced. The analysis revealed that some production sequences led to noticeably shorter cycle times and higher output. These results demonstrate that by adjusting the scheduling order, it is possible to enhance system performance, increase throughput, and better meet customer demand.

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LIST OF ACRONYMS/ABBREVIATIONS

CONWIP: Constant Work-In-Process

DBM: Drum Buffer Rope

DES: Discrete Event Simulation

EDD: Earliest Due Date

FIFO: First In, First Out

MILP: Mixed-Integer Linear Programming

MIP: Mixed-Integer Programming

MTBF: Mean Time Between Failure

MTTR: Mean Time to Repair

NP: Nondeterministic Polynomial Time

OEE: Overall Equipment Effectiveness

SMED: Single Minute Exchange of Die

SPRT: Shortest Processing Time

STR: Slack Time Remaining

VSM: Value Stream Mapping

WIP: Work-In-Progress

Chapter One

1 INTRODUCTION

1.1 HISTORY OF POWDERED FOOD MIX

The powdered food mix industry is an important part of the food and beverage industry, offering products that make meal preparation easier and more convenient. These products usually come in powdered form and only need water, milk, or a few other ingredients to be ready to consume. Some common examples include cake mixes, baking enhancers, juice mixes, and jelly powders. They're popular because they save time in the kitchen, are affordable, and have a long shelf life.

In Egypt, the powdered food mix market is valued at around $1.5 billion USD, which is about 3.75% of the total food and beverage industry, valued at $40 billion USD. Although it's a smaller part of the industry, it still plays a key role in Egypt's food market. Around 20-30% of Egypt's powdered food mix products are exported to various regions, with strong demand in the Middle East, North Africa, Europe, and the United States. These export markets are crucial to Egypt's trade strategy, benefiting from long-term agreements that make the process smoother. The increasing demand for Egyptian food products in these markets helps drive the success of the powdered food mix industry.

Scheduling is classified as an NP-hard problem, as the number of possible schedule solutions becomes enormous as tasks, machines, or resources increase. This complexity is further compounded by the limited availability of workers, machines, and tools, which adds significant challenges to creating feasible schedules. Additionally, many tasks required to complete a product must follow a specific order, with some depending on the completion of others, introducing dependencies that increase complexity. Scheduling can also be multi-objective in nature, where goals such as minimizing total production time, delays, or costs are difficult to achieve optimally and simultaneously.

In the powdered food mix industry, scheduling plays a vital role by planning and allocating resources such as machines, labor, and materials to ensure products are produced within a set timeframe. This is especially critical in the food sector, where smooth production operations are essential to optimizing output and ensuring product quality.

Products in this field are often made in batches, with production lines shared across different product types, leading to challenges such as frequent product changeovers. Effective scheduling addresses these complexities by ensuring each product is allocated to the most suitable machine, reducing the need for frequent adjustments and minimizing idle time. This approach supports multi-objective goals by maximizing machine utilization, minimizing downtime, and ensuring that production meets demand within constraints like limited resources and task dependencies. By doing so, efficient scheduling enables timely production, enhances operational efficiency, and ensures high-quality output, contributing significantly to the overall success of the powdered food mix industry.

1.2 PROBLEM STATEMENT

Factory X aims to determine the optimal schedule and product mix assignment for the new packaging machine, Machine X, in coordination with the existing machines to maximize efficiency and throughput.

1.3 STUDY AIM

The aim of this study is to enhance production efficiency in a powdered food mix manufacturing system by evaluating the impact of different product sequencing strategies. By taking into account sequence-dependent changeover times and real operational constraints, the project seeks to identify optimal scheduling approaches that reduce cycle time, increase throughput, and improve the overall performance of the production line.

1.4 STUDY OBJECTIVES

- To reduce average cycle time and increase total production output by evaluating different product sequencing strategies.
- To assess the impact of sequence-dependent changeover times on production performance.
- To identify operational constraints and company policies that affect scheduling decisions.
- To compare and analyze various scheduling scenarios to determine the most efficient production sequences for the powdered food mix line.

1.4.1 The Project's Objectives are SMART

- **S**pecific: Implement on specific product weight groups in the packaging area and on Machine X.

- **M**easurable: Key performance indicators such as average cycle time, total production output, and machine utilization are used to track improvements.

- **A**ttainable: Positive impact of scheduling on the performance of manufacturing systems (at no initial investment cost) is well documented in literature and meetings with company representatives confirmed that.

- **R**elevant: Evaluating and optimizing the sequence of different product types directly supports the goal of improving production flow. By reducing changeover times and addressing operational constraints, the project aims to increase output and streamline the performance of the powdered food mix packaging line.

- **T**imely: Achieve realistic results by the end of July 2025.

Chapter Two

2 LITERATURE REVIEW

Scheduling tasks in the food industry can be challenging, especially when the order of tasks affects how long it takes to switch between them. For example, moving from producing one type of product to another often requires cleaning equipment or setting up machines differently. These tasks, known as sequence-dependent setups, can slow down production and increase costs if not handled efficiently. The goal is to find the best way to schedule these tasks to save time, reduce WIP inventory, and avoid bottlenecks that can slow the entire process.

One effective way to study and improve scheduling systems is through discrete event simulation (DES). It is a powerful tool for analyzing and improving scheduling systems in the food industry. It allows researchers to create virtual models of production processes, making it easier to pinpoint inefficiencies and explore potential improvements. By simulating different strategies, DES provides insights into how adjustments in resource allocation or setup processes can enhance productivity without disrupting actual operations. This approach offers a practical way to identify and implement changes that reduce wasted time and improve overall system performance.

Changeovers, which occur when switching between tasks, are a major source of inefficiency in food production as they take time and can slow down the entire process. Reducing changeover times is essential to maintaining a smooth production flow. Similarly, bottlenecks, where certain tasks take longer than others, can limit overall output. Reducing bottlenecks and ensuring tasks flow evenly across the system significantly improves efficiency. Lowering WIP inventory is also crucial as it helps reduce clutter and ensures products move quickly through the system. Research has introduced various methods to address these challenges, focusing on optimizing the sequence of operations to minimize changeover times and balancing workloads to prevent parts of the production line from becoming overwhelmed. When paired with discrete event simulation, these strategies clarify how different schedules impact overall productivity.

This literature review provides an overview of the research on scheduling in the food industry, focusing on sequence-dependent tasks. It highlights the progress made so far and the challenges that still need to be addressed to make production systems more efficient. The review offers practical insights and serves as a helpful resource for both researchers and industry professionals looking to reduce changeovers, bottlenecks, and WIP inventory while improving overall performance.

2.1 OVERVIEW AND BACKGROUND

Improving production efficiency in sequence-dependent tasks is a major challenge for modern manufacturers, especially with growing customer demands. Research shows that smoother production can be achieved by optimizing scheduling. This means decreasing bottlenecks, reducing WIP levels, and cutting down on changeover times. In sequence-dependent tasks, bottlenecks often happen at machines or stations with the longest cycle times or the slowest changeovers (Li et al., 2023) [1]. On top of that, poorly managed WIP levels can slow things down even more, affecting throughput and machine utilization, and sometimes even creating new bottlenecks(Lödding et al., 2024) [2]. These problem areas can drag down the entire production line. By identifying and fixing these bottlenecks, manufacturers can create a smoother workflow for sequence-dependent tasks and run production lines that are faster, more efficient, and ready to meet demand.

2.1.1 Review Methodology

The research for related published articles on scheduling with sequence-dependent tasks, with a focus on reducing bottlenecks, minimizing WIP levels, and optimizing changeovers, was conducted using multiple academic sources. These included Google Scholar and The Egyptian Knowledge Bank, along with databases such as Taylor & Francis, Scopus, ProQuest, Emerald, and Web of Science. A total of 60 articles published between 2014 and 2024 were identified and reviewed from these sources. The analysis revealed numerous approaches and solutions to address the complex scheduling problem, with the majority employing simulation models as a primary method for problem-solving. Figure 2-1, titled "Flow Diagram for Article

Selection," provides a schematic representation of the methodology followed to identify and select relevant articles.

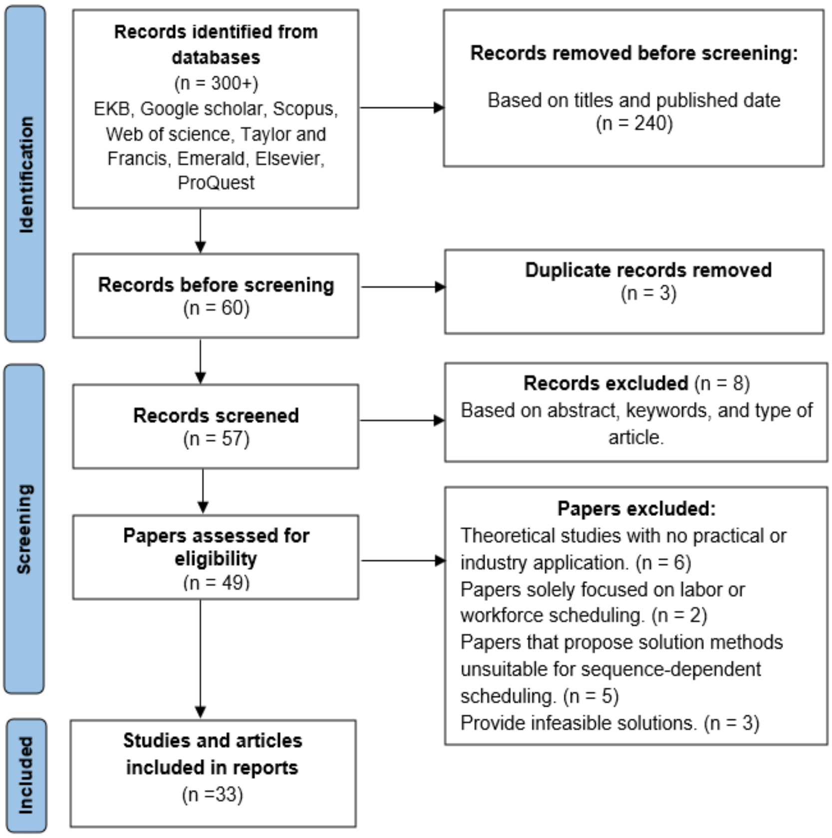

Figure 2-1 Flow Diagram for Article Selection

Out of the 60 papers reviewed, 33 were chosen as key references because they were the most relevant to the research problem. These papers were more closely related to the topic and used more extensively than the other 27 that were excluded. Real-world case studies, hypotheses, and different approaches from the selected papers were thoroughly analyzed and included in the literature review. This helped build a clearer understanding of the problem and contributed to defining, modeling, and addressing it within the field of study.

Criteria	Justification
Language: English	English was selected as it is the dominant language for academic publications, ensuring access to the most relevant and widely cited research.
Keywords: Scheduling, Bottlenecks, Changeover Times, Simulation, WIP Management, Sequence-Dependent	These keywords were chosen to pinpoint the most relevant studies that address the main challenges and methods related to the research topic.
Article Types: Journals and Conference Papers	Journals and conference papers were included because they are trusted sources of reliable information and offer both well-established research and the latest developments.
Date of Publication: 2014 to 2024	The selected date range ensures the research focuses on recent studies that reflect modern advancements and current practices in the field.

Table 2-1 Inclusions Criteria

Criteria	Justification
Theoretical studies with no practical or industry application.	They were excluded because they do not contribute directly to solving real-world scheduling challenges.
Solely focused on labour or workforce scheduling.	Because they fall outside the scope of sequence-dependent scheduling and the specific issues being addressed, like bottlenecks and changeovers.
Papers that propose solution methods unsuitable for sequence-dependent scheduling.	They were excluded because they wouldn't provide relevant or applicable solutions to the problem.
Provides infeasible solutions (changing layout, or add workers).	They were excluded because these approaches are not feasible within the constraints of this research.
Article Types: Dissertations, books, and reports.	They were excluded as they are often less accessible or lack the scholarly validation required for reliable academic research.
Date of Publication: Before 2014	To ensure the research incorporates only recent advancements and remains relevant to current trends and methodologies.

Table 2-2 Exclusions Criteria

After conducting a thorough search of the articles using the databases mentioned earlier and analyzing the results based on keywords, as illustrated in Figure 2-2, it was determined that the primary focus of the keywords was on scheduling, bottlenecks, changeover times, and simulation, which align closely with the objectives of this project. Additionally, the analysis of articles by publication date, as shown in Figure 2-

3, revealed a focus on recent publications to ensure the inclusion of valid and advanced solutions. This approach helps us incorporate the most valid and advanced methods into our work.

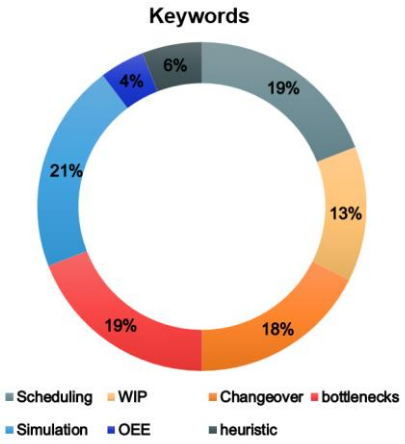

Figure 2-2 Keywords Used

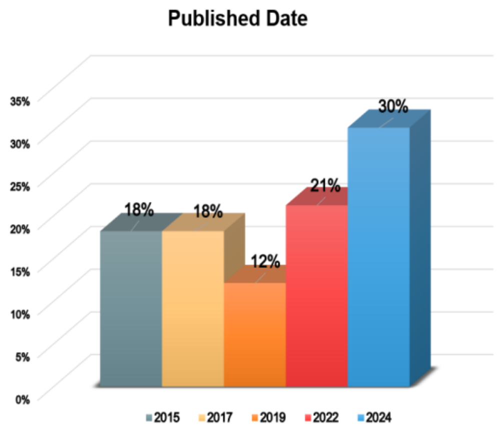

Figure 2-3 Published Date

2.2 IMPORTANCE OF SCHEDULING

Scheduling is a well-known NP-hard problem, as the effort required to find an optimal solution grows exponentially with the size of the problem. This challenge becomes even more pronounced in sequence-dependent setup scheduling, where setup times vary based on the order of tasks. While most existing methods address situations where a single operator manages setup tasks on a single machine, the complexity increases significantly in multi-machine systems. In such cases, changeover tasks must be coordinated across multiple machines or an entire production line, often requiring the collaboration of individuals with varying skill sets. Although optimizing setup times in sequence-dependent scenarios is highly relevant in practice, there is limited research dedicated to this issue. Developing advanced optimization techniques could help close this gap and enhance scheduling efficiency (Saeed Osman, 2021)[3].

2.3 SOLUTION METHODS IN LITERATURE REVIEW

From the reviewed literature, as shown in Figure 2-4, various solution methods have been identified. About 11 articles used optimization techniques like Mixed-Integer Linear Programming (MILP), Mixed-Integer Programming (MIP), and heuristic methods. Another 4 articles focused on data-driven and analytical approaches, such as Data-Enabled Mathematical Models and ABC Classification. The majority of the studies, 15 articles, relied on simulation models to handle the complexity of these problems. Different types of simulations were used, including Agent-Based Simulation, Digital Twin, and Monte Carlo Simulation, but the most commonly used approach was Discrete Event Simulation (Lohmer & Lasch, 2021)[4].

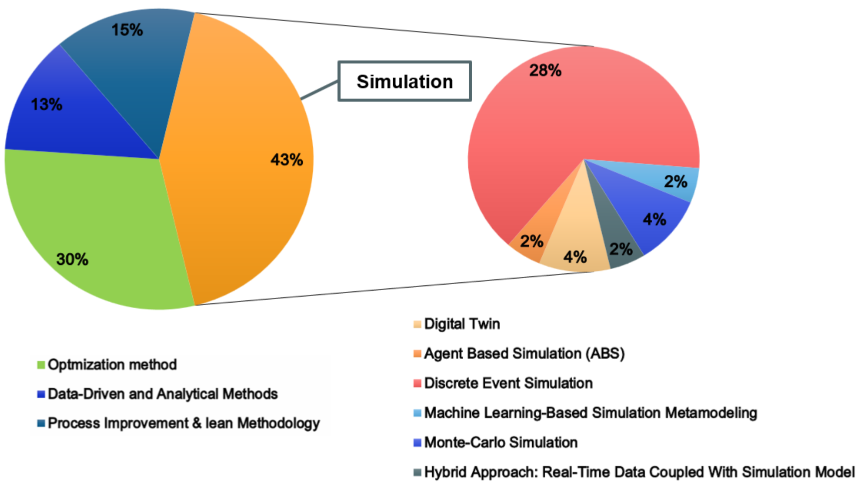

Figure 2-4 Solution Methods found in Literature Review

2.4 CHANGEOVERS IN SEQUENCE DEPENDENT SYSTEMS

In industrial manufacturing, converting raw materials into finished products is a key responsibility of the production department, achieved through various processes using individual machines or complex multi-machine systems. Machine efficiency can be hindered by several factors, including startups, minor stoppages, idling, reduced speed, tool changes, defective outputs, rework, and shutdowns. Among these, changeover losses stand out as the most significant obstacle. Reducing changeover times has become a priority for many factories, as it is a manageable aspect of production that can be optimized to boost efficiency. Shorter changeover times not only lower production costs but also provide greater flexibility, allowing production lines to adapt quickly to changing demands and customer needs. In many factories, machines often handle diverse products or variations within the same product family, requiring two primary types of changeovers: transitioning between different product types and adjusting for size variations within a single product type (Saeed Osman, 2021)[3].

2.4.1 Solution Methods to Reduce Changeovers

The problem has been addressed using various optimization techniques that have been screened, reviewed, and studied during literature research. Lean manufacturing tools such as Single Minute Exchange of Die (SMED), 5S, and Kanban were highlighted, along with heuristic methods like priority rule-based scheduling. Time-motion studies and deterministic tools, including CPM, were also explored. Priority rules have been extensively studied through simulation experiments over the past three decades (Haupt, 1989)[5]. The rule-based scheduling method, for instance, utilizes the simulation tool SchedulePro™, which employs predefined rules to organize production sequences. To minimize changeovers, products are grouped into families with similar characteristics, and production sequences are carefully planned to reduce transitions between families. Users can interactively modify schedules based on their knowledge of the facility, refining them further to reduce changeover times. While this approach does not guarantee optimal solutions, it is flexible and provides quick results, making it ideal for dynamic environments requiring frequent adjustments. Its effectiveness largely depends on the user's familiarity with the production process(Samouilidou et al., 2023) [6]. SMED is another lean manufacturing technique focused on reducing changeover times to enhance efficiency and minimize waste. It involves analyzing and reorganizing setup tasks to shift downtime activities to external ones, standardizing procedures, and employing parallel operations to speed up execution. This method reduces downtime, enables smaller production batches, improves defect detection, and increases flexibility, making it an essential tool for optimizing production processes. These are just a few of the solution methods for managing changeovers identified in the reviewed literature(Maalouf & Zaduminska, 2019) [7].

2.4.2 Time Motion Studies to Reduce Changeover Times

Time-motion studies are highly effective in reducing changeover times in food production industries by analyzing and optimizing the movements of workers and materials during processing and packaging tasks. Techniques such as Spaghetti Diagrams and Gemba Walks help map and evaluate the flow of activities on the production floor, where tasks often involve handling perishable goods and strict hygiene protocols. Spaghetti Diagrams visually trace the paths taken by workers and materials, identifying inefficient or redundant movements that can be streamlined to save time and reduce delays. Gemba Walks involve real-time observation of operations, enabling supervisors to spot inefficiencies and reorganize workflows to ensure smoother task transitions. Time-motion studies can significantly reduce changeover times by minimizing unnecessary steps, improving workstation layouts, and standardizing procedures, ensuring faster and more efficient production processes in the highly time-sensitive food industry(Oliveira & Lima, 2023) [8].

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2.5 ADDRESSING BOTTLENECKS IN A SYSTEM

Bottlenecks are critical problem areas in manufacturing systems that disrupt efficiency by restricting the production flow. They occur when a specific station or component cannot keep pace with the rest of the process, causing delays and disruptions. This often results in upstream stations becoming congested and downstream stations running out of work, which significantly impacts productivity. The challenge of bottlenecks increases in complex and unpredictable environments, where factors such as fluctuating cycle times and unplanned stoppages intensify inefficiencies. Addressing bottlenecks is essential to maintaining smooth operations, as they directly influence production rates, lead times, and overall efficiency. If left unresolved, bottlenecks can lead to higher costs, wasted resources, and missed deadlines, making their effective identification and resolution crucial for operational success(Li et al., 2023) [1].

2.5.1 Bottleneck Identification and Reduction

Bottleneck identification methods in sequence-dependent food production systems can be grouped into three main approaches. Queue-state methods focus on analyzing queue lengths and waiting times at various stages of production to locate bottlenecks. Process state methods examine metrics such as equipment utilization, active processing times, and the shifting nature of bottlenecks as production demands and durations vary. System state methods integrate data from both queue and process states, employing tools such as the Gemba Walk, bottleneck index, and sensitivity analysis to identify inefficiencies. Using these methods helps detect bottlenecks within sequence-dependent workflows in food production, ultimately enhancing throughput and improving production efficiency(Skoogh et al., 2023) [9].

Among these, techniques such as the Gemba Walk, DES, simulation modeling, and data-driven analytics have proven particularly effective. The Gemba Walk involves real-time observation of production floors to identify disruptions, such as equipment breakdowns or material delays, enabling quick decisions to reallocate resources and streamline workflows. DES complements this by creating virtual models of production systems, allowing processes and scenarios, such as equipment changes or schedule adjustments, to be simulated without disrupting operations. Data-driven analytics and simulation modeling further enhance these efforts by analyzing system behavior and predicting potential bottlenecks, supporting dynamic resource optimization. Together, these methods help manage bottlenecks effectively in complex manufacturing environments, including the food industry, where challenges like perishable inventory and strict schedules are common(Skoogh et al., 2023) (Mediouni et al., 2022) [9, 10].

2.5.2 Lean Techniques for Identifying and Reducing Bottlenecks

Lean manufacturing techniques also provide a robust framework for identifying and reducing bottlenecks in food production systems. Value Stream Mapping (VSM) offers a comprehensive overview of material and information flow, highlighting inefficiencies such as waiting times, unnecessary processes, and excess inventory. By categorizing activities into value-added and non-value-added tasks and pinpointing bottlenecks through differences between Takt time and process cycle times, VSM enables targeted improvements to streamline production flow (Woldemicael et al., 2024) [11]. Kanban systems further aid by synchronizing production with actual demand, regulating inventory, and preventing overproduction and delays. The 5S methodology enhances workplace organization by eliminating unnecessary movements and ensuring easy access to tools and materials, improving overall efficiency. Kaizen promotes continuous improvement through incremental process changes driven by employee input, while SMED minimizes changeover times, boosting flexibility and reducing downtime. Collectively, these methods provide an integrated approach to addressing bottlenecks and optimizing workflows, significantly enhancing productivity in food production systems (Oday & A. Mohamed, 2024) [12].

2.5.3 Streamlining Production with Drum Buffer Rope

The Drum Buffer Rope methodology is another proven strategy for reducing bottlenecks by synchronizing material flow. In this system, the "drum" represents the bottleneck, setting the production pace and dictating the rhythm of the entire process. Buffers are strategically placed before the bottleneck to maintain a steady supply of materials, reducing the risk of production stoppages caused by upstream delays or disruptions. The "rope" serves as a control mechanism, regulating the release of materials to match the bottleneck’s throughput capacity. By aligning production orders with buffer usage and demand, DBR streamlines operations, minimizes delays, and enhances overall efficiency. This approach is particularly effective in dynamic environments with shifting bottlenecks, as it optimizes resource utilization while maintaining consistent production flow(Yue et al., 2022) [13].

2.6 WIP LEVELS

In the powder food mix industry, WIP refers to ingredients and partially blended mixes that are in different stages of the production process, such as weighing, mixing, or packaging, but haven’t been completed yet. Managing WIP ensures the production line runs efficiently, prevents delays, and maintains the quality and safety of the final product(Tufano et al., 2018) [14].

WIP levels are essential for ensuring production systems operate efficiently. Properly managed WIP keeps materials moving steadily through the process, improving throughput times, maximizing resource utilization, and ensuring products are delivered to customers on schedule. However, if WIP levels are too high, they can lead to longer delivery times, higher inventory costs, and dissatisfied customers. On the other hand, if WIP levels are too low, production flow can be disrupted, resulting in idle resources and lower productivity. Maintaining the right WIP levels is not just about managing inventory but about optimizing the entire production system. By finding this balance, companies can reduce costs, improve delivery performance, and better meet customer demands (Lödding et al., 2024) [2].

2.6.1 Effective Strategies for Managing WIP

WIP management is crucial for improving manufacturing systems, particularly in the food industry, where efficiency and quality are essential. Various methods effectively identify and reduce WIP levels while enhancing overall performance. Simulation modelling analyzes production processes, identifies bottlenecks, and tests scenarios to optimize resource allocation. Machine learning-based prediction models forecast job completion times and potential risks, minimizing delays and maintaining optimal WIP levels. Heuristic and mathematical programming approaches, such as mixed-integer programming, support scheduling and lot-sizing, ensuring balanced production and efficient resource use(Shin et al., 2019) [15].

Lean production practices complement these strategies by focusing on waste elimination and process optimization. Just-in-time production aligns output with demand, preventing overproduction and reducing inventory, while value stream mapping and the 5S methodology streamline workflows and organize workspaces to eliminate inefficiencies. Continuous improvement initiatives, such as Kaizen, and automation techniques like error-proofing systems, minimize defects, rework, and unnecessary inventory build-up, contributing to a leaner, more efficient production process (Shah & Ganji, 2017) [16].

The CONWIP (Constant Work-In-Process) system introduces a pull-based production control method by limiting WIP through the use of CONWIP cards. A pull system is a production control method that regulates workflow by limiting the amount of work in progress (WIP) to ensure efficient resource utilization and reduce inventory build-up (Jaegler et al., 2018)[17]. These cards accompany jobs throughout production stages and authorize new job entries only upon completion. This system prevents inventory overflow, enhances lead time control, and improves key metrics such as delivery reliability, workstation utilization, and throughput. Together, these methods provide a comprehensive framework for effective WIP management in dynamic and complex industries like food production. (Muhammad et al., 2015)[18].

Bottleneck scheduling is another vital strategy for reducing WIP inventory. Bottlenecks occur at production stages where capacity constraints slow processes, causing delays and inventory build-up. Identifying bottlenecks, using tools such as Pareto analysis or process mapping, enables targeted resource allocation to constrained stages. Addressing bottlenecks often involves upgrading equipment, redistributing workloads, or optimizing scheduling to synchronize the bottleneck's throughput with upstream and downstream processes. For instance, a manufacturing plant implementing these measures successfully reduced WIP, improved efficiency, and lowered costs (Rane, n.d.)[19].

Effective coordination is crucial for bottleneck scheduling. Measures such as upgrading machinery, automating workflows, and aligning production rates across departments ensure balanced production stages and minimized inventory. These adjustments help achieve lean manufacturing goals by reducing operational inefficiencies and maintaining continuous flow (Rane, n.d.)[19].

Priority rule-based scheduling offers a flexible approach to managing WIP inventory under dynamic shop floor conditions. Common rules, such as First In, First Out (FIFO), Earliest Due Date (EDD), Shortest Processing Time (SPRT), and Slack Time Remaining (STR), influence production performance by addressing lateness and machine utilization. For example, EDD and STR prioritize jobs with the earliest due dates or least slack time, reducing delays and idle time while lowering WIP levels (Červeňanská et al., 2021)[20].

Incorporating these priority rules into multi-criteria optimization frameworks enhances resource allocation and balances throughput and efficiency. By tailoring scheduling rules to specific production goals, businesses can achieve lean manufacturing principles, minimizing excess inventory and maximizing operational performance(Červeňanská et al., 2021) [20].

Chapter Three

3 CASE STUDY

The increasing demand for packaged powdered mixes is creating challenges for manufacturing facilities. As consumers continue looking for convenient baking and cooking ingredients, factories need to keep up with higher production volumes while staying efficient. To meet this demand, manufacturers must focus on reducing bottlenecks, minimizing WIP, improving throughput, and reducing the number of changeovers.

In powdered mix production, many processes are sequence-dependent; meaning the order in which products are made can affect the efficiency of the whole production line. This can often lead to bottlenecks and changeovers, which disrupt the flow of production and cause unnecessary downtime. To address these issues, factories need a well-organized production schedule. A key strategy is optimizing product-to-machine allocations to balance workloads, minimize downtime, and reduce the number of changeovers between runs. By improving the allocation process, manufacturers can enhance efficiency and better respond to market demands.

This case study examines the importance of proper product-to-machine allocations and their impact on these key production factors. It will explore how effective product-to-machine assignments can enhance production efficiency and help manufacturing facilities meet demand.

3.1 FACTORY X

During the initial phase of our project, we explored several industries, including petrochemicals and garment manufacturing, but each presented challenges that made them less suitable for our research. In the petrochemical sector, we found that the specialized nature of the products created significant difficulties in applying our production scheduling techniques. The processes involved were highly complex and rigid, making them incompatible with the goals of our study. On the other hand, in the garment manufacturing industry, the majority of operations were manual, with only a few machines involved, mainly for sewing. This limited automation made it difficult to implement the advanced production optimization methods we aimed to explore, as the processes were relatively straightforward and lacked the complexity we needed for our study. After careful consideration, we chose Factory X as the focus of our case study. The company operates shared production lines that manufacture a wide range of products, making it a perfect match for our objective of optimizing scheduling in a multi-product manufacturing environment. Furthermore, Factory X was not only open to collaborating with us but also provided valuable access to their production data and processes, which was crucial for the development of our study. With its diverse product mixes, automated systems, and willingness to support our research, Factory X emerged as the ideal candidate for this case study, allowing us to explore real-world challenges in production scheduling and optimization.

3.2 FACTORY OVERVIEW AND BACKGROUND

Factory X is an Egyptian German Food company founded in the late 1970s. This company specializes in the production of powder dessert mixes, instant powder drinks, ice cream mixes, jelly desserts, and more for both Food Service markets and Consumers. Over the years, Factory X has emerged as the market leader in Egypt, offering high-quality ingredients, bakery enhancers, and flavorings for the bakery and pastry industries as well as for everyday household use. Factory X's Consumer Sector is passionate about exquisite taste and the process of making recipes and ingredients that help mothers and chefs prepare well-made food and make refreshing and warm beverages for everyone to enjoy.

3.2.1 Factory X’s Ethics

Factory X is dedicated to maintaining strong ethical standards to create a positive and professional workplace. The company places great importance on confidentiality, ensuring that sensitive business information, trade secrets, and intellectual property are protected at all times. This helps to keep important data secure and accessible only to authorized personnel. To ensure the health and safety of employees, Factory X has a strict drug-free workplace policy, which bans any use or abuse of drugs on the premises. As part of this policy, the company conducts drug tests every six months to maintain a drug-free environment and ensure a safe, focused workplace. The company also practices neutrality, encouraging employees to avoid participating in political activities while at work, ensuring that work priorities remain the main focus. Lastly, safety compliance is a top priority, with Factory X following all health and safety regulations to ensure a secure work environment. Regular training and safety protocols are in place to prevent accidents and protect the well-being of all employees.

3.2.2 Factory X's Product Families

Factory X produces a wide range of over 400 products, which are organized into five main product families to streamline production and meet various customer needs. The first family is the Powder Ice Cream Base, which includes popular products like Ice Cream Softy Vanilla, Ice Cream Softy Chocolate, and other ice cream bases that allow for easy preparation of different ice cream flavors. The second family, Powder Cake Mix, includes products designed for easy cake preparation, such as mixes for brownies, molten cakes, muffins, and other baked goods. The third family, Powder Baking Enhancers, features products like Cake Chef, baking powder, and vanilla, which enhance the texture, taste, and overall quality of baked items. The Powder Juice Mix family offers a variety of flavored powdered mixes, including apple, mango, and orange, that can be quickly prepared by adding water to create refreshing beverages. Lastly, the Powder Jelly Mix family includes products for making jelly in various flavors, such as strawberry and berry mixes, providing a convenient solution for dessert preparation. By organizing their products into these families, Factory X is able to efficiently manage its large product portfolio while ensuring they offer a broad selection of high-quality and convenient options to meet customer demands.

3.3. VISITS AND INTERVIEWS

The information-gathering process for this project began with thorough planning and preparation. A detailed list of questions was created to ensure that each visit would cover all important aspects of production scheduling and factory operations. Several visits were made to Factory X to observe the production processes and gain an in-depth understanding of the factory’s operations. During these visits, interactions were conducted with staff across various levels, including both managerial personnel and machine operators, to gather diverse perspectives on the challenges and inefficiencies present in the production process. Interviews were carried out with both managers and operators to investigate the underlying causes of issues such as bottlenecks, idle times, and changeovers. This hands-on approach, which combined direct observation with interviews, provided crucial insights that were instrumental in developing effective solutions to improve the production scheduling system.

3.4. FACTORY X PRODUCTION PROCESS

The production line at Factory X is structured across three floors, as seen in Figure 3-1, each playing a crucial role in the manufacturing process. The third floor is dedicated to sieving, a process where particles are separated based on size using mesh surfaces. This ensures uniformity in the powdered ingredients while removing any impurities, which is essential for maintaining the high quality of the final products.

On the second floor, mixers are employed to blend all the ingredients uniformly. The mixing process is critical for achieving a consistent and high-quality product. During this stage, a premix is added midway through the operation to further enhance the product's characteristics. The sieved powder is transported via tubes to the mixers, creating a seamless flow between these two stages of production. Once the powder mixture is prepared, it undergoes a thorough inspection to ensure it meets the factory’s quality standards. After passing the inspection, the mixture is transferred into storage tanks before being sent through tubes to the packaging machines located on the ground floor. The packaging process involves enclosing and protecting the final products using materials such as boxes, bags, or wraps. This step ensures the safety, quality, and ease of transport and storage of the products.

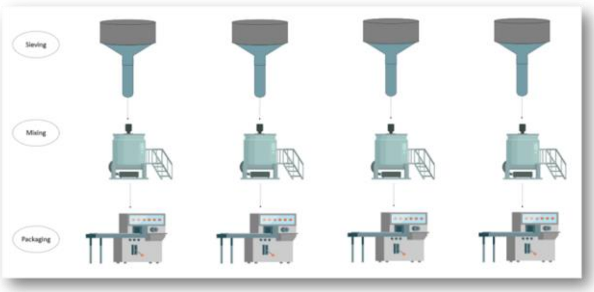

Figure 3-1 Three Floor Production Line

After packaging, an additional inspection is performed to verify the quality and accuracy of the finished product. Once the packaging is approved, the products are moved to the finished products inventory, ready for distribution or shipment. This flow of production is shown more clearly in Figure 3-2 as shown below.

Additionally, the ground floor houses the Research and Development (R&D) laboratory, which plays a vital role in product innovation and quality control. The floor is also equipped with scanning machines that print necessary information, such as production dates and batch details, on the packaging to ensure traceability and compliance with industry standards.

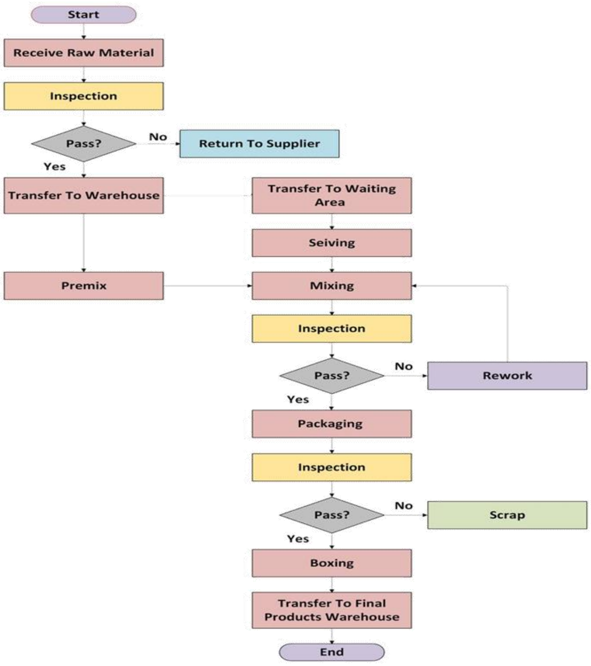

Figure 3-2 Flow Chart of the Production Line

3.5. PROBLEMS FACED AT FACTORY X

Through visits and interviews, we identified that the demand for certain products was not being met due to inefficiencies in some packaging machines and lengthy changeover times. Many of these machines, responsible for the unmet demand, had low OEE, primarily due to their age. The low OEE was caused by reduced availability, resulting from prolonged changeovers, and insufficient performance, as the machines were unable to operate at full efficiency.

To address the issue of unmet demand, Factory X decided to invest in a new packaging machine as a strategic decision to enhance revenue, reduce cycle times, and increase overall production capacity. While the new machine was intended to help meet the demand for high-priority products, its introduction also brought challenges, including the potential for increased bottlenecks, and extended changeover times. Addressing bottlenecks, which constrain the overall throughput of the production line, became a critical focus.

After acquiring the new machine, the challenge shifted to determining the optimal allocation of products between the new and existing machines to maximize overall efficiency. The 72 products with unmet demand were grouped by weight to minimize changeover times and streamline the product-to-machine assignment process.

3.6. DATA COLLECTION

Data collection is a key part of this project because it provides the information needed to study the system and support better decisions. In this case study, three main types of data were collected: structural, operational, and numerical.

Structural data describes how the system is organized and how its parts interact, which helps identify potential delays or issues. Operational data captures day-to-day activities, such as process times, waiting times, and resource usage, showing how the system functions in practice. Numerical data consists of measurements and figures that show patterns and help evaluate system performance using statistics like averages and standard deviation. By collecting these types of data carefully, we can check if our ideas about the system are correct and make our conclusions more reliable.

The project also used two types of inputs: deterministic and random. Deterministic inputs are fixed and do not change, such as standard processing times or schedules, and help illustrate the system's basic behavior. Random inputs vary each time and reflect real-life uncertainty, such as fluctuating arrival times or unexpected delays. Combining both types of inputs offer a more realistic representation of how the system actually operates.

3.6.1. Demand

The daily demand for these six products is different from one another, as shown in Table 3-1. For example, around 37,800 sachets of Juice Mix at 670 grams are needed each day, while the demand for Cake Mix at 450 grams is about 10,080 sachets. In terms of weight, daily production ranges from just over 1,100 Kg for Cooking Cocoa at 80 grams to more than 50,000 Kg for the large 2.5 Kg Juice Mix. The number of batches made each day also varies a lot, from roughly two batches for Cooking Cocoa to more than 100 batches for the biggest Juice Mix.

Having this demand data is really helpful for planning how much to produce, organizing storage space, and making sure workers and machines are used efficiently. By looking at the demand both in the number of sachets and the total production weight, it becomes easier to see how products flow through the system and find ways to make the process run more smoothly.

Product	Daily Demand Sachets	Kg	Kg/Day	Batch/Day
Ice Cream and Jelly (1Kg)	30240	1	30240	64
Cake Mix (450gm)	10080	0.45	4536	10
Juice Mix (670gm)	37800	0.67	25326	54
Juice Mix (750gm)	32600	0.75	24450	52
Juice Mix (2.5Kg)	20160	2.5	50400	107
Cooking Cocoa (80gm)	14400	0.08	1152	3

Table 3-1 Daily Demand for Each Product Type

3.6.2. Structural Data

Structural data describes the overall layout and design of the system, highlighting how different parts are organized and interact with each other. In this project, structural data was collected through a combination of direct observations and interviews with production engineers. Observations provided a clear view of how the production process operates in real conditions, while interviews offered deeper explanations and clarified details that are not always visible during observation. Interview questions were prepared to gather detailed information efficiently, and the responses were later analyzed. This approach helped develop a clear understanding of the system's structure and the relationships between its key components.

3.6.2.1. Factory Layout

In the case study, a detailed facility layout analysis was conducted to understand how the production process is organized across the factory. The facility is distributed over three floors, each playing a specific role in the overall material flow and production cycle. The process starts on the first floor, where raw materials are stored in the raw materials inventory area until they are needed for production. From there, the raw materials are moved upward by elevator to the third floor, marking the starting point of the production line.

On the third floor, as shown in Figure 3-3, the sieving stage takes place using sieving machines designed to separate and refine the raw materials. Although the factory is equipped with a total of ten sieving machines, this study focuses on the five machines that are actively used to produce the six product types analyzed. During sieving, the raw powder passes through fine mesh screens that remove impurities, break up clumps, and ensure that only particles of the correct size proceed further in the process. This step is crucial for achieving a uniform texture in the final product, maintaining product consistency, and meeting quality standards. The sieving operation helps reduce the risk of defects in later stages and supports smoother downstream processing.

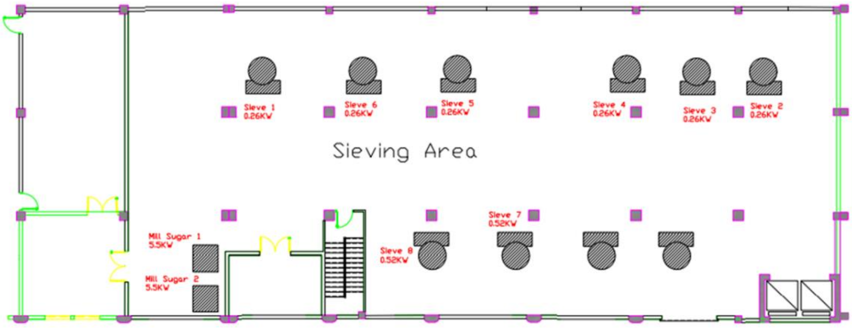

Figure 3-3 Top Floor Layout

Once sieving is complete, the processed powder is transferred through a system of connecting tubes to the second floor, where the mixing operations are carried out as shown in Figure 3-4. Here too, the factory has ten mixers installed, but only five are currently in use for the product types covered by the case study. The mixing stage plays a vital role in combining different ingredients in the right proportions to create the final product blends. The mixers work by rotating or agitating the powders, ensuring that additives, flavors, and other components are evenly distributed throughout the batch. Consistent mixing is essential for delivering a uniform taste, appearance, and quality in every sachet produced. Close monitoring during mixing helps prevent issues such as uneven distribution, clumping, or loss of product quality.

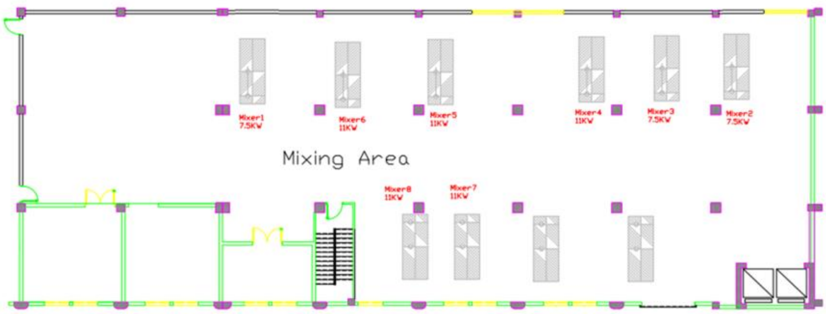

Figure 3-4 Second Floor Layout

After the mixing stage, the product continues down to the first floor, where the packaging area is located as shown in Figure 3-5. Packaging operations include a mix of automated packaging machines that handle large volumes efficiently and manual processes for products or pack sizes requiring more flexible handling. In addition to the packaging section, the first floor contains a research and development (R&D) room, where new product ideas and process improvements are explored, and an inspection room dedicated to quality control. This room is responsible for checking product samples and ensuring they meet the company's standards before final release.

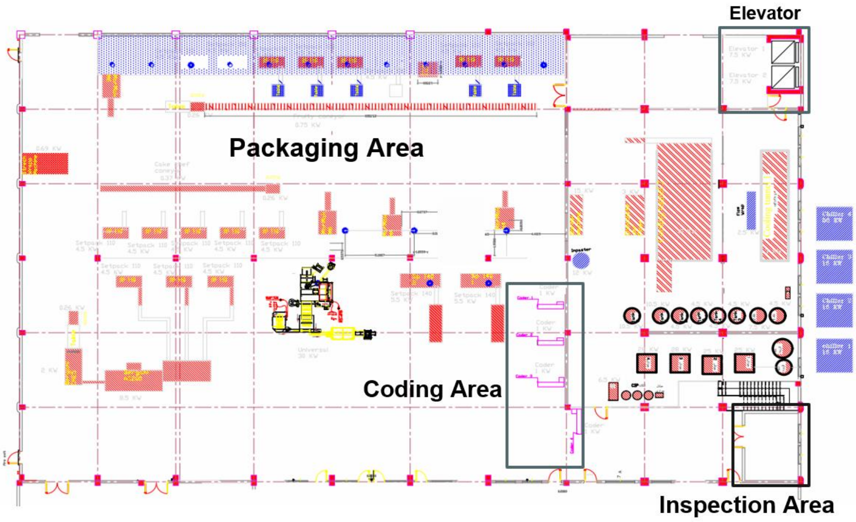

Figure 3-5 Ground Floor Layout

Studying the layout in detail and focusing specifically on the equipment currently in operation provides a realistic view of how the factory manages daily production. This approach helps explain how each stage of the process, from raw material preparation and sieving to mixing and packaging, contributes to keeping production efficient, maintaining consistent product quality, and meeting customer demand.

3.6.2.2. Labor Analysis

Human resources capacity, often called labor capacity, refers to the total amount of work that a team can complete within a certain timeframe, based on the number of workers, their skill levels, working hours, and overall efficiency. Analyzing labor capacity is essential because it shows whether the existing workforce can meet the project's production targets and timelines. This understanding helps in making informed decisions about staffing, training, and workflow planning.

When it comes to production processes, labor capacity directly influences how many units can be prepared, packaged, and quality-checked each day. In this case study, evaluating labor capacity is especially valuable for identifying whether there are enough qualified workers to keep each step of the process (including sieving, mixing, packaging, and final inspection) running smoothly without delays or disruptions. Effectively managing human resources helps maintain steady production, ensures consistent product quality, and supports the overall efficiency of operations.

The table below, Table 3-2, shows how many workers are assigned to each part of the process, from sieving and mixing to packaging and final packing. This gives a clearer picture of how the team is organized to keep production running smoothly.

	Work Stations	Description	Capacity
1	Sieving Setup	The worker sets up and adjusts the sieving machine to make sure materials are properly sorted and ready for the next step.	5
2	Mixer	The worker prepares the mixing machine, adds the premix ingredients, and ensures the materials are blended evenly for the next stage.	3
3	Packaging Setup	The worker sets up the packaging machine, adjusts it for the correct pack size, and makes sure it runs smoothly to fill and seal the product properly.	3
4	MK1 Packaging Machine	The worker places the filled powder bags from the packaging machine into cartons, then packs these cartons into larger boxes for storage or shipping.	6
5	MK2 Packaging Machine	The worker places the filled powder bags from the packaging machine into cartons, then packs these cartons into larger boxes for storage or shipping.	6
6	MK3 Packaging Machine	The worker places the filled powder bags from the packaging machine into cartons, then packs these cartons into larger boxes for storage or shipping.	6
7	200Filler Packaging Machine	The worker places the filled powder bags from the packaging machine into cartons, then packs these cartons into larger boxes for storage or shipping.	6
8	Machine X Packaging Machine	The worker places the filled powder bags from the packaging machine into cartons, then packs these cartons into larger boxes for storage or shipping.	8

Table 3-2 Labor Analysis

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3.6.2.3. Machine Capacities

In a multi-product powdered mix factory, machine capacity refers to the number of machines available and operating in the facility, as shown in table 3-3, for all the operations such as sieving, mixing, and packaging. This number directly affects how much the factory can produce during each shift, so their quantity directly impacts overall production output. When there are more machines, more work can be done at the same time. Knowing the machine capacity is important for organizing production schedules, managing resources, and making sure the factory meets its daily or weekly demand and targets efficiently.

As mentioned in Table 3-3, the current project focuses on optimizing the production of six specific product families using a set of 15 machines designated for this purpose. While the facility has more equipment overall, these 15 machines are the ones involved in the production of these products. The sieving stage is carried out on the third floor with 5 machines. On the second floor, 5 mixing machines prepare the powders, which are then transferred through tanks to the ground floor. There, 5 packaging machines complete the final stage. All 15 machines operate simultaneously across the three floors to support a smooth and efficient production flow for these six product families.

Step #	Name	Description	Capacity
1	Sieving	Mechanical machine that helps clean the powder by removing any clumps or unwanted materials, ensuring smooth texture.	5
2	Mixing	Mechanical machine that combines all ingredients thoroughly, so the powder mix is uniform in every pack.	5
3	Packaging	Mechanical machine that packs the final product into bags seals them properly, and adds labels for identification and shipping.	5

Table 3-3 Machine Capacities

3.6.3. Operational Data

Operational data is the foundation of any accurate model, particularly in simulation modeling. It plays a critical role when simulating manufacturing systems, where real-world dynamics must be accurately represented. In this case, data from Factory X was used to build a detailed model that reflects their actual production process. This information includes machine cycle times, setup durations, interarrival rates, product demand, and resource availability, ensuring that the simulation mirrors how the factory truly operates.

Factory X produces a wide variety of powdered mix products, which results in frequent changeovers and complex scheduling challenges. To gather accurate operational details, several interviews were conducted with both operators and managers to understand the flow of materials and the timing between each activity. This operational data was then integrated into the simulation model, defining when products arrive, how long each process takes, and how resources are allocated throughout the system. With this structure in place, the model enabled the monitoring of machine utilization, the testing of realistic scheduling scenarios, and the evaluation of Machine X’s performance.

3.6.3.1. Changeover Matrix

The sieving setups changeover matrix, as shown in Table 3-4, shows how much time is needed to clean and prepare the sieving machine when switching from one product to another. These times are based on what actually happens in the factory. A changeover time of 90 minutes means a wet cleaning is required. This involves fully washing the machine to avoid any contamination, usually when switching between completely different products. When the time is 30 minutes, that’s considered a dry changeover. No water is used, and the team simply wipes or airs out the machine. This is common when moving between similar products, like different types of Juice Mix. If the time is 0 minutes, it means there’s no changeover at all. The same product is being processed, so the machine keeps running without stopping. This matrix was built into the simulation so that the model can automatically apply the right setup time depending on the product sequence. Including these real-world setup rules helps the simulation stay true to how the factory actually works and makes the scheduling results much more useful and reliable.

		Setup Sieving					
		From					
		Ice Cream and jelly (1Kg)	Cake Mix (450gm)	Juice Mix (670gm)	Juice Mix (750gm)	Juice Mix (2.5Kg)	Cooking Cocoa (80gm)
To	Ice Cream and jelly (1Kg)	0	90	90	90	90	90
	Cake Mix (450gm)	90	0	90	90	90	90
	Juice Mix (670gm)	90	90	0	30	30	90
	Juice Mix (750gm)	90	90	30	0	30	90
	Juice Mix (2.5Kg)	90	90	30	30	0	90
	Cooking Cocoa (80gm)	90	90	90	90	90	0

Table 3-4 Sieving Changeover Matrix

Different changeover matrices were developed for the Packing Machine MK1 and Packaging Machine 200Filler setup, the Packaging Machine MK2 and Packaging Machine MK3 setup, and Packaging Machine X, each reflecting the specific cleaning requirements between product transitions. In the Packing Machine MK1 and Packaging Machine 200Filler setup, as shown in Table 3-5, changeover times were set at 120 minutes for full cleaning, 90 minutes for partial cleaning, and 0 minutes when no changeover is needed. For the Packaging Machine MK2 and Packaging Machine MK3 setup, as shown in Figure 3-6, the corresponding times were 90, 60, and 0 minutes, respectively. Packaging Machine X, as shown in Figure 3-7, required longer changeovers, with values of 180 minutes for full cleaning, 120 minutes for partial cleaning, and 0 minutes when continuing with the same product. All three matrices were implemented in the simulation model through lookup tables to ensure that accurate setup times were applied based on the specific product sequences. This helped maintain realistic machine behaviour and supported a more precise evaluation of scheduling strategies.

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		Packaging MK1 and 200Filler					
		From					
		Ice Cream and jelly (1Kg)	Cake Mix (450gm)	Juice Mix (670gm)	Juice Mix (750gm)	Juice Mix (2.5Kg)	Cooking Cocoa (80gm)
To	Ice Cream and jelly (1Kg)	0	120	120	120	120	120
	Cake Mix (450gm)	120	0	120	120	120	120
	Juice Mix (670gm)	120	120	0	90	90	120
	Juice Mix (750gm)	120	120	90	0	90	120
	Juice Mix (2.5Kg)	120	120	90	90	0	120
	Cooking Cocoa (80gm)	120	120	120	120	120	0

Table 3-5 MK1 and 200 Filler Changeover Matrix

		Packaging MK2 and MK3					
		From					
		Ice Cream and jelly (1Kg)	Cake Mix (450gm)	Juice Mix (670gm)	Juice Mix (750gm)	Juice Mix (2.5Kg)	Cooking Cocoa (80gm)
To	Ice Cream and jelly (1Kg)	0	90	90	90	90	90
	Cake Mix (450gm)	90	0	90	90	90	90
	Juice Mix (670gm)	90	90	0	60	60	90
	Juice Mix (750gm)	90	90	60	0	60	90
	Juice Mix (2.5Kg)	90	90	60	60	0	90
	Cooking Cocoa (80gm)	90	90	90	90	90	0

Table 3-6 Mk2 and MK3 Changeover Matrix

		Packaging Machine X					
		From					
		Ice Cream and jelly (1Kg)	Cake Mix (450gm)	Juice Mix (670gm)	Juice Mix (750gm)	Juice Mix (2.5Kg)	Cooking Cocoa (80gm)
To	Ice Cream and jelly (1Kg)	0	180	180	180	180	180
	Cake Mix (450gm)	180	0	180	180	180	180
	Juice Mix (670gm)	180	180	0	120	120	180
	Juice Mix (750gm)	180	180	120	0	120	180
	Juice Mix (2.5Kg)	180	180	120	120	0	180
	Cooking Cocoa (80gm)	180	180	180	180	180	0

Table 3-7 Machine X Changeover Matrix

3.6.3.2. Overall Equipment Effectiveness Analysis

Overall Equipment Effectiveness (OEE) is a common way to measure how well machines are performing in a factory. It brings together three key factors: availability, which shows how often the machine is actually running when it should be; performance, which looks at how fast the machine works compared to its maximum speed; and quality, which measures how many products come out without defects. By combining these three parts, OEE gives a single percentage score that helps show the true efficiency of a machine. A perfect score of 100% would mean the machine is running non-stop, at full speed, and producing only good products. In most industries, an OEE of 80% or above is seen as a sign of very good performance.

In the case study, some packaging machines have lower OEE scores because of long changeover times and years of use, which lead to more downtime and lower output. For example, MK1 has an OEE of 54.79% and MK3 has 61.16%, both below the target of 80%. On the other hand, MK2 and M200 are performing better, with OEEs of 81.08% and 82.95%, showing they are more reliable and efficient. Because of these differences, the factory decided to buy a new packaging machine. However, there is still a challenge in deciding which products should go to this new machine (Machine X) to get the best overall efficiency across all the machines. This shows why monitoring OEE is so important for keeping production smooth and meeting demand.

3.6.3.3. Batching/Unbatching

In this project, batching and unbatching techniques are used to make production, inventory, and distribution run more smoothly. The unbatching quantity refers to the net weight or size of a single item, which helps calculate costs accurately, predict demand, and keep quality consistent for each product. The batching quantity, which is the number of items packed together in a carton, makes it easier to handle, store, and transport products. By keeping track of both these numbers, the organization can manage inventory more accurately, speed up packing, and keep better track of products throughout the supply chain.

The unbatching values in Table 3-8 below represent the weight of a single unit after bulk material is separated for individual processing. Ice Cream and Jelly is unbatched into 1 kilogram units, Cake Mix into 450-gram units, and the three Juice Mix products into 670-gram, 750-gram, and 2.5 kilogram units, respectively. Cooking Cocoa is unbatched into 80-gram units. This unbatching process ensures accurate material handling, proper flow within the simulation, and consistency in downstream operations such as sieving, mixing, and packaging.

	Products by Weight	Unbatch (bulk)	Batch (Carton)
1	Ice Cream and jelly (1Kg)	1kg	10
2	Cake Mix (450gm)	450gm	12
3	Juice Mix (670gm)	670gm	15
4	Juice Mix (750gm)	750gm	10
5	Juice Mix (2.5Kg)	2.5Kg	4
6	Cooking Cocoa (80gm)	80gm	48

Table 3-8 Batch and Unbatch

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3.6.4. Numerical Data

In this project, numerical data refers to all the measurable information used in the simulation, such as product weights, setup times, batch sizes, and arrival rates. Using these numbers allows the model to show how the factory actually runs. It also helps track performance more accurately, test different scenarios, and make decisions based on real numbers instead of guesses.

3.6.4.1. Processing Times

Processing time refers to the total duration required to complete a specific task from start to finish. In the context of this project, it represents the time each machine takes to package a particular product. Accurately tracking these times is important for identifying inefficiencies, evaluating machine performance, and improving the overall flow and productivity of the production system.

	MK1	MK2	MK3	M200	Machine X
Ice Cream and jelly (1Kg)	39.58	39.58	39.58	31.67	9.5
Cake Mix (450gm)	x	87.92	x	70.33	26.38
Juice Mix (670gm)	51.67	51.67	51.67	51.67	19.38
Juice Mix (750gm)	46.2	46.2	46.2	46.2	17.33
Juice Mix (2.5Kg)	17.25	x	17.25	x	5.18
Cooking Cocoa (80gm)	x	x	x	433.07	162.4

Table 3-9 Packaging Machines Processing Times

The table below, Table 3-10, outlines the processing times for each product across different activities, including sieving, mixing, inspection, and packaging. Each product follows a fixed processing time within each operation, but the times vary from one product to another. For example, Ice Cream and Jelly requires 30 minutes for sieving and 45 minutes for inspection, while Juice Mix (670g) has shorter times, requiring only 15 minutes for sieving and 5 minutes for inspection. Packaging times also vary depending on the product's weight and carton size. These differences make it important to schedule and assign resources based on each product's specific needs.

	Sieving Operation	Mixing Operation	Inspection	Packaging per Box (Batch)	Packaging per Carton
Ice Cream and jelly (1Kg)	30	20	45	61.75	0.95
Cake Mix (450gm)	40	20	60	73.85	0.8
Juice Mix (670gm)	15	10	5	62	1.12
Juice Mix (750gm)	40	10	5	62.37	0.76
Juice Mix (2.5Kg)	60	10	5	35.19	0.8
Cooking Cocoa (80gm)	30	5	0	584.64	4.25

Table 3-10 Activities Processing Times

3.6.4.2. Mean Time Between Failure & Mean Time to Repair

Mean Time Between Failure (MTBF) is the average amount of time a machine or system runs before it breaks down. It is calculated by dividing the total operating time by the number of times the system has failed. MTBF helps measure how reliable a system is because a higher MTBF means the system usually runs longer without problems.

Mean Time to Repair (MTTR) is the average time it takes to fix a broken machine or system and get it working again. This includes the time spent finding what went wrong, getting tools or spare parts ready, and completing the repair itself. MTTR shows how easy it is to maintain a system. A lower MTTR means repairs are done quickly, which reduces downtime and keeps everything running more smoothly

As shown in Table 3-11, MK2 proves to be the best-performing machine. It can run for around 260 hours before it needs repairs, and fixing it takes only about 30 minutes, which makes it both reliable and quick to maintain. M200 has the same running time as MK2 but takes longer time to repair, around 40 minutes. MK1 also performs well, running for about 150 hours before breaking down and needing roughly 35 minutes to fix. Machine X and MK3 have shorter running times of around 50 to 52 hours and take about 44 to 45 minutes to repair. Still, even though the Machine X has a higher repair time and lower MTBF, it is still doing its job and helping keep daily production on track.

	MTBF	MTTR
MK1	65 hr	33.7 min
MK2	260 hr	30 min
MK3	52 hr	44.5 min
M200	260 hr	40 min
Machine X	50 hr	45 min

Table 3-11 Shutdown

Chapter Four

4. MODEL DEVELOPMENT

This chapter focuses on developing and testing a simulation model to optimize how products are allocated to machines in a factory with sequence-dependent tasks. The goal is to address key challenges such as reducing changeover times, minimizing cycle times, resolving bottlenecks, and lowering WIP levels.

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The factory's production process is complex, with certain tasks requiring specific sequences that impact changeover durations and machine utilization. The simulation model replicates these operations, providing a practical way to analyze and improve how products flow through the system. It highlights where bottlenecks occur, evaluates machine workloads, and explores strategies for balancing production to improve efficiency.

By using the developed model, we tested different scenarios to find the best sequence-dependent schedule in order to streamline operations, and reduce unnecessary delays. Ultimately, the model serves as a powerful tool for making better decisions, helping the factory meet demand more effectively while improving overall performance.

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4.1. DISCRETE EVENT SIMULATION

Discrete Event Simulation (DES) is a powerful decision-support tool widely recognized for its ability to model and analyze complex manufacturing environments. It provides a detailed representation of real-world processes, capturing system dynamics, variability, and uncertainty to help optimize production systems. By simulating dynamic behaviors such as breakdowns, setup times, and rework, DES enables decision-makers to evaluate alternatives and improve key performance measures, including cycle times, resource utilization, and production schedules (Loacker et al., 2024) (Nejati et al., 2024) [21,22].

In manufacturing, DES is particularly valuable for optimizing sequence-dependent tasks, addressing inefficiencies, and identifying bottlenecks. By visualizing system behaviors, it streamlines resource allocation, enhances operational efficiency, and supports the development of effective strategies to meet production goals. Its data-driven approach empowers decision-making and helps improve overall system performance, making it a critical tool for tackling the challenges of modern manufacturing environments (Loacker et al., 2024) (Nejati et al., 2024)[21, 22].

4.2. EXTENDSIM SOFTWARE

4.2.1. Definition and Features

ExtendSim is a powerful simulation software designed to model and analyze real-world production processes. It enables users to create virtual representations of factory operations or system workflows, facilitating detailed study and optimization of these processes. The software utilizes "blocks" to represent individual steps or activities, such as initiating tasks, transporting materials, or executing operations. These blocks are interconnected to build comprehensive workflows, providing a clear visualization of system interactions. Key features of ExtendSim include the "Executive block," which oversees overall system management, the "Create block," responsible for generating inputs, and the "Activity block," where task durations and specific operations are defined. A notable advantage of ExtendSim is its ability to present results through intuitive visualizations, making complex data easier to interpret and supporting informed decision-making for process improvements (Saderova & Ambrisko, 2023) (Rosova et al., 2022)[23, 24].

4.2.2. Importance of ExtendSim

ExtendSim is a useful tool for businesses that want to improve their processes without disrupting their actual operations. It lets companies test and fine-tune ideas in a virtual model, avoiding the risks of making changes directly in the real world. This helps save resources, reduce potential losses, and prevent expensive mistakes. With ExtendSim, businesses can find ways to boost productivity, cut down on waste, and make better use of their equipment and staff. The software is especially helpful in competitive industries where accuracy, efficiency, and good time management are key to reaching goals and staying ahead.(Saderova & Ambrisko, 2023) (Rosova et al., 2022)[23, 24].

4.2.3. How ExtendSim Works

ExtendSim operates by enabling the creation of a digital model of a production system, which can then be used for testing and analysis. Details such as task durations, equipment constraints, and system rules are input to construct the model. Once completed, experiments can be run to evaluate the impact of changes, such as adding machines or adjusting schedules. The software provides visual results, making it easier to identify bottlenecks, delays, or other inefficiencies. This allows for issues to be resolved and solutions tested virtually before implementing any real-world changes (Saderova & Ambrisko, 2023) (Rosova et al., 2022) [23, 24].

4.3. PERFORMANCE MEASURES FOR THE SIMULATION MODEL

The simulation model developed for this project focuses on two key performance measures that are important for improving the efficiency of the manufacturing process. The first is average cycle time, which represents the amount of time it typically takes to complete the full production process for a single product. This measure helps identify delays, bottlenecks, or inefficiencies in the workflow. The second is throughput rate, which reflects the total number of cartons produced during a shift. This provides a clear indication of the system’s ability to meet production goals and handle demand. Together, these two performance measures offer valuable insight into how the system is functioning and support better decision-making when testing and comparing different scheduling scenarios.

4.4. SIMULATION MODEL

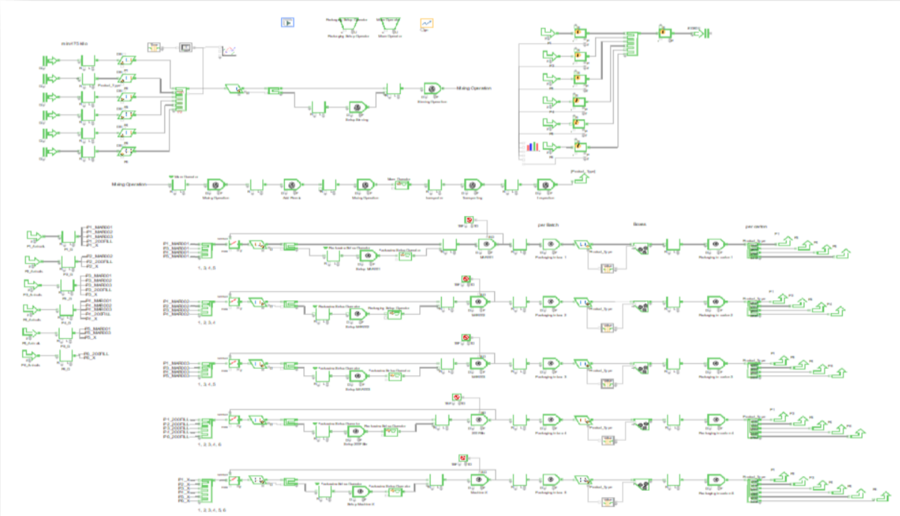


Figure 4-1 Factory Flow Simulation Model

4.5. BLOCKS DESCRIPTION

Block Number	Block Name	Block Description
1	**Create**	It introduces new items into the simulation model, serving as the entry point for the process flow.
2	**Queue**	It holds items waiting to be processed and represents waiting lines or storage areas in the system.
3	**Set**	It is used to assign, update, or change the attributes of items as they pass through the simulation. It can set values like batch size, priority level, processing time, or any other custom property that affects how items move through the system.
4	**Select Item In**	It is used to choose which incoming item should enter the process next. It looks at the items waiting to enter and selects one based on rules or conditions set in the model, such as priority or arrival time.

5	**Select Item Out**	It helps decide which path each item should take based on its properties or certain conditions. It checks the details of each item and then sends it in the right direction.
6	**Lookup Table**	It stores data that the simulation can check during a run. It helps the model quickly find an output value based on an input, making it easier to handle complex rules or decisions without writing out detailed equations.
7	**Display Value**	It shows the current value of a variable or attribute on the screen while the simulation is running. This makes it easy to track key numbers and see how they change in real time.
8	**Line Chart**	It is used to display data as a graph over time. It helps visualize trends, patterns, or changes in values during the simulation, making it easier to understand how the system behaves.
9	**Get**	It is used to read or access the values of attributes that have been assigned to items earlier in the simulation. This information can then be used to guide decisions, control the flow of items, or apply specific rules within the model.
10	**Activity**	It represents a process where an item stays for a certain amount of time. It's often used to model operations like processing, assembling, or inspecting, where each item spends time before moving to the next step.
11	**Resource Pool**	It keeps track of shared resources, such as workers, machines, or tools, that items may need during the simulation. It helps manage when resources are available or in use, making the model more realistic by reflecting real-world constraints.
12	**Resource Pool Release**	It is used to return resources, like workers or machines, back to the resource pool after they've finished being used. This makes those resources available for other items in the simulation, helping keep the process flow efficient.
13	**Shutdown**	It is used to temporarily stop or disable part of the system when certain conditions are met. This helps model planned maintenance, unexpected breakdowns, or other events that interrupt normal operation.

14	**Unbatch**	It is used to split a group of items back into individual items. It helps model processes where items that were packaged or grouped earlier need to continue separately through the system.
15	**Throw Item**	It is used to send items from one part of the simulation to another without needing a direct link between them. It helps move items to the next stage by passing them to a corresponding “Catch” block.
16	**Catch Item**	It is used to receive items sent by a “Throw Item” block from another part of the simulation. It brings these items back into the process flow at the correct location, helping to manage item movement across different parts of the model without direct connections.
17	**Gate**	It controls whether items are allowed to pass through or must wait, based on conditions or signals set in the model. It helps manage flow by holding items back until certain criteria are met, keeping the process organized and synchronized.
18	**Information**	It is used to display key details about the simulation, such as values, statistics, or messages. It also shows important metrics like the cycle time of the model, helping users track performance and understand how the system is working in real time.
19	**Bar Chart**	It is used to visually display data as bars, making it easy to compare values quickly. It helps track and illustrate key metrics or counts during the simulation, so users can clearly see how different parts of the system are performing.
20	**Exit**	It is used to remove items from the simulation once they have completed all necessary steps. It marks the end of the process flow for those items, helping keep the model organized and reflecting when products leave the system.
21	**Statistics**	It is used to collect and report data about the simulation’s performance. It helps track important measures like averages, counts, utilizations, and totals, so users can analyze how the system behaves and identify areas for improvement.
22		It is used to run and compare different what-if scenarios within the same simulation model. It helps test how changes in inputs or

	Scenario Manager	settings affect system performance, making it easier to evaluate options and support better decision-making.
23	**Simulation Variable**	It is used to store a value that can change during the simulation, like keeping track of a number or condition that other blocks can use or update.
24	**Clear Statistics**	It is used to reset the statistical data collected by other blocks, such as queues or activities. It is typically used after a warm-up period to ensure that only relevant data is included in the final simulation results.

Table 4-1 Blocks Descriptions

4.6. MODEL DESCRIPTION

This part of the simulation, as shown in Figure 4-2, shows where each product enters the system and starts its process through the production line. It plays an important role in assigning product-specific information and improving how cycle time is measured. Each of the six products, including Ice Cream and Jelly, Cake Mix, three Juice Mixes, and Cooking Cocoa, is created using a Create block. This block introduces items based on how often they should arrive, according to their daily demand. These items then move into a Queue block that holds them until the system is ready, helping to manage flow and avoid overloading later steps.

After the queue, each product goes through a Set Attribute block. This block assigns two attributes. One is the Product Type, which tells the system what kind of product it is. The other is Time In, which marks the start time for measuring cycle time. Adding the Time In attribute after the queue is intentional. It ensures the cycle time only includes the actual processing steps such as sieving, mixing, transporting, and packaging, and does not include time spent waiting in line.

All six product streams are then combined into one using a Select Item In block. This allows the simulation to treat all product types in a consistent way and makes it easier to track how they move through the rest of the system.

By starting the cycle time measurement after the queue, the model gives a more realistic picture of how long it takes to process each product. This leads to cleaner and more reliable data that helps you compare different production scenarios and make better decisions about sequencing and setup changes. It is a small adjustment, but it makes a big difference in the quality of your results.

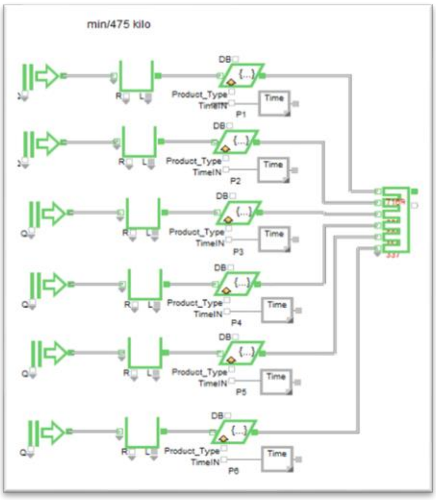


Figure 4-2 Product Arrivals

The three blocks shown in Figure 4-3 below are used to visualize the production schedule, highlighting how the product flow changes over time within the production line. This setup helps manage how each product type is assigned to specific production lines and supports the testing of various scheduling strategies within the simulation model.

The Lookup Table Block is used to define a time-based schedule for the simulation. It outputs a specific product type based on the simulation time, allowing the model to follow a pre-defined production sequence. This block plays an important role in reducing changeovers and balancing the production load, all while maintaining the output required to meet demand.

The Display Value Block displays the current product type coming from the Time Block. This enables the user to see which product type is active at any given moment during the simulation. It is also used to track and verify schedule transitions, such as confirming when the product changes from Cake Mix to Juice Mix.

The Graph Block generates a time-based graph that visualizes the changes in the production schedule. This graphical representation is helpful when analyzing or presenting the simulation results, as it clearly shows how product types are sequenced over time in response to the scheduling logic.

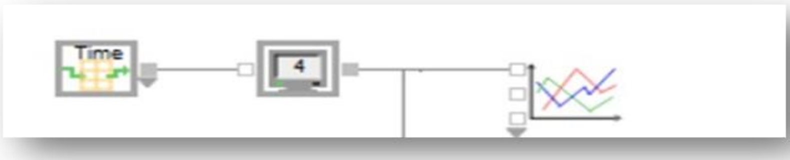


Figure 4-3 Base Schedule

This part of the model, as shown in figure 4-4, focuses on the sieving stage in the production line. The sieving section of the model includes a logic structure that checks whether a product transition requires setup. A Get block first identifies the Product_Type attribute of each item. Then, a Select Item Out block compares the incoming product type with the last processed one. If it’s the same, the item moves straight to the sieving operation. If it’s different, the item is routed through a Setup Sieving activity. The duration of this setup is determined by a Time block connected to a database-driven Lookup Table known as the changeover matrix, which stores the required changeover times between every possible product pair.

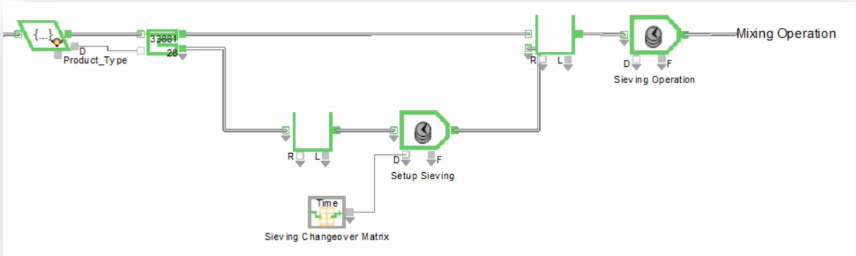


Figure 4-4 Sieving Operation

Although the number of changeovers at this stage may seem relatively low, as shown in Figure 4-5, this outcome is intentional and a direct result of the production schedule design. Instead of allowing products to enter the system randomly, the model uses a fixed scheduling approach where each product is introduced in a specific, timed sequence. This structured flow helps reduce how often the sieving machine needs to switch between different products.

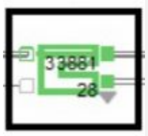


Figure 4-5 Product Changeovers

The schedule is controlled using a Lookup Table, as shown in Figure 4-6, that assigns a product to each time interval across a defined 672-hour cycle shown in Figure 4-7. By doing so, the model ensures that similar product types are grouped together, minimizing unnecessary changeovers. This organization not only keeps the line running smoothly but also improves production efficiency by reducing downtime between product switches.

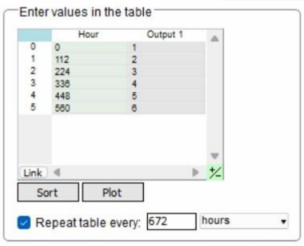


Figure 4-6 Scheduling Times

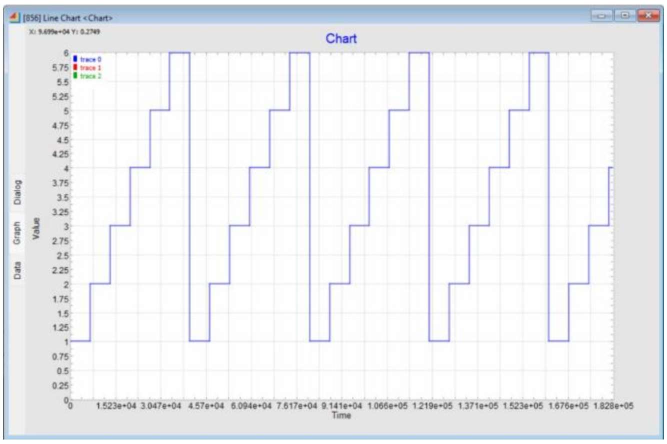


Figure 4-7 Production Cycle

This setup helps simulate real production requirements, where powdered products must be sieved separately to avoid cross-contamination. By linking this logic with a planned production schedule, the model not only reflects operational details but also demonstrates how thoughtful sequencing can reduce changeover delays, lower cycle time, and improve overall system performance. Multiple internal databases were created in ExtendSim to organize and manage key data used throughout the simulation model. One of the most important databases was used to store the changeover matrix, which defines how much setup time is required when switching from one product to another. Each row and column in this matrix represent a specific product, and the value in each cell shows the time, in minutes, needed to clean or prepare the equipment between two product types.

Instead of entering these values manually into Lookup Table blocks, the matrix was stored in a dedicated database table, as shown in Figure 4-8, making it easier to retrieve and update. This method also reduces the chance of input mistakes and makes future changes more efficient. If setup times need to be adjusted or tested, they can be updated directly in the database without editing each block in the model.

Databases were also used to store the different production scenarios that were tested throughout the simulation. This helped automate the comparison of multiple scheduling combinations and allowed the Scenario Manager to read and apply different product sequences and time allocations without manually updating each one.

Using databases in this way helped keep the model organized, improved accuracy, and made it easier to evaluate which strategies performed best under realistic production conditions.

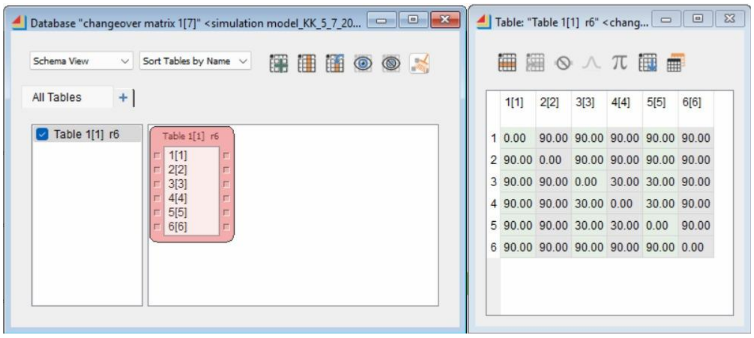


Figure 4-8 Changeover Matrix Database

Figure 4-9 below shows the steps that happen after the sieving process, starting with the mixing stage. It begins with a mixer operator resource pool queue, which makes sure an operator is available before mixing can begin. The item then goes through a mixing operation where the initial blending takes place. After that, it waits in a queue before moving to the add premix stage, where another ingredient is added. A second mixing operation follows to complete the final blend. An operator is also required for this step, which is why the resource is released once the mixing is done. After that, the product enters a queue waiting to be transported and is moved using the transporting block, which simulates transferring the powder to the next area.

The item then waits in one last queue before going through inspection, where it is checked for quality. Throughout the process, the product type is tracked so it can be directed to the correct packaging line. This part of the simulation helps show how the factory handles mixing, moving, and inspecting the product while also considering the availability of operators at each step.

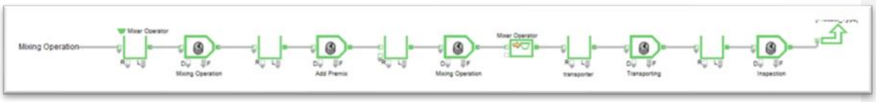


Figure 4-9 Mixing Operation

This part of the simulation shows how each product enters the system and is directed to the appropriate packaging machine, as shown in Figure 4-10. There are six different products, each with its own arrival point. Product One is ice cream and jelly in one-kilogram bags. Product Two is cake mix in 450-gram bags. Product Three is juice mix in 670-gram bags, and Product Four is another juice mix in 750-gram bags. Product Five is a larger juice mix packaged in 2.5-kilogram bags, while Product Six is cooking cocoa in small 80-gram bags.

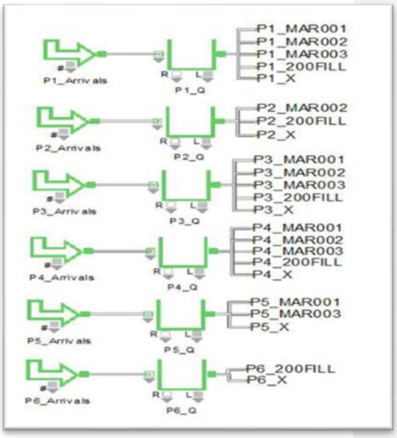


Figure 4-10 Product Machine Allocation

Each product enters the system through its assigned arrival block, such as P1_Arrivals for ice cream and jelly, and then moves into a corresponding queue (P1_Q to P6_Q). These queues hold the products until a packaging machine becomes available, which helps manage the flow and prevents the system from becoming overloaded.

The packaging machines in this section are labeled MAR001, MAR002, MAR003, 200FILL, and X. Each product is routed only to the machines that are suitable for its size and packaging type. For example, Product One can be sent to any of the five machines, offering the most flexibility. Product Two, the 450-gram cake mix, is limited to MAR002, 200FILL, or X, likely due to specific packaging requirements. Products Three and Four, the medium-sized juice mixes, are also compatible with all five machines. Product Five, which is the heaviest at 2.5 kilograms, can only be processed by MAR001, MAR003, or X, as these machines are better suited for larger bags. Product Six, the small cocoa powder, is sent only to 200FILL or X, which are more suitable for lightweight, fine-powdered products.

This routing setup helps the simulation manage multiple product types efficiently by sending each one to the appropriate machine based on its characteristics. It keeps the system organized and mirrors real factory operations, where different packaging lines are assigned based on product size, weight, and material.

The section of the simulation, shown in Figure 4-11 below, controls the flow and setup logic for the shared packaging machine MAR001, which is used by product types 1, 3, 4, and 5. It begins with a Select Item In block that merges incoming items from these four product lines into a single stream, allowing them to access the same packaging resource. A Gate block follows, which controls the release of items based on certain logic conditions, ensuring products only move forward when the machine is ready to receive them.

Next, a Get Attribute block retrieves the product type of the incoming item. This information is passed to a Select Item Out block, which determines whether a changeover is required. If the incoming product is different from the last product processed on the machine, the item is routed through the setup path. If no changeover is needed, the item is sent directly to the packaging process.

When a changeover is required, the item is routed through a setup branch that includes a Time block. This block does not apply a fixed delay but instead refers to a changeover matrix stored in the project's database. The matrix contains setup times for every possible transition between products. By using this matrix, the Time block dynamically identifies how long the changeover will take, depending on which product was previously run and which one is coming next.

The Resource Pool Queue in this model shows the need for an operator in this area. In this case, it simulates the operator that is needed for the changeovers and the cleaning of machines in between different product changes. This queue makes sure that the operator is available for cleaning before proceeding with the setup. The operator is then released, and the activities are continued, and the products carry on through the system to the packaging machine.

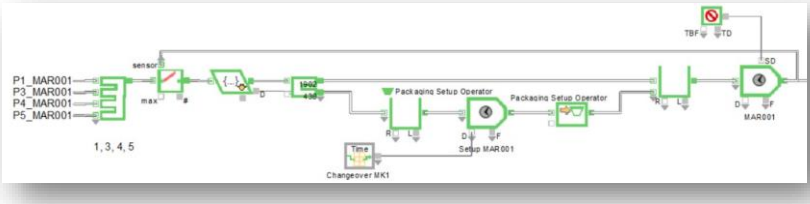


Figure 4-11 Automated Packaging Station

The Shutdown Block is used to simulate equipment breakdowns and repairs, helping make the production model more realistic by reflecting unexpected stops or maintenance events. In this example, which comes from one of the production lines, failures are based on time and happen independently of any specific condition. The block is set to trigger a failure every 3,900 minutes, followed by a fixed repair time of 33.7 minutes, as shown in Figure 4-12. These values are just one case and do not apply to every machine in the model. Other machines may have different failure patterns and repair times depending on their role and how often they are used.

By including this block in the model, the simulation more closely reflects real factory conditions where machines can break down and require repairs. This helps produce more accurate estimates of downtime, lost capacity, and the overall impact on cycle time and throughput. Factoring in shutdown behavior during scenario testing also makes it possible to evaluate how different production schedules perform under realistic operating conditions, which is important when selecting plans that are both efficient and reliable.

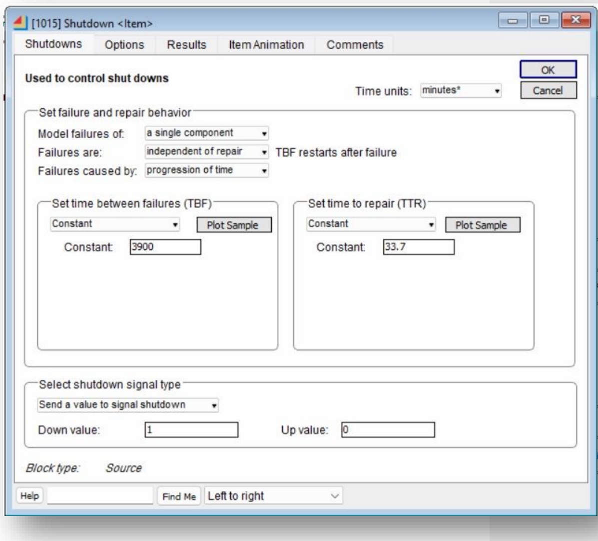


Figure 4-12 Shutdown Block

This process is repeated across five different production lines, each representing a separate packaging machine. While the overall flow and setup remain the same, the processing times vary depending on the machine used and the type of product being packaged. This helps the simulation reflect the unique performance of each line while keeping a consistent structure throughout the system.

After products finish the automated packaging step, they go through two manual packaging steps to get them ready for shipping. In this part of the model, as shown in Figure 4-13, the Packaging in box block represents the part where each bag is put into a box, and the process time is based on the whole batch instead of each single bag.

Once the batch is packed into boxes, the model uses a Get block to read the Product_Type attribute for each item. This detail is important because each product type might need a different number of bags in each carton. The product type is then sent to a Lookup Table block, which holds data showing exactly how many bags should go into one carton for each product type. This step helps make sure the manual Packaging in carton part of the process puts the right number of bags in each carton, depending on the product type.

Finally, after the cartons are formed, the select item out directs each carton to the correct output path (P1, P3, P4, or P5), depending on the type of product it contains. This setup helps keep the packaging process organized and makes sure that different product types are sorted and sent to their correct destinations, reflecting a real-world factory flow from items to boxes, and from boxes to cartons.

This manual packaging process is carried out across five production lines, following the same steps of first packing bags into boxes and then grouping those boxes into cartons, before directing them to the correct output path based on product type.

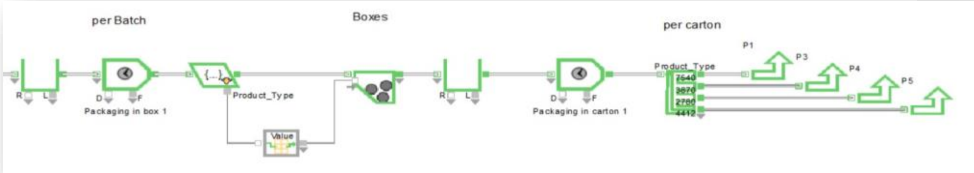


Figure 4-13 Manual Packaging Station

This part of the model, as shown in Figure 4-14 shows the final output stage, where the results from all six product lines, Product One to Product Six, are collected and reviewed. Each line is connected to an information block that tracks important details like the cycle time for each product and the total number of units produced by the end of the simulation. This helps show how long each product takes to complete and how much was made.

All six product flows are then brought together using a Select Item In block, which combines them into one stream. That combined flow goes to a final information block that shows the total cycle time for the whole system. This makes it easier to see how efficiently everything is running overall.

To help visualize the output, a bar graph is included at the bottom left of the model. It shows the number of units produced for each product, giving a quick and clear view of the production levels across all six lines. Altogether, this part of the model gives a clear picture of how each product performed and how the entire system worked as a whole.

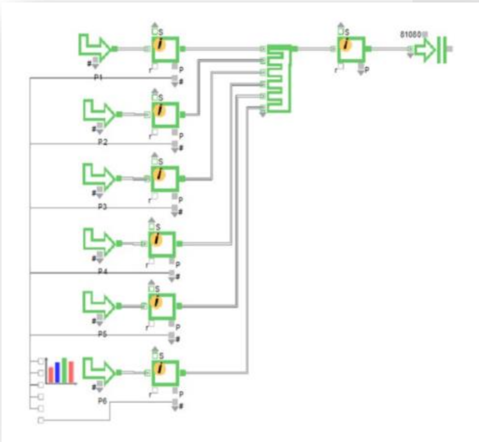


Figure 4-14 Output Stage of the Model

Figure 4-15 shows the resource pools used in the simulation to manage the availability of workers for key operations. The Packaging Setup Operator is used whenever a changeover is needed, such as when switching from one product to another, so that the machine can be cleaned or adjusted before continuing. The Mixer Operator works during the mixing stage, helping with tasks that need human supervision or input. Each of these resource pools includes three operators, as shown in Figure 5-16, so only three tasks of that type can happen at the same time. If all three are busy, the system has to wait until one becomes available. The Statistics block on the right is used to monitor the utilization of all activities in the model. This helps track how busy each part of the system is and can highlight areas where improvements are needed. Together, these blocks make the model feel more realistic by accounting for real-life constraints like limited labor and machine usage.

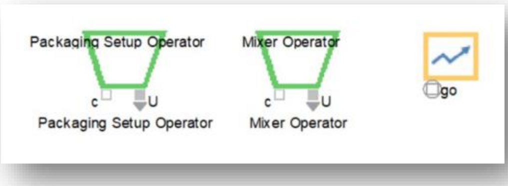


Figure 4-15 Resource Pools

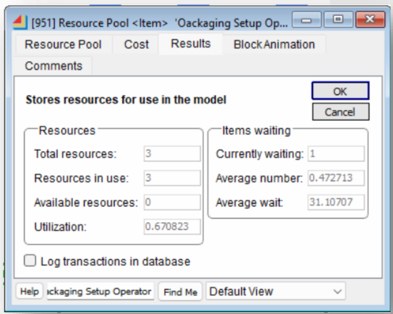


Figure 4-16 Number of Resources

4.7. PERFORMANCE EVALUATION

4.7.1. Average Cycle Time

The average cycle time is an important performance measure that indicates how long it takes, on average, for a unit to move through the entire system from entry to exit. The average cycle time was 36,274.2 minutes, as shown in Figure 5-17. This includes the time spent in processing and any movement between different parts of the system. To measure this accurately, the "Time IN" attribute was assigned in the Set block placed immediately after the queue. This ensures that the cycle time starts only when the unit begins actual processing.

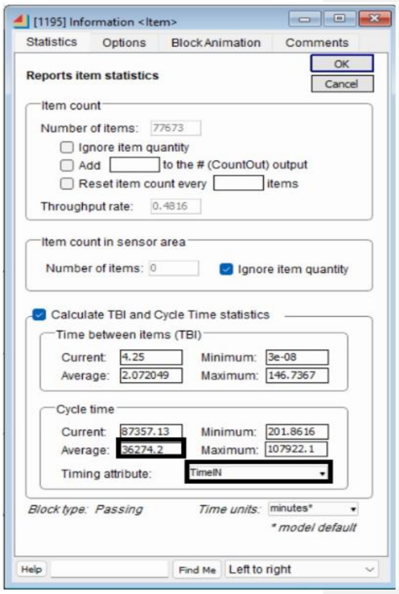


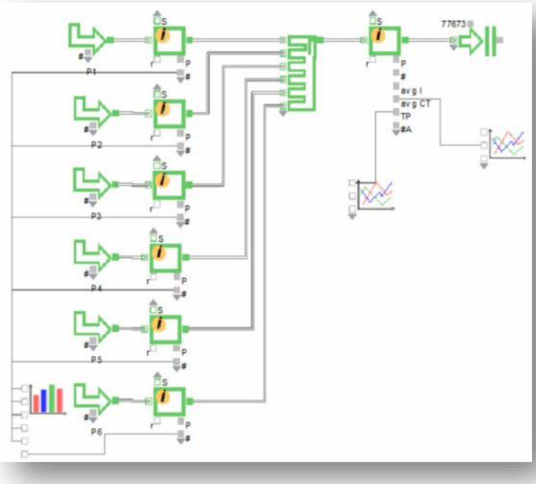
Figure 4-17 Information Block

By starting the time measurement after the queue, the focus is placed on the performance of the system during the main processing phase. The cycle time is completed when the unit exits the system. This setup provides a better understanding of how efficiently the system operates and helps identify areas where time may be reduced to improve overall performance.

4.7.2. Throughput Rate

The throughput rate is a key performance metric that indicates how many units are completed or produced within a specific period of time, as shown in Figure 5-18. In this simulation model, throughput is measured in cartons, which is the standard unit used to represent the output of each product type. The model tracks the flow of six different powdered food products, and by the end of the 4-month period, a total of 77,673 cartons were produced across all product types, as shown in Figure 5-19.

To measure this, each production line is connected to an Information block, which counts the number of cartons exiting the system. These blocks continuously monitor the flow and record the output in real time throughout the simulation. The collected data is then displayed in the Statistics block, which provides a clear numerical summary of the total production volumes for each individual product type, as well as the combined output.



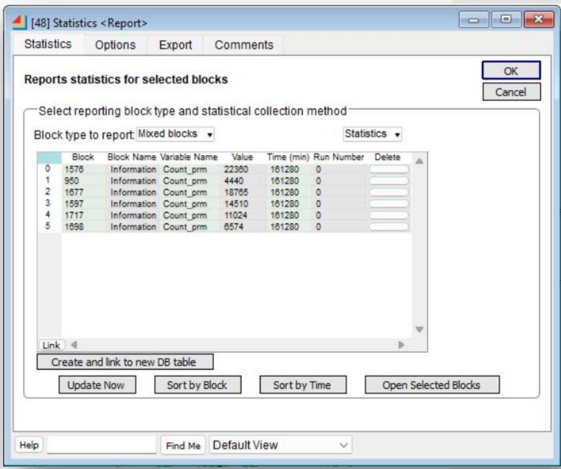


Figure 4-18 Number of Throughput

Figure 4-19 Throughput Per Product Type

In addition to numerical reporting, the model uses visual tools to better illustrate throughput performance. Line chart blocks connected to the Information blocks display how production levels change over time, helping identify patterns such as consistent production periods or fluctuations between product types, as shown in Figure 4-20. Additionally, a bar chart is used to provide a clear visual comparison of the total number of cartons produced per product type, as shown in Figure 4-21. This graphical representation makes it easier to evaluate the relative performance of each production line and supports quick, informed decision-making for improving production planning and balancing output across the different product types.

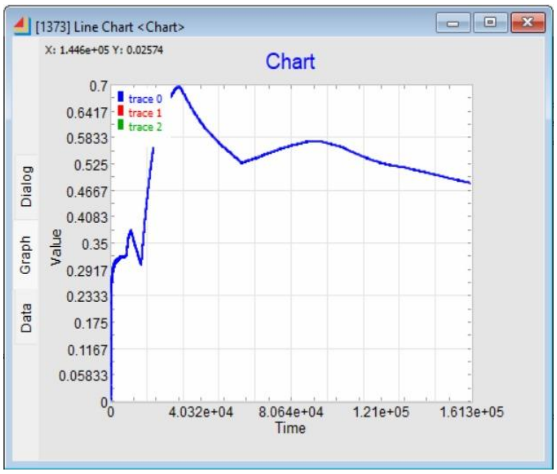


Figure 4-20 Throughput Line Chart

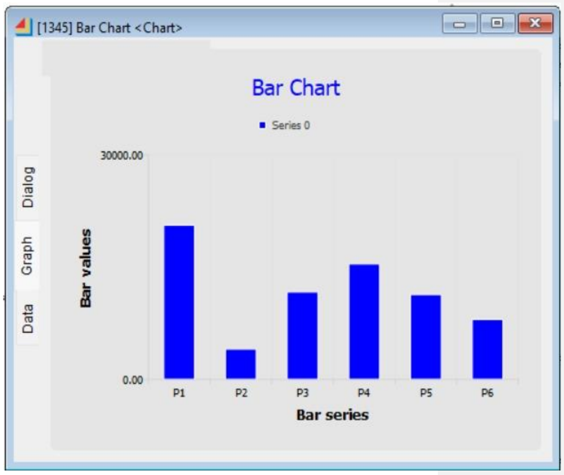


Figure 4-21 Throughput Bar Chart

4.8. MODEL VERIFICATION AND VALIDATION

4.8.1. Model Verification

Model verification is the process of checking that the simulation model was built correctly and performs as expected based on the system's design. In this project, the model was carefully reviewed to ensure that all components were properly connected and followed the intended workflow. Different scenarios and input values were tested to confirm that the outputs were consistent and reasonable. The simulation was also examined step by step, and the model was paused at different points to predict the next event, then resumed to compare the actual behavior with the expected outcome. This helped ensure that the sequence of events and block interactions matched the logic of the real system. The movement of items through the model was traced to verify that they followed the correct paths, and ExtendSim's animation feature was used to observe the system's performance visually. Additional checks were made for specific functions, such as confirming that processing times adjusted correctly during changeovers. These verification steps helped ensure that the model accurately reflects the real operation of the powder mix production process and behaves as expected under various conditions

4.8.2. Model Validation

Model validation is about making sure that a simulation model behaves in a way that accurately reflects the real-world system it represents. It's a key step in the modeling process because it helps confirm that the model's results are trustworthy and meaningful. Validation gives confidence that the logic, data, and assumptions used in the model are appropriate and that the outcomes can be relied on when making decisions. This process often includes checking model outputs against actual data or expert expectations. When a model is properly validated, it can be used confidently to test different scenarios, improve operations, and support strategic planning.

To ensure the model is properly validated, a standard validation equation was used to compare the simulation results with real-world data, allowing the percentage error to be calculated and the accuracy of the model to be assessed.
Calculated as:

$$(Simulation\ Value – Actual\ Value)/\ Actual\ Value\ x\ 100 = \%\ of\ Error$$

$$(77{,}686 – 80{,}900)/\ 80{,}900\ x\ 100 = 3.98\%\ of\ Error$$

The validation shows that the simulation model gives results that are very close to what would be expected in real life. The model predicted a total output of 77,687 cartons, as shown in Figure 4-22, while experts estimated around 80,900 cartons for the same period. This small difference, with an error of just 3.98%, means the model is performing accurately. Such a low error confirms that the logic, data, and structure of the model are reliable. Because of this, the model can now be used with confidence to test different production scenarios, make improvements, and support planning decisions, without needing to test every change in the real production line.

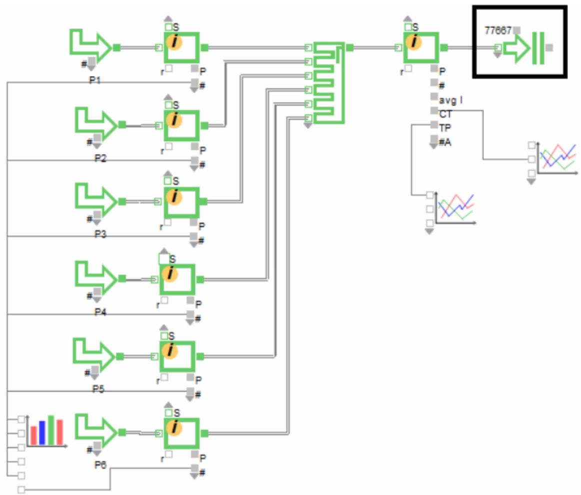


Figure 4-22 Model Throughput

Chapter Five

5. EXPERIMENTATION RESULTS AND ANALYSIS

This chapter presents the experiments and results from a simulation model developed using ExtendSim to schedule jobs involving sequence-dependent changeover times. The objective was to identify the most efficient job sequence that minimizes average cycle time and enhances overall system performance.

The model was used to simulate a variety of random job sequences, with each run capturing key performance indicators such as cycle time, resource utilization, and throughput. Since the time required to switch between jobs depends on their sequence, the experiments were designed to explore combinations that reduce these changeover times.

A "what-if" analysis approach was applied, changing input parameters, running simulations, analyzing outcomes, and then adjusting inputs for further testing. This iterative process enabled a deeper understanding of how different job sequences affect system behavior.

The results showed that specific sequences led to lower average cycle times by minimizing delays and making more efficient use of resources. These findings not only demonstrate the effectiveness of the simulation model in optimizing job scheduling but also provide useful insights that can help improve scheduling in real-life operations.

5.1. SIMULATION PARAMETERS

5.1.1. Warmup Period

In simulation modelling, the warm-up period is used to allow the system to move from its initial, often unrealistic state to a more stable and typical operating condition. During the early phase of a simulation, performance measures such as throughput can be unstable due to starting conditions like empty queues or idle machines. Collecting data during this time can lead to biased or inaccurate results. To ensure reliable analysis, data collection begins only after the system reaches steady-state behavior.

In this case, the simulation model was run for a total of 161,280 minutes across 20 independent runs to analyze system performance over time. The primary performance measure examined was based on throughput, which showed the most noticeable variation during the early stages of the simulation. By observing the throughput curve, it became clear that the system experienced fluctuations at the beginning but eventually stabilized. After analyzing the graph, it was determined that the system reached a steady state at 21,530 minutes. This point was selected as the end of the warm-up period because the throughput rate became more consistent and reflected the system's typical behavior. By identifying 21,530 minutes as the warm-up duration, all data collected before this point was excluded from the analysis, as shown in Figure 5-1. This approach helps eliminate initialization bias and ensures that the performance results reflect the long-term behavior of the system rather than the temporary effects of start-up conditions.

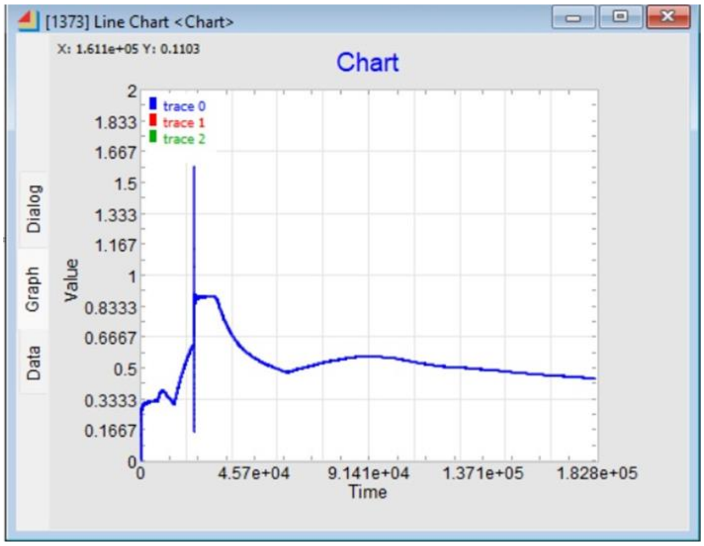


Figure 5-1 Graph After Warmup Period

5.1.2. Number of Replication

In simulation modeling, running the model several times is important because each run can produce slightly different results due to the variations involved. Since each simulation run is influenced by different input conditions or timing of events, the outcomes can vary. To account for this, the model was executed 20 times, with each run producing slightly different results. This approach provides a better view of how the system behaves under different conditions and helps produce more accurate average values. To make sure the results were accurate and not affected by short-term fluctuations, the model's performance, specifically the average cycle time was examined across all runs. This was done after applying a warm-up period of 21,530 minutes to remove the impact of the initial adjustment phase. The results were tracked and plotted to observe when the average stabilized, as shown in Figure 5-2. Although 20 replications were performed, the graph showed that the cycle time began to stabilize after the 8th replication. From that point, the values showed minimal change, and the confidence interval became much tighter. This indicates that 8 replications would have been sufficient to produce stable and statistically reliable results, as shown in Table 5-1. However, completing all 20 replications added confidence and ensured greater accuracy in the final outcomes.

Replications	CT (From Extendsim)	Cum avg CT	Cum Stdev	Error	UL	LL	% Error
1	48999	48999					
2	48972	48985.5	9.545941546	85.76688	49071.27	48899.73	0.1751%
3	49001	48990.66667	6.811618614	16.921	49007.59	48973.75	0.0345%
4	48987	48989.75	5.648408084	8.987878	48998.74	48980.76	0.0183%
5	49033	48998.4	5.849149986	7.262679	49005.66	48991.14	0.0148%
6	48994	48997.66667	5.616250397	5.893893	49003.56	48991.77	0.0120%
7	49003	48998.42857	5.455204217	5.045222	49003.47	48993.38	0.0103%
8	49046	49004.375	6.200397856	5.183662	49009.56	48999.19	0.0106%
9	48991	49002.88889	6.304706131	4.846226	49007.74	48998.04	0.0099%
10	49025	49005.1	6.563647063	4.69535	49009.80	49000.40	0.0096%
11	49009	49005.45455	6.708303193	4.506699	49009.96	49000.95	0.0092%
12	48990	49004.16667	6.64466732	4.22182	49008.39	48999.94	0.0086%
13	49019	49005.30769	6.640037716	4.012535	49009.32	49001.30	0.0082%
14	49006	49005.35714	6.603475049	3.812733	49009.17	49001.54	0.0078%
15	48982	49003.8	6.462396049	3.578756	49007.38	49000.22	0.0073%
16	49043	49006.25	6.452912829	3.438515	49009.69	49002.81	0.0070%
17	49003	49006.05882	6.411231842	3.296351	49009.36	49002.76	0.0067%
18	48989	49005.11111	6.314840094	3.140296	49008.25	49001.97	0.0064%
19	49041	49007	6.302833485	3.037868	49010.04	49003.96	0.0062%
20	49032	49008.25	6.341476626	2.967902	49011.22	49005.28	0.0061%

Table 5-1 Average Cycle Time Replications

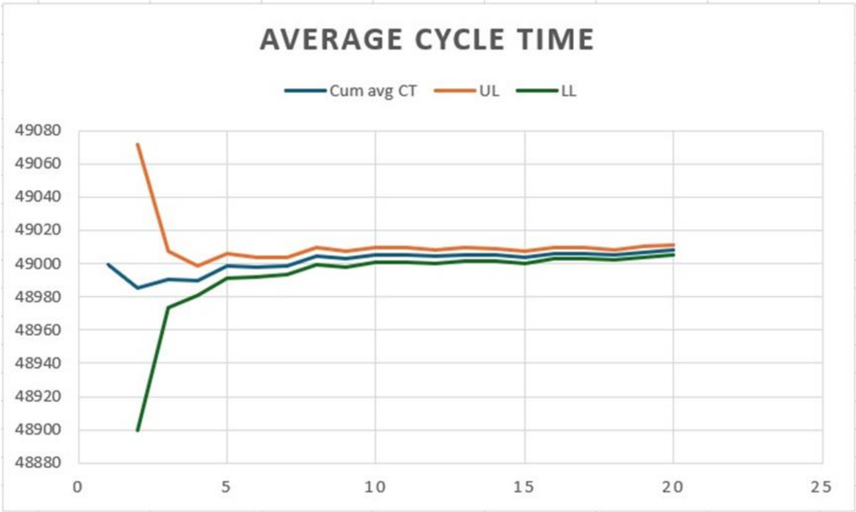


Figure 5-2 Average Cycle Time Graph

5.1.3. Run Length

Determining the right run length is a key step in ensuring the accuracy of simulation results. The run length defines how long the simulation runs during each replication, and it should be long enough to gather sufficient performance data. In this project, a run time of 161,280 minutes was selected per replication, as shown in Figure 5-3, based on the system's actual working schedule. The calculation was made using 7 working days per week, across 4 weeks each month, for a total of 4 months. With 2 shifts per day, each shift lasting 12 hours, and 60 minutes per hour. The total simulation time adds up to 161,280 minutes.

This time frame was chosen to fully capture the system's behavior under continuous operation. Running the model for this duration ensures that the data collected reflects realistic and consistent performance, allowing for more accurate evaluation of key metrics like cycle time and throughput.

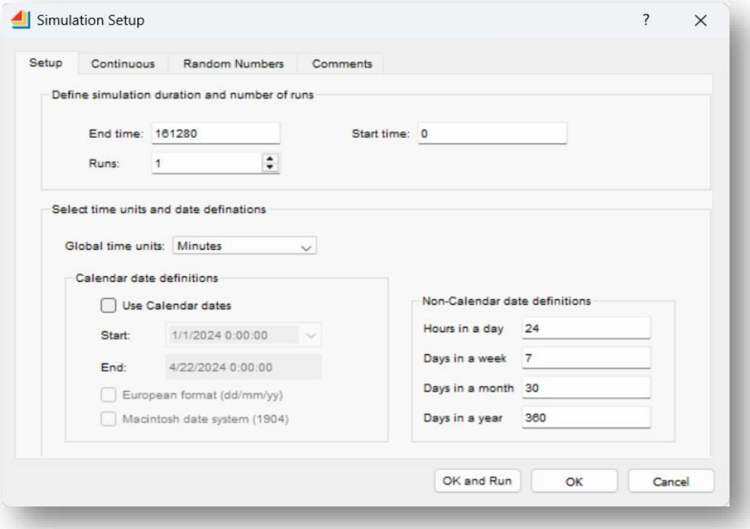


Figure 5-3 Run Length

5.2. DESCRIPTION OF EXPERIMENTS

In this powdered food mix factory, changeovers between products are costly in both time and efficiency due to setup and cleaning requirements. Because each product has unique processing times and works better on certain machines, the order in which they are scheduled has a significant impact on the total cycle time, the utilization of machines, and the number of units that can be produced. This makes production sequencing a key factor in improving overall system performance.

To improve the performance of changeovers and optimize the production process, a total of 206 different scenarios were tested in this project using a variety of scheduling strategies. Out of these, 100 scenarios focused on changing the sequence in which the products were introduced, while keeping the original run times fixed. Another 100 scenarios kept the product sequence unchanged but varied the amount of time each product was produced. The remaining 6 scenarios were designed to explore seasonality, simulating what would happen if one product experienced a spike in demand and was run for a longer period, while the remaining products shared the leftover time equally. These variations allowed for a comprehensive comparison of cycle times and throughput across different scheduling approaches, helping identify the most efficient production setups and reduce unnecessary changeovers.

The company focuses on two main performance measures to evaluate each experiment: the average cycle time, which is the time it takes to produce one batch, and the production throughput, which is the total number of batches produced during the simulation period. The goal is to find the best setup that minimizes the time per batch while maximizing the total output over the time the model is running.

5.2.1. Base Scenario Analysis

After running the simulation with the initial parameters, the model provided results on two key performance indicators: the average cycle time and the total number of batches completed during the simulation. These results, detailed in Table 5-2, serve as a baseline for evaluating system performance. Using this baseline, several new scenarios were designed and tested to explore ways of reducing production time and increasing output. The purpose of these experiments is to identify more efficient production schedules that can improve the overall operation of the powdered food mix line.

Performance Metrics	Results
Average Cycle Time	36,267 minutes
Throughput	77673 Cartons
Product Sequence	1-2-3-4-5-6

Table 5-2 Base Scenario

5.2.2. Scenario 1

While there are over 720 possible sequencing combinations for scheduling six products, this study tested 100 selected scenarios to compare how different sequences perform. Each scenario was evaluated based on key outputs such as average cycle time and total number of units produced.

This type of scenario testing is essential because it allows for data-driven decisions about which sequence minimizes downtime and maximizes efficiency. By identifying the best performing sequences, the factory can reduce bottlenecks, improve resource usage, and enhance overall productivity without needing to change physical operations, only the production order.

Figure 5-4 below shows how ExtendSim’s Scenario Manager was used to test 100 different production sequences. In each scenario, the total production time of 672 hours is divided equally between the six products, so every product gets 112 hours of production. What changes from one scenario to the next is the order in which the products are scheduled across the six time blocks, starting at hour 0, then 112, 224, 336, 448, and finally 560.

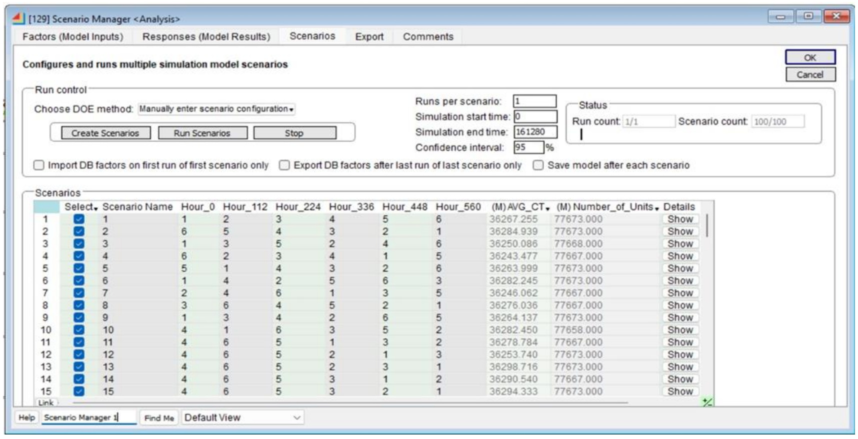


Figure 5-4 Scenario Manager 1

Table 5-3 below displays a selection of 20 example production scenarios taken from a total of 100 tested, offering a snapshot of how different product sequences impact performance. Each scenario maintains a fixed total run time of 672 hours, with only the order of product batches changing. The column labeled “Avg_CT” represents the average cycle time recorded for each scenario, while “Number of Units” shows the total output during the simulation. By comparing these metrics, it becomes possible to evaluate which sequences result in shorter processing times. Among the scenarios listed, Scenario 45 achieved the lowest average cycle time at 36,298.237 minutes, making it the most time-efficient of the full set. These results help identify more effective batch schedules that reduce changeovers and idle time, contributing to smoother production flow and better overall plant performance.

Scenario #	Hour 0	Hour 112	Hour 224	Hour 336	Hour 448	Hour 560	Avg_CT	Number of Units
45	4	6	2	3	1	5	36298.237	77667
13	4	6	5	2	3	1	36298.716	77673
63	5	2	4	3	6	1	36300.218	77667
91	5	2	3	1	6	4	36303.219	77668
18	5	1	2	4	3	6	36304.004	77673
61	**5**	**2**	**6**	**4**	**1**	**3**	**36242.014**	**77667**
32	4	6	3	2	5	1	36242.057	77667
4	6	2	3	4	1	5	36243.477	77667
76	5	2	4	1	3	6	36267.959	77658
71	5	3	2	4	1	6	36267.981	77658
77	5	1	4	6	3	2	36268.135	77673
85	5	2	1	3	6	4	36269.82	77673
100	4	2	1	3	6	5	36278.525	77673
11	4	6	5	1	3	2	36278.784	77667
27	5	1	3	6	4	2	36278.94	77667
48	4	6	2	5	3	1	36278.955	77673
97	5	3	2	6	1	4	36279.903	77667
5	5	1	4	3	2	6	36263.999	77673
50	4	6	3	1	5	2	36264.004	77668
9	1	3	4	2	6	5	36264.137	77673

Table 5-3 Scenario 1

5.2.3. Scenario 2

The second analysis prioritized scenarios based on the highest number of completed units rather than just speed. While many scenarios produced a similar number of units, Scenario 53 slightly outperformed the others with 77,766 units, making it the top performer in terms of output, as shown in Table 5-4. Although its cycle time was not the shortest, this scenario demonstrates that optimizing solely for production volume can yield different results than optimizing for speed. This highlights the importance of selecting evaluation criteria that align with specific operational goals.

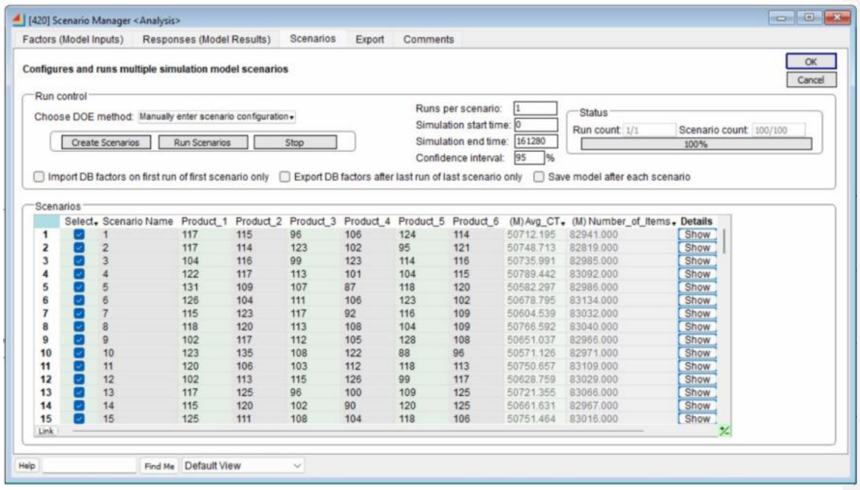
Scenario #	Hour 0	Hour 112	Hour 224	Hour 336	Hour 448	Hour 560	Avg_CT	Number of Units
23	5	1	3	2	6	4	36257.134	77673
24	5	1	3	4	2	6	36276.416	77673
25	5	1	3	4	6	2	36255.895	77673
26	5	1	3	6	2	4	36278.3	77673
52	5	1	4	2	6	3	36287.167	77673
57	5	2	6	1	3	4	36271.441	77673
58	5	2	6	1	4	3	36256.784	77673
66	5	3	1	4	6	2	36264.587	77673
67	5	3	1	6	2	4	36287.836	77673
21	5	1	2	6	4	3	36278.339	77667
27	5	1	3	6	4	2	36278.94	77667
31	4	6	3	5	1	2	36278.309	77667
32	4	6	3	2	5	1	36242.057	77667
53	**4**	**5**	**6**	**1**	**3**	**2**	**36253.375**	**77766**
1	1	2	3	4	5	6	36267.255	77673
2	6	5	4	3	2	1	36284.939	77673
88	5	2	1	6	3	4	36277.631	77667
90	5	2	3	1	4	6	36283.47	77667
93	5	2	3	4	6	1	36247.653	77667
95	5	2	3	6	4	1	36290.116	77667

Table 5-4 Scenario 2

5.2.4. Scenario 3

Figure 5-5 below shows how ExtendSim's Scenario Manager was used to test 100 different production scenarios. In each one, the total production time for all six product types is fixed at 672 hours. What changes from scenario to scenario is how those 672 hours are divided among the six products. Instead of giving each product the same amount of time, the schedules vary. Some products are assigned more hours, others less depending on the strategy being tested.

This experiment was done to better understand how different time allocations affect overall performance. For every scenario, the model calculates two key results: the average cycle time and the total number of items produced during the full simulation period of 4 months.



	Select	Scenario Name	Product_1	Product_2	Product_3	Product_4	Product_5	Product_6	(M) Avg_CT	(M) Number_of_Items	Details
1	☑	1	117	115	96	106	124	114	50712.195	82941.000	Show
2	☑	2	117	114	123	102	95	121	50748.713	82819.000	Show
3	☑	3	104	116	99	123	114	116	50735.991	82985.000	Show
4	☑	4	122	117	113	101	104	115	50789.442	83092.000	Show
5	☑	5	131	109	107	87	118	120	50582.297	82986.000	Show
6	☑	6	126	104	111	106	123	102	50678.795	83134.000	Show
7	☑	7	115	123	117	92	116	109	50604.539	83032.000	Show
8	☑	8	118	120	113	108	104	109	50766.592	83040.000	Show
9	☑	9	102	117	112	105	128	108	50651.037	82966.000	Show
10	☑	10	123	135	108	122	88	96	50571.126	82971.000	Show
11	☑	11	120	106	103	112	118	113	50750.657	83109.000	Show
12	☑	12	102	113	115	126	99	117	50628.759	83029.000	Show
13	☑	13	117	125	96	100	109	125	50721.355	83066.000	Show
14	☑	14	115	120	102	90	120	125	50661.631	82967.000	Show
15	☑	15	125	111	108	104	118	106	50751.464	83016.000	Show

Figure 5-5 Scenario Manager 2

Table 5-5 presents a selection of 20 scenarios out of the 100 that were simulated in ExtendSim, specifically chosen to compare cycle time performance. Each scenario assigns a specific runtime in hours to the six different products, ensuring the total production time remains within the defined limit of 672 hours. The scenarios were selected based on their average cycle time results, with the goal of identifying which time allocations led to the most efficient production performance.

The highlighted row, Scenario 97, achieved the lowest average cycle time of 36,235.329 minutes, making it the most efficient configuration not only among the 20 shown but across all 100 scenarios tested. This suggests that the way production time was allocated across the six products in this scenario led to fewer disruptions and a more continuous flow. The reduced cycle time may be attributed to minimized changeover times between products and better sequencing that allowed equipment to be used more effectively.

Scenario #	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6	Avg_CT	Number of Units
40	128	124	106	97	123	94	36264.247	77667
17	111	99	100	113	113	136	36264.581	77673
37	95	120	124	109	109	115	36264.823	77667
67	113	120	104	109	118	108	36264.961	77673
86	116	135	125	103	104	89	36265.249	77667
68	119	116	112	114	98	113	36265.432	77667
50	113	116	119	110	100	114	36266.098	77673
87	135	88	115	115	110	109	36277.568	77667
75	112	104	114	108	115	119	36277.571	77668
36	130	110	121	93	101	117	36277.628	77667
4	122	117	113	101	104	115	36277.879	77673
100	119	122	99	120	107	105	36285.767	77673
99	127	111	124	110	97	103	36286.143	77673
97	**114**	**98**	**114**	**130**	**106**	**110**	**36235.329**	**77667**
35	118	100	104	108	120	122	36237.625	77667
2	117	114	123	102	95	121	36243.007	77667
93	122	110	117	119	95	109	36243.86	77668
78	120	100	126	94	121	111	36245.051	77667
94	116	107	125	102	107	115	36248.439	77667
41	140	128	116	104	101	83	36304.931	77673

Table 5-5 Scenario 3

5.2.5. Scenario 4

Table 5-6 shows 20 selected scenarios from the 100 tested in ExtendSim, this time focusing on total production output. Each scenario keeps the total runtime fixed at 672 hours but adjusts how that time is split between the six products.
Scenario 51 stands out with the highest number of units produced, reaching 77,766. While its cycle time is not the lowest, its time allocation across the products led to better overall throughput. This suggests that giving more time to products with faster processing or fewer changeovers can significantly improve output, making Scenario 51 the most productive setup among all tested.

Scenario #	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6	Avg_CT	Number of Units
100	119	122	99	120	107	105	36285.767	77673
12	102	113	115	126	99	117	36299.075	77668
51	**96**	**103**	**132**	**109**	**123**	**109**	**36263.603**	**77766**
1	117	115	96	106	124	114	36287.123	77673
3	104	116	99	123	114	116	36284.356	77673
91	113	119	106	112	117	105	36298.393	77668
93	122	110	117	119	95	109	36243.86	77668
95	113	113	98	114	105	129	36298.55	77668
2	117	114	123	102	95	121	36243.007	77667
5	131	109	107	87	118	120	36285.453	77667
6	126	104	111	106	123	102	36281.466	77667
11	120	106	103	112	118	113	36299.416	77667
92	109	97	123	113	123	107	36251.534	77667
94	116	107	125	102	107	115	36248.439	77667
97	114	98	114	130	106	110	36235.329	77667
9	102	117	112	105	128	108	36282.248	77658
27	116	109	112	102	120	113	36281.853	77658
42	114	107	127	117	102	105	36268.177	77658
44	106	116	113	120	105	112	36257.309	77658
33	104	120	108	119	103	118	36299.906	77673

Table 5-6 Scenario 4

5.2.6. Scenario 5

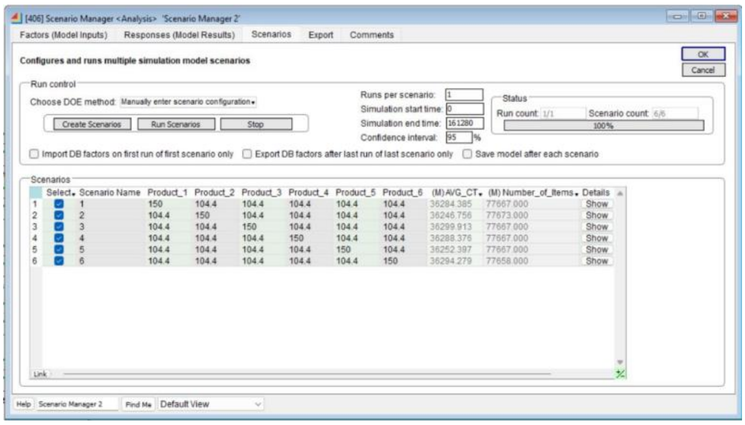


Figure 5-6 Scenario Manager 3

In this set of scenarios, shown in Figure 5-6, we explored the effect of assigning longer production durations to individual products while keeping the total production cycle fixed at 672 hours. In each scenario, one product is given a runtime of 150 hours, while the remaining five products each receive 104.4 hours. This maintains the total cycle time (150 + 5 × 104.4 = 672 hours) and allows us to simulate what would happen if one product experienced a spike in demand during a particular season. For instance, Juice Mix (2.5 kg) might be prioritized in the summer, while Cocoa (80 gm) might require more production time in the winter. Each scenario tests a different product in the high-demand slot to reflect these seasonal shifts, as shown in Table 5-7. This approach helps identify how prioritizing one product over others affects the average cycle time and total output, and supports better planning for seasonal production strategies.

Scenario #	Product 1	Product 2	product 3	Product 4	Product 5	Product 6	Avg_CT	Number of Items
1	150	104.4	104.4	104.4	104.4	104.4	36284.385	77667
2	**104.4**	**150**	**104.4**	**104.4**	**104.4**	**104.4**	**36246.756**	**77673**
3	104.4	104.4	150	104.4	104.4	104.4	36299.913	77667
4	104.4	104.4	104.4	150	104.4	104.4	36288.376	77667
5	104.4	104.4	104.4	104.4	150	104.4	36252.397	77667
6	104.4	104.4	104.4	104.4	104.4	150	36294.279	77658

Table 5-7 Scenario 5

5.3. RESULTS AND ANALYSIS

The results of the different scenarios tested in the simulation model were analyzed to evaluate their impact on production performance. Each scenario followed a unique sequence for scheduling the six product types. Using the key performance metrics, average cycle time and total number of units produced, the analysis compared how each sequence performed. The results, as shown in Table 5-8 and Table 5-9, include a comparison between the tested scenarios and highlight which ones achieved better efficiency. Some sequences led to shorter cycle times and higher output, showing that adjusting the production order can improve the overall performance of the system.

Performance Metrics	Base Scenario	Scenario 1	Scenario 2
Average Cycle Time (min)	36,267	36,242.01	36,253.38
Throughput (Cartons)	77,673	77,667	77,766
Product Sequence	1-2-3-4-5-6	5-2-6-4-1-3	4-5-6-1-3-2

Table 5-8 Sequence Based Result Summary

Scenario 3	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
Scheduling time	114	98	114	130	106	110
Average Cycle Time (min)	36,235.33					
Throughput (Cartons)	77,667					
Scenario 4	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
Scheduling time	96	103	132	109	123	109
Average Cycle Time (min)	36,263.60					
Throughput (Cartons)	77,766					
Scenario 5	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
Scheduling time	104.4	150	104.4	104.4	104.4	104.4
Average Cycle Time (min)	36,246.76					
Throughput (Cartons)	77,673					

Table 5-9 Time Based Result Summary

Based on the comparison shown in the tables above, it is clear that different scenarios offer different advantages depending on the performance objective. If the primary goal is to minimize the average cycle time, then Scenario 3 is the most effective choice, as it achieves the lowest cycle time among all tested scenarios. On the other hand, if the focus is on maximizing total production output, then Scenario 4 should be selected, as it results in the highest number of units produced. This comparison highlights the importance of aligning the production scheduling strategy with the specific performance goals of the factory.

6. CONCLUSION

In conclusion, the simulation model developed for this project proved to be a valuable tool for evaluating the impact of different production sequences in a powdered food mix factory. By accounting for sequence-dependent changeover times and testing a wide range of scheduling scenarios, the model provided meaningful insights into how production order affects key performance metrics such as average cycle time and total output. The results clearly showed that adjusting the sequence of products can significantly enhance overall system efficiency by minimizing unnecessary changeovers and making better use of production time.

The model's ability to generate and compare multiple scenarios allowed for informed decision-making, supported by quantitative data rather than assumptions. Its validation against expected real-world throughput further confirmed its accuracy and reliability. These outcomes demonstrate the practical benefits of using simulation to test and refine production strategies before implementation.

To build on these findings, it is recommended that the company considers implementing lean scheduling methods such as a Kanban system. Kanban uses visual signals to control production based on actual demand, helping to reduce excess inventory, minimize waiting times, and maintain a steady workflow, which is especially useful in systems with costly changeovers. Another effective strategy is CONWIP, which limits the total number of items in the system and provides more flexibility when managing different product types. Both methods can support better flow and reduce delays.

These strategies can be integrated into the current simulation model to assess their impact on performance under various conditions. This allows decision-makers to test potential improvements in a risk-free environment before making changes on the shop floor, using the model as a tool for both evaluation and continuous improvement.

7. REFERENCES

[1] Li, C., Yu, T., Fan, H.-T., Xiao, G., Arinez, J., & Chang, Q. (2023). Manufacturing Letters Dynamic Bottleneck Identification and Production Loss Evaluation for Assembly Lines. In *Manufacturing Letters* (Vol. 35). www.sciencedirect.com

[2] Lödding, H., Steffens, C., & Winter, M. (2024). The strong effect of flexible capacities on achievable WIP levels and throughput times: a simple model and its implications. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2024.2399732

[3] Saeed Osman, M. (2021). A computational optimization method for scheduling resource-constraint sequence-dependent changeovers on multi-machine production lines. Expert Systems with Applications, 168. https://doi.org/10.1016/j.eswa.2020.114265

[4] Lohmer, J., & Lasch, R. (2021). Production planning and scheduling in multi-factory production networks: a systematic literature review. In International Journal of Production Research (Vol. 59, Issue 7, pp. 2028–2054). Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2020.1797207

[5] Haupt, R. (1989). A Survey of Priority Rule-Based Scheduling. In OR Spektrum (Vol. 11). Springer-Verlag.

[6] Samouilidou, M. E., Georgiadis, G. P., & Georgiadis, M. C. (2023). Food Production Scheduling: A Thorough Comparative Study between Optimization and Rule-Based Approaches. Processes, 11(7). https://doi.org/10.3390/pr11071950

[7] Maalouf, M. M., & Zaduminska, M. (2019). A case study of vsm and smed in the food processing industry. Management and Production Engineering Review, 10(2), 60–68. https://doi.org/10.24425/mper.2019.129569
[8] Oliveira, C., & Lima, T. M. (2023). Setup Time Reduction of an Automotive Parts Assembly Line Using Lean Tools and Quality Tools. Eng, 4(3), 2352–2362. https://doi.org/10.3390/eng4030134

[9] Skoogh, A., Thürer, M., Subramaniyan, M., Matta, A., & Roser, C. (2023). Throughput bottleneck detection in manufacturing: a systematic review of the literature on methods and operationalization modes. Production and Manufacturing Research, 11(1). https://doi.org/10.1080/21693277.2023.2283031

[10] Mediouni, A., Zufferey, N., Rached, M., & Cheikhrouhou, N. (2022). The multi-period multi-level capacitated lot-sizing and scheduling problem in the dairy soft-drink industry. Supply Chain Forum, 23(3), 272–284. https://doi.org/10.1080/16258312.2021.2007735

[11] Woldemicael, W. W., Berhan, E., Kitaw, D., & Tesfaye, G. (2024). Enhancing operation efficiency of leather manufacturing industry through hybrid of value stream mapping and discrete event simulation. Cogent Engineering, 11(1). https://doi.org/10.1080/23311916.2024.237542

[12] Oday, Eng. M., & A. Mohamed, Prof. T. (2024, July 16). The Use of Innovative Mechanical Solutions to Implement Lean Methodologies in a Meat Manufacturing Factory in Egypt. https://doi.org/10.46254/af05.20240106

[13] Yue, L., Xu, G., Mumtaz, J., Chen, Y., & Zou, T. (2022). Order Releasing and Scheduling for a Multi-Item MTO Industry: An Efficient Heuristic Based on Drum Buffer Rope. Applied Sciences (Switzerland), 12(4). https://doi.org/10.3390/app12041925

[14] Tufano, A., Accorsi, R., Garbellini, F., & Manzini, R. (2018). Plant design and control in food service industry. A multi-disciplinary decision-support system. Computers in Industry, 103, 72–85. https://doi.org/10.1016/j.compind.2018.09.007

[15] Shin, M., Lee, H., Ryu, K., Cho, Y., & Son, Y. J. (2019). A two-phased perishable inventory model for production planning in a food industry. Computers and Industrial Engineering, 133, 175–185. https://doi.org/10.1016/j.cie.2019.05.010

[16] Shah, S.R. and Naghi Ganji, E. (2017), "Lean production and supply chain innovation in baked foods supplier to improve performance", British Food Journal, Vol. 119 No. 11, pp. 2421-2447. https://doi.org/10.1108/BFJ-03-2017-0122

[17] Jaegler, Y., Jaegler, A., Burlat, P., Lamouri, S., & Trentesaux, D. (2018). The ConWip production control system: a systematic review and classification. In International Journal of Production Research (Vol. 56, Issue 17, pp. 5736–5756). Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2017.1380325

[18] Nur Amalina Muhammad, Jeng Feng Chin, Shahrul Kamarrudin, Mohd Azizi Chik & Joshua Prakash (2015) Fundamental simulation studies of CONWIP in front-end wafer fabrication, Journal of Industrial and Production Engineering, 32:4, 232-246, DOI: 10.1080/21681015.2015.1045562

[19] Rane, A. (n.d.). REDUCING WORK IN PROCESS INVENTORY TO IMPROVE BUSINESS PERFORMANCE. https://doi.org/10.7508/aiem.02.2020.33.42

[20] Červeňanská, Z., Važan, P., Juhás, M., & Juhásová, B. (2021). Multi-criteria optimization in operations scheduling applying selected priority rules. Applied Sciences (Switzerland), 11(6). https://doi.org/10.3390/app1106278

[21] Loacker, P., Pöchtrager, S., & Fikar, C. (2024). Discrete-event simulation to analyse the impacts of a reduced minimum order quantity in the food industry: proposing a shared-savings contract. *Journal of Simulation*. https://doi.org/10.1080/17477778.2024.2386440

[22] Nejati, E., Ghaedy-Heidary, E., Ghasemi, A., & Torabi, S. A. (2024). A machine learning-based simulation metamodeling method for dynamic scheduling in smart manufacturing systems. *Computers and Industrial Engineering*, *196*. https://doi.org/10.1016/j.cie.2024.110507

[23] Saderova, J., & Ambrisko, L. (2023). Simulation of operations on the production line as a tool for making the production process more efficient. *Acta Logistica*, *10*(4), 549–556. https://doi.org/10.22306/al.v10i4.432

[24] Rosova, A., Behun, M., Khouri, S., Cehlar, M., Ferencz, V., & Sofranko, M. (2022). Case study: the simulation modeling to improve the efficiency and performance of production process. *Wireless Networks*, *28*(2), 863–872. https://doi.org/10.1007/s11276-020-02341-z