



Addis Ababa University

College of Technology and Built Environment

School of Mechanical and Industrial Engineering

Industrial Engineering Stream

**“Improving Printing Process Efficiency by Identifying and Mitigating
Production Delays through System Modelling and Simulation at
Berhanena Selam Printing Enterprise”**

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of Technology and Built Environment, Addis Ababa University in partial
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By: Getaw Yirga

Advisor: Dr. Gezahegn Tesfaye (PhD)

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By

Getaw Yirga
Id No: GSE/6602/15

Student’s Signature _____

Approved by the Board of Examiners:

<u>Dr. Gezahegn Tesfaye</u> Advisor Name	_____	<u>Jun - 18 - 2025</u> Date
	Signature	
<u>Dr. Kassu Jilcha</u> Internal Examiner	_____	<u>Jun - 18 - 2025</u> Date
	Signature	
<u>Dr. Ameha Mulugeta</u> External Examiner	_____	<u>Jun - 18 - 2025</u> Date
	Signature	
<u>Dr. Gezahegn Tesfaye</u> Members of school AC	_____	<u>Jun - 18 - 2025</u> Date
	Signature	
<u>Dr. Abdulkadir Aman</u> Interim Head SMIE	_____	<u>Jun - 18 - 2025</u> Date
	Signature	
<u>Dr. Shegaw Ahmed</u> Interim Academic Affair CTBE	_____	<u>Jun - 18 - 2025</u> Date
	Signature	

Declaration

I hereby declare that the work which is being presented in this thesis entitled “Improving Printing Process Efficiency by Identifying and Mitigating Production Delays through System Modelling and Simulation at Berhanena Selam Printing Enterprise” is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

Getaw Yirga



Signature

Jun - 18 - 2025
Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. Gezahegn Tesfaye (PhD) (Advisor)

Signature

Jun - 18 - 2025
Date

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Acronyms

AAiT	-----	Addis Ababa Institute of Technology
AAU	-----	Addis Ababa University
ABM	-----	Agent-Based Modeling
BPR	-----	Business Process Reengineering
BSC	-----	Balanced Scorecard
BSPE	-----	Berhanena Selam Printing Enterprise
CF	-----	Customer Focus
CI	-----	Continuous Improvement
DES	-----	Discrete Event Simulation
ISO	-----	International Organization for Standardization
JIT	-----	Just-In-Time
LCG	-----	Linear Congruential Generator
M&S	-----	System modelling and simulation
PDF	-----	Probability Density Function
PMF	-----	Probability Mass Function
OEE	-----	Overall Equipment Effectiveness
QMS	-----	Quality Management System
SCM	-----	Supply Chain Management
SD	-----	System Dynamics
SMIE	-----	School of Mechanical and Industrial Engineering
TQM	-----	Total Quality Management

Abstract

In the competitive printing industry, operational efficiency is crucial to staying ahead. Efficient operations minimize downtime, reduce waste, and improve resource utilization, which directly impacts profitability and customer satisfaction. Operational efficiency also enables companies to be more agile and responsive to market changes, ultimately giving them a competitive edge in an industry where margins can be tight and customer expectations are high. The Overall Equipment Effectiveness of Berhanena Selam Printing Enterprise for the 2023/24 period, standing at 14.84%, indicates room for significant improvement in operational efficiency. In light of this evidence, it is crucial to propose a research agenda focused on identifying and mitigating production delays through system modeling and simulation approaches to improving operational efficiency.

This study adopts a quantitative approach to enhance operational efficiency by analyzing job order processing data through system modeling and simulation. The study investigates the operational efficiency of the wave-offset and offset machines in a printing process by identifying key factors contributing to production delays: operating speed, machine failures, setup time, and make-ready time. Using ARENA software for simulation and analysis, various improvement scenarios were evaluated. Increasing machine capacity to 90% of design speed, reducing machine failure and repair times by half, and cutting setup and make-ready times by half were proposed as strategies to enhance efficiency. These actions resulted in improved Overall Equipment Effectiveness by 4.62% for the wave-offset machine and 28.73% for the offset machine, respectively.

Key words: System Modeling and Simulation, Production delays, improving production efficiency.

Chapter One

1. Introduction and Problem Justification

1.1. Introduction

In the modern industrial landscape, the demand for operational excellence has never been more critical. Industries across the globe are under pressure to deliver high-quality products quickly and cost-effectively. Among these, the printing industry stands out due to its intricate workflows, reliance on machinery, and sensitivity to time constraints. As Law and Kelton (2000), customer expectations rise and competition intensifies, printing enterprises must adopt innovative strategies to maintain efficiency and ensure timely delivery. One such strategy is the use of system modeling and simulation, a powerful analytical tool that enables organizations to replicate real-world operations in a virtual environment. This approach allows for the testing of various scenarios without interrupting actual production. By simulating different operational conditions, companies can identify inefficiencies, predict outcomes, and make informed decisions that enhance productivity and reduce waste.

System modeling creates a digital twin of the enterprise's processes a virtual replica that mirrors the behavior of physical systems. This twin can be manipulated to explore the effects of changes in scheduling, resource allocation, machine maintenance, and other variables. The insights gained from these simulations are invaluable for strategic planning and continuous improvement. As Law and Kelton (2000) emphasize, the accuracy of simulation models depends heavily on reliable data collection and thoughtful design.

The process of building a simulation model begins with comprehensive data gathering. This includes information on production delays, machine performance, operator efficiency, and workflow patterns. Once collected, this data is used to construct a model that reflects the actual operations of the enterprise. The model must be verified and validated to ensure it accurately represents reality a step that Sargent (2013) identifies as essential for credibility and usefulness. Once validated, the simulation model can be used to run experiments under various conditions. These experiments help uncover recurring problems such as bottlenecks, breakdowns, and scheduling conflicts. For example, frequent machine failures may point to inadequate

maintenance routines, while uneven workloads may suggest poor resource distribution. By analyzing these issues, enterprises can develop targeted interventions that address root causes rather than symptoms.

Iterative testing is a key component of simulation-based optimization. As Pidd (2004) notes, refining operational strategies through repeated simulation runs allows organizations to evaluate the effectiveness of proposed solutions before implementing them. This reduces the risk of costly errors and ensures that changes are grounded in evidence. Adjustments to maintenance schedules, operator shifts, and machine assignments can be tested and fine-tuned until optimal configurations are found. Ultimately, system modeling and simulation offer a data-driven foundation for decision-making in the printing industry. By leveraging this technology, enterprises can enhance their agility, reduce delays, and improve overall efficiency. The approach not only conserves resources but also empowers managers with actionable insights. This study explores the application of simulation modeling in the printing sector, focusing on its potential to transform operational performance and drive sustainable growth.

1.2. Background and Justification of the Study

The printing industry has a long and storied history, dating back to ancient civilizations. While rudimentary forms of printing existed as early as 2500 BCE, the invention of the printing press by Johannes Gutenberg in 1447 marked a revolutionary turning point. Gutenberg's innovation enabled the mass production of books and documents, democratizing access to information and fuelling cultural, scientific, and political advancement across Europe and beyond. Over the centuries, printing technology has evolved dramatically. From manual presses to digital printers, the industry has embraced automation, precision, and speed. Today, printing enterprises operate in a highly competitive environment, producing a wide array of materials from newspapers and books to packaging and promotional items. The sector plays a vital role in education, communication, commerce, and governance, making its efficiency a matter of national importance.

To meet modern demands, printing companies worldwide are adopting lean manufacturing principles. These principles focus on minimizing waste, maximizing resource utilization, and continuously improving processes. As Acharyulu (2014) notes, lean practices help organizations

respond quickly to customer needs, maintain high quality standards, and reduce operational costs. In this context, system modeling and simulation emerge as complementary tools that support lean objectives.

In Ethiopia, the history of printing began in 1887 with the publication of Aemiro, the country's first newspaper. This milestone marked the beginning of a new era in Ethiopian media and communication. Since then, the printing industry has grown steadily, contributing to national development and cultural preservation. Among the leading institutions in this sector is Berhanena Selam Printing Enterprise (BSPE), founded on September 21, 1922.

BSPE has played a central role in Ethiopia's printing landscape for over a century. It has produced countless books, newspapers, official documents, and educational materials. As a state-owned enterprise, BSPE serves both public and private clients, making its operational efficiency crucial to national service delivery. BSPE operates regularly on production schedule of 11 hour per day and sometimes on a continuous production schedule, maintaining a full-day (24-hour) printing cycle to meet the demands of its diverse clientele. This workflow is essential for fulfilling high-volume orders, especially for government publications, educational materials, and commercial print jobs. The enterprise's commitment to operational efficiency is reflected in its adoption of quality management systems, which support consistent output. The production day is structured to optimize machine utilization, minimize downtime, and ensure that each stage of the process is executed with precision.

The printing operations are powered by 5 wave offset machines and 16 standards offset machines. The wave offset machines are typically used for high-speed, large-scale newspaper, book and publication printing, capable of producing tens of thousands of copies per hour. Meanwhile, the offset machines handle a broader range of tasks, including booklets, brochures, and official documents, offering flexibility in print size and quality. These 21 machines form the backbone of BSPE's production infrastructure, and their performance is central to the study's analysis using OEE metrics.

The enterprise has consistently expanded its capacity and strived to keep pace with technological advancements to fulfil its founding objectives. As a government development company, BSPE has continually evolved to meet the growing demands of its customers and stakeholders.

However, challenges persist in addressing the ever-increasing customer expectations and the rapid development of technology. The company has implemented various processes and continuously monitors their performance to fulfil its customers' printing needs in terms of quality, delivery time, and cost. To enhance print quality and operations, the company has adopted ISO 9001:2015 Quality Management, Kaizen, and the Balanced Scorecard (BSC). Additionally, the enterprise identifies key performance indicators, which provide insights to formulate action plans when performance falls short of objectives or to drive process efficiency and innovation.

BSPE has adopted a multi-pronged strategy to reduce production delays, anchored in internationally recognized quality and performance frameworks. The implementation of ISO 9001:2015 Quality Management System ensures that standardized procedures are followed across all stages of production, minimizing variability and enhancing consistency. Through Kaizen, the enterprise promotes a culture of continuous improvement, encouraging employees to identify inefficiencies and propose incremental changes that collectively enhance workflow. The Balanced Scorecard (BSC) further supports strategic alignment by linking operational activities to broader organizational goals, enabling BSPE to monitor performance across key dimensions such as customer satisfaction, internal processes, and innovation. These systems work in tandem to streamline operations, reduce waste, and improve responsiveness to customer demands.

In addition to these frameworks, BSPE utilizes key performance indicators (KPIs) to track and evaluate production metrics in real time. These indicators help identify bottlenecks, monitor machine utilization, and assess task completion rates. The enterprise's investment in high-capacity wave offset and standard offset machines reflects its commitment to meeting large-scale printing demands efficiently.

However, like many large-scale printing facilities, BSPE faces challenges such as machine breakdowns, production delays, and inefficient resource management. Recognizing these challenges, the study initiated a project to apply system modeling and simulation to its operations. The goal was to identify inefficiencies, test alternative strategies, and implement solutions that improve performance. The project began with a detailed data collection phase,

focusing on production delays and machine utilization. This data formed the basis for constructing a simulation model that accurately represented BSPE's workflows.

Through simulation, the study was able to experiment with different maintenance schedules, workload distributions, and operator shifts. The results revealed key problem areas and suggested practical interventions. By validating these solutions through further simulations and applying them in the real production environment, BSPE achieved measurable improvements in efficiency and delivery timelines. This case study highlights the transformative potential of simulation modeling in revitalizing traditional industries and ensuring their relevance in a rapidly changing world.

1.3. Statement of Problem

In today's highly competitive printing industry, where production costs are rising and digital technologies are increasingly displacing traditional printing methods, companies like BSPE face significant challenges. Despite implementing the ISO 9001:2015 quality management system, Kaizen, and BSC, BSPE still struggles with maintaining competitiveness and meeting customer expectations.

The performance evaluation for the fiscal year 2023/24 conducted by Ethiopia Investment Holding reveals that out of a total of 29 points, the company scored 20 green, 5 yellow, 3 gray, and 1 red. The green scores indicate strong performance in production, quality of output, innovation, technology adoption, cost management, and environmental sustainability. The yellow scores suggest minor issues requiring improvement, while the gray scores highlight inefficiencies in material waste, digital transformation, and inventory management (excess stock). The single red score signifies significant delays in task completion. These areas need immediate attention to streamline operations and enhance overall efficiency.

The Overall Equipment Effectiveness (OEE) of the enterprise for the 2023/24 period stands at 14.84%, which is significantly below the theoretical average of 60% and the world-class target of 85%. This indicates substantial room for improvement in operational efficiency. While the quality (97.86%) metrics are commendable, the performance (29.62%) and availability (51.18%) considerably drags down the overall OEE (14.84%). These discrepancies highlight the

challenges in maintaining operational efficiency and meeting customer expectations. In light of this evidence, it is crucial to propose a research focused on identifying and mitigating production delays through a System Modeling and Simulation approach to improve operational efficiency.

1.4. Research Questions

After completion of this study, it is expected to answer the following questions:

- How can a simulation model be developed to accurately represent the real-world operations of Berhanena Selam Printing Enterprise (BSPE)?
- What are the potential sources of production delays at BSPE based on simulation outcomes?
- What strategies reduce production delays and improve the printing process efficiency?
- What are the impacts of different operational scenarios on the production efficiency of BSPE as tested within the simulation model?

1.5. Objective

1.5.1. General Objective

To improve the printing process efficiency at Berhanena Selam Printing Enterprise by identifying and mitigating production delays through the application of system modeling and simulation.

1.5.2. Specific Objective

- To develop a simulation model that accurately represents the real-world operations of BSPE.
- To identify the potential sources of production delays at Berhanena Selam Printing Enterprise (BSPE).
- To develop production delays reduction strategies.
- To test various operational scenarios within the simulation model.

1.6. Scope of the Study

This study encompasses collecting detailed information on production delays and developing a simulation model. The scope includes testing various operational scenarios within the model to identify and implement potential solutions for reducing production delays. The study was also validating the effectiveness of these solutions through further simulations and establishes a framework for on-going optimization and continuous improvement in the printing processes. The geographical scope is limited to BSPE in Ethiopia only regular printing operations four wave-offset and fifteen offset machine, and the time frame for the study is set at 9-10 months to allow for thorough analysis and implementation.

1.7. Limitations of the Study

The primary limitation of this study lies in the reliance on the accuracy and completeness of the data collected from the enterprise. Additionally, the study is constrained by its focus on a single enterprise, which may limit the generalizability of the findings to other printing enterprises with different operational contexts. The 9-10 month timeframe may also limit the ability to observe long-term effects and adjustments following the implementation of identified solutions. Lastly, external factors such as market changes and technological advancements during the study period could influence the outcomes, posing challenges in segregating the effects of the interventions.

1.8. Significance of the Study

This study grasps significant importance as it aims to improve the operational efficiency and overall performance of BSPE. By leveraging system modeling and simulation, the study offers a data-driven approach to identify and mitigate production delays, leading to improved delivery times and customer satisfaction. The insights gained from this research will not only benefit BSPE but also offer valued lessons for other printing companies facing similar challenges. Furthermore, the study contributes to the wider field of industrial process optimization, demonstrating the practical application and transformative potential of system modeling and simulation in addressing real-world operational inefficiencies. Through this study, BSPE can set a pattern for continuous improvement and innovation in the printing industry, ensuring sustainable growth and competitive advantage.

The contribution of this research to the body of knowledge lies in its demonstration of how system modeling and simulation can successfully address operational inefficiencies within the printing industry. Additionally, the findings from this study improve existing literature on industrial process optimization, presenting new insights and innovative approaches to achieving operational excellence. This research thus bonds the gap between theoretical concepts and practical applications, paving the way for future studies and improvements in the field.

Chapter Two

2. Literature Review

2.1. Introduction System Modeling and Simulation

System modelling and simulation (M&S) are essential tools for Improving operations in printing enterprises by analyzing complex processes, predicting outcomes, and enhancing decision-making. System modelling involves making abstract representations of real-world processes, while simulation uses these models to duplicate the behaviour of systems over time. By providing valuable understandings into operational dynamics without incurring the costs and risks of real-world experimentation (Law & Kelton, 2000), M&S help printing companies. Improve processes by analyzing workflows and identifying bottlenecks (Chung, 2018), improve resource allocation by predicting resource usage and Improving scheduling (Wang et al., 2015), and model quality control processes to assess the effectiveness of quality assurance methods and minimize defects (Talha, 2020).

Recent research has increasingly focused on leveraging system modelling and simulation to identify and mitigate production delays, thereby enhancing operational efficiency. Abdul Rahman and Adeboye (2025) explored the use of Siemens Tecnomatix Plant Simulation to optimize Automatic Guided Vehicle (AGV) systems in manufacturing environments. Their study demonstrated that simulating material flow and testing various scenarios significantly reduced line stoppages and improved throughput. Similarly, Abay et al. (2025) applied discrete-event simulation using JaamSim to a drilling equipment factory, where bottlenecks were identified through queue metrics and machine activity data.

Several methodologies are commonly employed in M&S for printing enterprises the Discrete Event Simulation (DES), which is widely used in manufacturing settings to model systems where events occur at discrete points in time. Research has shown that DES can effectively represent complex printing workflows, enabling detailed study of performance metrics (Güven & Kucuk, 2020). Agent-Based Modeling (ABM) simulates interactions between autonomous agents, making it suitable for modeling complex systems with many cooperating components, such as customer orders and production schedules in printing (Macal & North, 2009). System Dynamics

(SD) focuses on the feedback loops and time delays in systems. It is mostly useful for understanding long-term trends and behaviours in printing operations, such as inventory management and production scheduling (Forrester, 1961).

Gunananthan and Singh (2025) focused on cycle time reduction and workforce optimization, using simulation to evaluate task reallocation and inventory control strategies. Their approach led to a 30% improvement in production output. Another study published in MDPI's *Applied Sciences* proposed a five-step systematic improvement model that integrates simulation with early-stage data analysis and iterative refinement. This model not only improved performance and quality but also aligned with economic goals through the application of the Theory of Constraints

The implementation of M&S in printing enterprises offers numerous benefits. It improves decision-making by providing a stand to test various scenarios, helping managers make informed choices about process changes, resource allocation, and production planning (Robinson, 2014). Simulation helps identify inefficiencies and potential cost savings before changes are made in real operations, thereby reducing financial risk (Law & Kelton, 2000). Additionally, M&S enhances flexibility and responsiveness, allowing printing enterprises to simulate different market conditions and customer demands, and adapt their operations accordingly (Wang, 2015).

Moreover, the SIMUL (2025) Conference emphasized the importance of multi-resolution and hybrid simulation models in capturing both macro and micro-level dynamics in printing systems. These models associated discrete-event, agent-based and continuous simulation techniques to reflect the nuanced behavior of modern print environments. As printing enterprises adopt Industry 4.0 technologies, such as IoT-enabled presses and cloud-based job scheduling, simulation tools are evolving to incorporate real-time data streams, enhancing their predictive power and operational relevance.

The growing role of AI-enhanced simulation tools in printing enterprises. According to COMSOL's (2025) industry forecast, simulation platforms are increasingly integrating replacement models and neural networks to deliver faster, more accurate predictions of system behavior. These tools permit printing firms to simulate complex workflows and equipment interactions in real time, enabling rapid scenario testing without disrupting operations. This shift

toward collaborating simulation apps has democratized access to modeling, allowing even non-experts to explore optimization strategies.

Despite these advantages, several challenges exist when implementing M&S in printing enterprises. Developing accurate models that imprisonment the complexities of printing operations can be difficult and simplifying assumptions might lead to inaccuracies in simulations (Robinson, 2014). The availability and quality of data are crucial for actual modeling and simulation, but many printing enterprises fight to collect and maintain high-quality data for their processes (Güven & Kucuk, 2020). Furthermore, gaining stakeholder buy-in can be challenging, especially if they do not fully understand the advantages or applications of M&S (Macal & North, 2009).

The study emphasized maximizing production efficiency in competitive environments by combining simulation with workplace optimization and inventory control. The strategies that addressed both human factors and operational bottlenecks were offering a holistic framework for continuous improvement. Collectively, these underscore the transformative potential of simulation-based approaches in modern manufacturing, providing actionable insights for reducing delays and boosting productivity.

Overall, system modeling and simulation are influential tools for improving operational efficiency in printing enterprises by enabling the analysis of complex processes and facilitating informed decision-making. However, challenges such as model complexity and data quality must be addressed to fully understand the advantages of these techniques. The existing literature presents various M&S methodologies but does not investigate deeply into how these methodologies can be customized and custom-made to the specific needs of different types of printing enterprises.

2.2. Production Delays

Production delays in printing enterprises can considerably affect efficiency, customer satisfaction, and profitability. To mitigate these delays, it's indispensable to understand their causes and impacts. Several factors subsidize to production delays like inefficient workflow processes, equipment downtime, supply chain disruptions, and human factors. Inefficient

workflows, particularly in pre-printing, printing, and post-printing stages, can create blockages and increase lead times (Koenig, 2014). Equipment failure and maintenance issues also contribute to delays, disrupting schedules and causing missed deadlines (Baldwin, 2013). Additionally, supply chain disturbances, such as delays in the delivery of raw materials like paper and ink, can halt production (Klein & Wiegand, 2016). Employee-related issues also contributed, including skill gaps and labour shortages, further contribute to inefficiencies and delays (Noe, 2014).

The 2025 State of Print Production Report by Gelato recognizes labour shortages, rising material costs, and logistics disruptions as the top contributors to production delays. Over 80% of surveyed print providers cited AI-driven workflow automation as a critical solution to mitigate these issues. By automating job routing, inventory tracking, and maintenance scheduling, printing firms are dropping idle time and improving throughput. Additionally, predictive analytics is being used to forestall supply chain disruptions and proactively adjust production plans.

Despite widespread adoption and implementation of digital workflows, many printing enterprises still face delays due to poor integration between legacy systems and new digital platforms. According to the Printing Outlook 2025 report, nearly 40% of surveyed firms reported bottlenecks caused by incompatible software and fragmented data systems. These gaps delay real-time job tracking, slow down approvals, and complicate coordination across departments. Without continuous integration, even automated systems can become inefficient, leading to missed deadlines and reduced throughput.

Another key trend is the adoption and implementation of smart factory technologies, which integrate sensors, machine learning, and cloud platforms to monitor and optimize every stage of the print process. These systems detect differences in real time such as temperature fluctuations or ink inconsistencies that could lead to delays. By addressing these issues proactively, companies are reducing downtime and improving delivery reliability and production. This shift toward data-driven delay management is converting how printing enterprises respond to operational bottlenecks.

The consequences and impact of production delays are significant. Customer dissatisfaction can result from unmet expectations, leading to lost business and hurt reputations (Talha, 2020).

Financial implications are also considerable, as delays can increase operational costs due to advanced shipping, overtime labour, and wasted resources (Davenport, 2013). Furthermore, production delays can reduce a company's competitive benefit, making it harder to compete effectively in the market (Berk, 2015).

2.3. Overall Equipment Effectiveness

OEE is a critical metric in maximizing the efficiency of production systems. By analyzing OEE, companies can identify inefficiencies and implement action plans to enhance productivity. Production delays directly impact the Availability portion of OEE, which measures actual operating time versus planned production time. According to Hansen (2006), the adoption of a correct measurement system and the management of key parameters can significantly contribute to increased productivity across multifunctional areas and the plant. OEE is calculated by multiplying three factors: availability, performance efficiency, and quality.

Studies have shown that simulation and data analytics can be powerful tools for improving OEE by identifying and mitigating these delays. For example, Lindegren et al. (2022) proposed a hybrid approach that combines discrete-event simulation with data analytics to create a risk-free environment for testing improvement strategies. Their model helped uncover hidden interdependencies in production processes and forecast the impact of changes on OEE, enabling managers to make informed decisions.

Another study by Hernández-Vázquez et al. (2024) tackled the Buffer Allocation Problem in a cup sublimation production line. Using simulation meta-models and optimization algorithms, they demonstrated that improper buffer placement could reduce OEE, while strategic allocation improved both throughput and equipment utilization.

Additionally, Naik et al. (2025) developed a simulation model for calculating OEE in a generic production line. Their work incorporated fuzzy logic to account for uncertainties in machine downtime and setup time, offering a more nuanced view of how delays affect equipment availability and overall efficiency.

In short, simulation allows manufacturers to visualize and test how different delay scenarios affect OEE, and to proactively design systems that minimize downtime, optimize performance,

and maintain high quality. It's not just about fixing problems it's about forecasting and preventing them before they happen.

The theoretical average OEE for printing machines is approximately 60%, whereas the world-class standard exceeds 85% (James, 2024). The current OEE of the Ethiopian manufacturing industry varies across different sectors. For instance, a study on the Mughher Cement Factory found that the average OEE for the period 2014-2018 was 22.2%, which is significantly below the world-class target of 85%. In 2025, OEE continues to be a cornerstone metric for print operations, but its application has become more sophisticated. A recent study by Deshpande (2025) in the *International Journal of Research and Analytical Reviews* demonstrated how real-time OEE dashboards powered by IoT and AI enable continuous monitoring of availability, performance, and quality. These systems provide actionable insights, such as identifying recurring downtime causes or pinpointing underperforming shifts, allowing for targeted interventions and continuous improvement.

Furthermore, the integration of predictive maintenance algorithms has significantly improved equipment availability. By analyzing historical and real-time machine data, these tools forecast potential failures and schedule maintenance during low-demand periods. This proactive approach has been shown to increase OEE scores by up to 15% in pilot implementations. As a result, printing enterprises are moving beyond static OEE tracking toward dynamic, AI-enhanced performance optimization, aligning with broader smart manufacturing trends.

2.4. Improving Operational Efficiency

Improving operational efficiency is a central goal in modern manufacturing and service industries, and simulation modelling has emerged as a powerful tool to achieve it. Simulation allows organizations to replicate complex systems, test alternative scenarios, and identify inefficiencies without disrupting real-world operations. A study by Abdul Rahman and Adeboye (2025) demonstrated how simulating Automatic Guided Vehicle (AGV) systems using Siemens Tecnomatix Plant Simulation helped reduce material transport delays and improve throughput, directly enhancing operational flow and reducing downtime. Similarly, Abay et al. (2025) applied discrete-event simulation via JaamSim to a drilling equipment factory, identifying bottlenecks and implementing parallel workstations, which led to a 37.9% reduction in

production time and a notable boost in efficiency. Gunananthan and Singh (2025) focused on human resource optimization, using simulation to test task reallocation and inventory control strategies. Their approach resulted in a 30% increase in production output, showing how operational efficiency can be improved by addressing workforce-related delays. A broader framework was proposed in a study published in *Applied Sciences* (MDPI), where a five-step systematic improvement model integrated simulation with early-stage data analysis and iterative refinement.

To achieve and sustain a high OEE score, continuous improvement efforts and the implementation of various efficiency-enhancing methodologies are essential. Womack and Jones (2003) emphasize that Lean implementation streamlines processes, reduces lead times, and enhances product quality. Techniques like Value Stream Mapping and Just-In-Time (JIT) inventory management are particularly relevant for improving print production workflows (Rother & Shook, 2003). Additionally, Total Quality Management (TQM) plays a crucial role in ensuring high-quality outputs in printing operations. Deming (1986) highlights the importance of continuous improvement and customer satisfaction, with studies showing that TQM practices lead to better operational efficiency by reducing errors and enhancing customer feedback mechanisms (Talha, 2020).

In addition to these frameworks, several process improvement methodologies are particularly effective in printing enterprises. Business Process Reengineering (BPR) involves the radical redesign of printing processes to achieve significant improvements. Hammer and Champy (1993) note that successful BPR initiatives can lead to enhanced efficiency but require careful change management and employee buy-in. Research indicates that BPR can streamline complex printing workflows (Davenport, 1993). Six Sigma which focuses on reducing defects and variability in printing process, is another key methodology.

Technological advancements are reshaping operational efficiency in printing enterprises. Research shows that digital printing reduces setup times and allows for shorter print runs, thereby increasing flexibility and responsiveness to market demands (Baldwin, 2013). Automation technologies, including pre-printing and post-printing automation, enhance the efficiency of printing operations. Studies indicate that integrating automated workflows can

significantly reduce turnaround times and improve resource allocation (Koenig, 2014). Furthermore, the use of data analytics in printing enterprises enables better decision-making and operational insight. Analytics can improve production schedules, predict maintenance needs, and analyse customer preferences, leading to enhanced efficiency (Davenport, 2013).

Human capital plays a vital role in improving operational efficiency in the printing industry. Continuous training programs for employees are essential for maintaining high operational standards. Research indicates that skilled labour leads to improved productivity and quality outcomes (Noe, 2014). Engaging employees in process improvement initiatives fosters a culture of continuous improvement. Studies show that involving frontline workers in decision-making can lead to innovative solutions for operational challenges (Cotton, 1993).

Sustainability is becoming an increasingly important focus in the printing industry. Implementing environmentally sustainable practices such as using eco-friendly inks and reducing waste, can improve efficiency while enhancing brand reputation (Berk, 2015). Research highlights that sustainable practices often lead to cost savings and operational efficiencies in printing (Klein & Wiegand, 2016).

2.5. Production Delays Reduction Scenarios

Production delay reduction scenarios are increasingly being developed and tested through simulation modelling, offering a proactive and data-driven approach to improving manufacturing efficiency. Simulation enables organizations to replicate complex production environments and evaluate the impact of various delay mitigation strategies without disrupting actual operations. For instance, Abdul Rahman and Adeboye (2025) used Siemens Tecnomatix Plant Simulation to model AGV systems in a manufacturing setup. Their study revealed that optimizing material flow and routing through simulation significantly reduced transport-related delays and improved overall throughput. Similarly, Abay et al. (2025) applied discrete-event simulation using JaamSim to identify bottlenecks in a drilling equipment factory. By testing scenarios such as parallel workstation deployment and dynamic resource allocation. Workforce-related delays, using simulation to explore task reallocation and inventory control strategies were another way. In a broader context, a study published in Applied Sciences proposed a five-step systematic improvement model that integrates simulation with early-stage data analysis. This model allowed

for the identification of delay patterns and the testing of corrective actions, ultimately enhancing quality, performance, and economic outcomes through iterative refinement.

Reducing production delays is a cornerstone of operational excellence in manufacturing, and the five scenarios presented offer a multifaceted approach to achieving this goal. Increasing machine speed to design capacity directly boosts throughput, enabling faster order fulfilment and better utilization of resources. This aligns with the Theory of Constraints (Goldratt, 1984), which emphasizes elevating bottlenecks to improve overall system performance. By optimizing machine speeds and balancing workloads, manufacturers can reduce idle time and increase the percentage of productive hours, leading to a more agile and responsive production environment.

Halving repair, setup, and make-ready times reflects a commitment to lean manufacturing and TPM, both of which aim to eliminate waste and maximize equipment effectiveness. Nakajima (1988) highlights that reducing downtime through preventive and predictive maintenance not only improves reliability but also enhances workforce engagement by empowering operators to take ownership of machine health. Streamlining setup and make-ready processes through standardization, training, and workspace organization (e.g., 5S methodology) further accelerates production transitions and minimizes delays between runs. These improvements contribute to a smoother, more consistent output and reduce the risk of cascading delays across the production schedule. Reducing machine failures by half are a transformative strategy that enhances long-term reliability and operational stability. This can be achieved through root cause analysis, predictive analytics, and investment in durable components. When machines operate consistently with fewer breakdowns, production becomes more predictable, enabling better planning and inventory control. Moreover, fostering a culture of continuous improvement where teams actively seek out inefficiencies and propose solutions ensures that these gains are sustained and built upon over time. Together, these scenarios form a comprehensive blueprint for reducing delays, improving efficiency, and driving competitive advantage in manufacturing operations.

2.6. Identified Gaps

While the previous study provides valuable insights into system modeling and simulation, production delays and machine failure, it lacks an in-depth exploration of how these methodologies can be effectively tailored to consider non value adding process like setup time,

make ready time and others in specific types of printing businesses especially in developing country like Ethiopia. Most studies focus on general concepts and established methodologies but do not provide detailed case studies or practical applications that demonstrate how different printing enterprises such as Wav-offset and offset printing processes can uniquely benefit from these approaches.

OEE is a crucial metric for assessing and improving the efficiency of production systems. It provides a comprehensive evaluation based on three key factors: availability, performance efficiency, and quality, helping companies identify areas of inefficiency and optimize their operations. Although OEE is widely recognized as a valuable performance measurement tool in manufacturing, the case company has not yet implemented. Addressing these gaps could to measure the performance effectively, identify the bottleneck, reduce operational costs and enhance productivity through both technological and human factors.

Chapter Three

3. Methodology

3.1. Research Design

This study adopts a quantitative research design to explore and enhance operational efficiency in printing enterprises through the analysis of processing data. Utilizing system modeling and simulation tools, particularly discrete event simulation, the study aims to develop a detailed and accurate model of the printing operations. The fitted distribution functions derived from the collected data will serve as the basis for this model. The model's accuracy and efficiency will be validated through iterative simulation runs. Based on the validated results, the study will identify potential areas for delay optimization and provide recommendations to enhance decision-making processes and reduce production delays, thereby improving the overall operational efficiency of printing enterprises.

3.2. Sampling Design

3.2.1. Target Population

The target population for this study comprises all active printing operational units within Berhanena Selam Printing Enterprise (BSPE). These include a total of 21 machines, specifically 5 wave offset machines and 16 standard offset machines. These machines collectively represent the full range of printing capabilities at BSPE, covering critical stages such as setup, make-ready, printing, and breakdown. However, while all machines contribute to the overall production output, they do not operate identically. Differences in machine type, age, function, and workload distribution mean that each unit has unique performance characteristics. Therefore, the study does not treat the population as homogeneous but instead recognizes the need for categorical segmentation to reflect operational realities.

To ensure meaningful analysis, the machines are categorized based on their technical specifications, functional roles, and operational behavior. The wave offset machines typically handle high-volume jobs and are more complex in setup and maintenance, while the standard offset machines are used for medium to low-volume tasks with faster turnaround times. This categorization allows the study to differentiate performance metrics such as OEE across

machine types. It also enables targeted modeling of delays, breakdowns, and resource allocation strategies that are specific to each category.

3.2.2. Sampling Technique

Given the heterogeneity of the machine population, a stratified random sampling technique is employed. The population is first divided into two strata; wave offset machines and standard offset machines. Within each stratum, machines are randomly selected to ensure unbiased representation. This method balances the need for diversity in machine types with the statistical rigor of random sampling. It also ensures that the sample reflects the operational dynamics of BSPE's production system, allowing for more accurate simulation and analysis.

Although all 21 machines contribute to production, sampling is necessary to manage the complexity of data collection and simulation modeling. A full census would be resource-intensive and may introduce redundancy, especially if certain machines exhibit similar performance patterns. By selecting a representative subset from each category, the study maintains analytical depth while optimizing resource use. The sample size is determined based on the variance in performance metrics, ensuring that the selected machines capture the full spectrum of operational behavior.

3.3. Data Collection

The type of data required includes arrival time of the job order, failure of the machine, repair time, setup time, make ready time, printing time and unite of good and bad production had been conducted systematically across the printing process within the specified timeframe 10/01/2025 – 07/02/2025. The data had collected through stopwatch measurements for time studies and printing job order schedules.

3.4. Statistical Input Analysis

To accurately model the data, we conducted distribution fitting using Arena software's input analyzer. The p-values and square errors from the input analyzer facilitate goodness-of-fit tests across various distributions. The chosen distributions provided the best fit for processing time data, consistently showcasing the highest and lowest test statistics. This rigorous analysis ensured that our input data was accurately represented, serving as a solid foundation for

subsequent modeling.

3.5. System Modeling

The system models will develop that accurately represents the current printing processes at BSPE. This model should include all critical variables and parameters affecting the production flow. Metrics that affect OEE were calculated from Value stream mapping and time function mapping information that led to the calculation of the current OEE. Having the data collected and fitted distribution function the model was developed with create module and then assign module to record the length of time the entity spent in the process. After assign module there was decide module which determines the failure of printing machine.

For the machine at failure state there was the process module for repair time, record module to record the length of repair time and lastly dispose module. For the machine at function state there was the process module for setup time, makes ready time, printing time and decide module to determine the products produced fulfill the quality and not. After this there was record module to record the length of time the good and bad product spent in the system and lastly dispose module.

A mathematical model will be used to build this model, which allows for experimentation with different scenarios and changes without disrupting actual operations. The goal is to understand how various factors interact and impact overall efficiency.

3.6. Verification and Validation

To ensure the model's accuracy, the ARENA simulation was executed for 1460 days with 12 replications per simulation. Initial simulations replicated the current state using existing machine performance data, confirming the model's accurate construction. The real world machine availability, performance, and qualities were calculated as:

$$\text{Performance} = \frac{\text{Actual production}}{\text{Expected production}} \text{-----} (1)$$

$$\text{Availability} = \frac{\text{Operating time}}{\text{Planned production time}} \text{-----} (2)$$

$$\text{Quality} = \frac{\text{Good units produced}}{\text{Total units produced}} \text{-----} (3)$$

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality} \text{-----} (4)$$

Once the current state was accurately replicated in the ARENA simulation, machine availability, performance, and quality were calculated to determine the OEE of the wave-offset and offset machines as follows:

$$\text{Performance} = \frac{\text{Number out} \times \text{Value adding time (VA)} \times \text{Run rate}}{\text{Total run time} \times \text{Ideal run rate}} \text{-----} (5)$$

$$\text{Availability} = \frac{\text{Number out} \times \text{Value adding time (VA)}}{\text{Total run time}} \text{-----} (6)$$

$$\text{Quality} = \frac{\text{Good units time} \times \text{Run rate}}{\text{Total units time} \times \text{Run rate}} \text{-----} (7)$$

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality} \text{-----} (8)$$

Detailed code reviews, debugging, and parameter checks were conducted to align input data with real-world values. The model outputs were then compared to historical data. The simulation results, which closely matched real-world availability, performance, quality and OEE data, validated the model's reliability.

3.7. Simulation Output Analysis

The primary goal is to determine the optimal number of replications required so that the sample size meets the desired level of precision within a 95% confidence interval. By increasing the number of replications, researchers can reduce variability and enhance the reliability of their estimates. Using mathematical models, such as the formula the minimum required replications were determined.

$$R \geq \left(\frac{t_{\frac{\alpha}{2}, R-1} S_0}{\epsilon} \right)^2 \text{-----} (9)$$

Here, $t_{\frac{\alpha}{2}, R-1}$ represents the critical value from the t-distribution, S_0 is the sample standard

deviation, and ϵ is the margin of error. The smallest integer satisfying the error criterion $R \geq \left(\frac{t_{\alpha, R-1} S_0}{\epsilon}\right)^2$ ensures that the sample size R is enough to keep the margin of error within acceptable limits when estimating a population parameter. This process also involves examining the results generated by a simulation model to draw meaningful conclusions. It includes statistical analysis to interpret the model's outputs and determine their reliability and significance. Metrics that affect OEE were calculated from Value stream mapping and time function mapping information that led to the calculation of the current OEE. Key aspects include evaluating the performance measures, identifying trends, and comparing the performance of two (or more) systems results. Effective output analysis ensures that the insights gained from the simulation are valid and can be applied to decision-making processes.

3.8. Improvements in Operational Efficiency

In the pursuit of operational efficiency within BSPE, a substantial enhancement has been realized by leveraging insights and recommendations formulated from a validated system model and simulation outcomes. This approach involved meticulously pinpointing and remedying critical bottlenecks and inefficiencies plaguing the printing process. Consequently, this methodical and data-driven strategy has demonstrated a notable improvement scenario, effectively streamlining operations and boosting overall productivity in the printing enterprise. The study underscores the transformative impact of utilizing system models and simulations to drive informed decisions and foster significant efficiency gains in business operations.

Chapter Four

4. Results and Discussion

4.1. Production Delays Analysis

Understanding the impact of production delays is crucial for evaluating operational efficiency. In this study, delays were quantified not only in terms of time lost but also in terms of their economic implications such as reduced throughput, increased labour costs, and missed delivery deadlines. By assigning a monetary value to each minute of downtime, the analysis revealed that even minor disruptions in the wave-offset and offset processes could lead to significant cumulative losses over time. These findings underscore the importance of proactive delay mitigation strategies, such as predictive maintenance and real-time monitoring.

The total production delays for the wave-offset and offset printing processes amounted to approximately 663.2 hours, derived from repair time, setup time, and make-ready time combined. Specifically, the wave-offset process experienced 66.6 hours of repair, 47.6 hours of setup, and 132.2 hours of make-ready, while the offset process encountered 28.9 hours of repair, 49.2 hours of setup, and a significantly higher 338.7 hours of make-ready time. These figures reveal that operational readiness and preparation stages particularly in the offset process were major contributors to lost time. If we assume an average output of 1,000 units per hour, this cumulative downtime could account for a potential shortfall of over 663,000 units, illustrating the profound impact of inefficiencies beyond machine breakdowns alone and highlighting the need for targeted interventions in pre-production processes.

System modeling is needed because it transforms complex, fragmented production data into a coherent, actionable framework that helps BSPE tackle its operational inefficiencies. In a high-volume printing environment where even small delays can lead to massive output losses, modeling allows the enterprise to simulate real-world scenarios, pinpoint root causes of downtime, and test solutions virtually before applying them on the production floor. It bridges the gap between raw machine data and strategic decision-making, enabling predictive maintenance, optimized scheduling, and smarter resource allocation. Without system modeling,

BSPE would be limited to reactive measures, missing the opportunity to proactively enhance performance and stay competitive in a rapidly evolving industry.

System modeling is essential to provide a structured and analytical framework to understand the complex dynamics of production delays. Traditional observation and manual tracking methods often fail to capture the intricate interdependencies between machine performance, setup procedures, and repair cycles. By using simulation tools like ARENA, it can replicate real-world production scenarios and test various operational strategies in a virtual environment. This allows the enterprise to identify bottlenecks, quantify the impact of delays, and evaluate the effectiveness of proposed interventions without disrupting actual production. The ability to simulate and visualize production flows offers a powerful lens through which inefficiencies can be diagnosed and addressed with precision.

Moreover, system modeling supports predictive and proactive decision-making. Instead of reacting to delays after they occur, it can use simulation data to anticipate potential disruptions and implement preventive measures such as predictive maintenance schedules or optimized setup protocols. The model's integration of real-time data such as cycle times, failure rates, and repair durations enables the enterprise to forecast performance outcomes under different operational conditions. This predictive capability is particularly valuable in high-volume environments where even minor delays can lead to substantial losses in output and revenue. By simulating various scenarios, BSPE can prioritize improvements that yield the highest return on investment and align with strategic goals. To accurately capture the causes and frequency of these delays, a systematic approach was used to determine which machines required data collection. Machines were selected based on their criticality to the production line, historical failure rates, and contribution to overall output. Data was gathered using sensors and loggers integrated into the ARENA simulation model, which tracked variables such as cycle time, failure frequency, and repair duration. This targeted data collection ensured that the most impactful sources of inefficiency were identified and addressed.

Finally, system modeling enhances communication and strategic alignment across departments. The visual and quantitative outputs of simulation models make it easier for managers, technicians, and stakeholders to understand the root causes of delays and the rationale behind

proposed changes. This shared understanding fosters collaboration and supports a culture of continuous improvement. As BSPE strives to meet growing customer demands and adapt to technological advancements, system modeling becomes a vital tool for navigating complexity, improving operational efficiency, and sustaining competitive advantage in the printing industry.

The simulation results, when compared with real-world performance metrics, demonstrated a strong correlation between machine-specific delays and OEE. Machines with higher delay frequencies consistently showed lower availability and performance scores. By focusing data collection on these machines, the model provided actionable insights into where improvements would yield the greatest return. This approach not only validated the simulation’s accuracy but also highlighted the strategic value of data-driven decision-making in optimizing production systems.

4.2. Statistical Input Analysis

To model the data accurately, distribution fitting was carried out using Arena software's input analyser. Figure 1 illustrates the basic process module generated and populated with values corresponding to each process. The input analyser performed statistical analyses such as p-values and square error to facilitate goodness-of-fit tests for various distributions. The results demonstrated that the chosen distribution provided the best fit for processing time data, consistently showing the highest and lowest test statistics across p-values and square error goodness-of-fit tests respectively.

Process - Basic Process													
	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Expression	Report Statistics
1	Wave offset print	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Hours	Value Added	-0.001	3.69	3	LOGN(4.5, 3.2)	<input checked="" type="checkbox"/>
2	Offset print	Standard	Seize Delay Release	Medium(2)	1 rows	Uniform	Hours	Value Added	11	9.8	58	0.88	<input checked="" type="checkbox"/>
3	Wave offset make ready	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Hours	Non-Value Added	3.69	6.02	1	LOGN(5.22, 4.6)	<input checked="" type="checkbox"/>
4	Offset make ready	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	2	6.9	9	0.88	<input checked="" type="checkbox"/>
5	Wave offset reparaie	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Hours	Other	0	6.02	1	BETA(1.19, 1.23	<input checked="" type="checkbox"/>
6	Offset reparaie	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Hours	Other	2	3.62	9	BETA(0.633 ,	<input checked="" type="checkbox"/>
7	Wave offset setup	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Hours	Other	3.69	6.02	1	BETA(1.19, 1.23	<input checked="" type="checkbox"/>
8	Offset setup	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Hours	Transfer	3.69	6.02	1	NORM(3.62, 1)	<input checked="" type="checkbox"/>

Figure 1: Fitted distribution in ARENA

4.3. System Modeling

A model for the wave-offset and offset processes was created using the ARENA software, with input parameters chosen carefully, as shown in Figure 2. For wave-offset processes the create module with expression (EXPO (12.9)) and assign module to record the length of time the entity spent in the process. After assign module there was decide module which determines the percentage of Wave offset machine failure (2.88%) computed as by dividing the number of failures to total cycles or process time (19/595.66). For failure state there was the process module for repair time with expression (0.23 + 6.42 * BETA (1.19, 1.23)). For function state there was the process module for setup time with expression (BETA (1.19, 1.23)), makes ready time (LOGN (5.22, 4.6)), printing time (LOGN (4.0, 2.71)) and decide module to determine the percentage of good units produced (98.61%) computed as good units produced divided by total units produced $((1,630,145/1,653,123) \times 100)$. Lastly, records of good units, bad units, and repair times were assigned in the record module to track the overall time duration in the system.

For Offset processes the create module with expression (UNIF (-0.001, 92)) and assign module to record the length of time the entity spent in the process. After assign module there was decide module which determines the percentage of Offset machine failure (1.97%) computed by dividing the number of failures to total cycles or process time (11/625.57). For failure state there was the process module for repair time with expression (BETA (0.633, 0.609)). For function state there was the process module for setup time with expression (NORM (3.62, 1)), makes ready time (TRIA (2, 6.9, 9)), printing time (Uniform (14, 60)) and decide module to determine the percentage of good units produced (98.09%) computed as good units produced divided by total units produced $((566,227/577,253) \times 100)$. Lastly, records of good units, bad units, and repair times were assigned in the record module to track the overall time duration in the system.

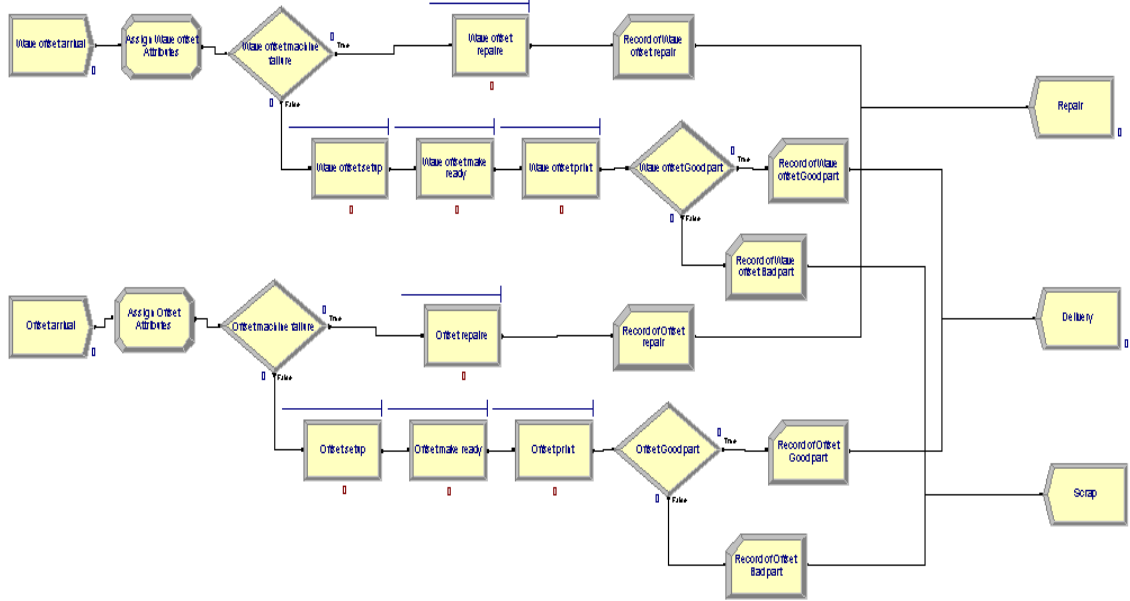


Figure 2: ARENA model design

4.4. Verification and Validation

The ARENA simulation was executed for 1460 days with 12 replications per simulation. Initially, the current state was simulated using data from the existing machine performance as a pre-test. This step confirmed that the simulation model was accurately constructed and functioned as intended. Detailed code reviews, debugging, and parameter checks were conducted to ensure the input data was precise and aligned with real-world values.

4.4.1. OEE Calculation for Real-World

The OEE calculation for the real-world wave-offset machine considers three key factors: performance, availability, and quality. Performance is measured by the total units produced compared (1,653,123 units) to the maximum possible output (7,920,000 units), resulting in 20.87% efficiency. Availability is calculated based on actual operating hours (230.35 hours) versus scheduled hours (660 hours), yielding an availability rate of 34.90%. Quality, which reflects the ratio of defect-free units (1,630,145) to total production (1,653,123), stands at 98.61%. Multiplying these factors, the final OEE for the real-world wave-offset machine is 7.18%, indicating significant room for improvement in both efficiency and machine utilization.

Similarly, for the real-world offset machine, the performance metric shows that the machine operates at 29.15% (1,653,123 units/7,920,000 units) efficiency, while availability is 73.55% (230.35 hours/660 hours), suggesting better uptime than the wave-offset machine. The quality rate remains high at 98.09% (1,630,145 units/1,653,123 units), demonstrating consistent production standards. The overall OEE calculation for this machine comes out to 21.03%, showing a more efficient operation compared to the wave-offset machine.

For the simulated model of the wave-offset machine, the performance, availability, and quality values are 20.80%, 34.78%, and 99.09% respectively, resulting in a simulated OEE of 7.22%, which closely aligns with the real-world findings. Meanwhile, the simulated offset machine yields an OEE of 20.91%, based on a 28.96% performance rate, 73% availability, and 98.89% quality, indicating that the simulated model effectively mirrors real operational conditions. These results suggest that targeted improvements in performance efficiency and availability could greatly enhance the overall productivity of both machine types.

4.4.2. OEE Calculation for Simulated Model

The Overall Equipment Effectiveness (OEE) calculation for the simulated wave-offset machine was derived using ARENA simulation, ensuring an accurate replication of the current operational state. The performance metric, which measures the actual output relative ($1,278.63 \times 4.43 \times 7,178$) to the maximum possible production ($16,060 \times 12,000$), stands at 20.80%, indicating room for improvement in efficiency. Availability, calculated as the ratio of actual operating hours ($1,278.63 \times 4.43$) to planned hours (16,060), is 34.78%, suggesting potential downtime issues. The quality metric, which represents the ratio of defect-free production ($7,864.01 \times 7,178$) to total production ($7,879.56 \times 7,178$), is notably high at 99.09%, demonstrating strong output consistency. When combined, the overall simulated OEE for the wave-offset machine is 7.22%, showing that significant improvement efforts are needed to enhance machine utilization and efficiency.

For the simulated offset machine, the OEE calculation follows a similar methodology. Performance efficiency is 28.96% ($(350.38 \times 33.39 \times 1,190) / (16,060 \times 3,000)$), reflecting moderate production effectiveness compared to the wave-offset machine. Availability is 73.00% ($(350.38 \times 33.39) / (16,060)$), which suggests better uptime and fewer interruptions in

operations. The quality factor remains strong at 98.89% $((8,018.06 \times 1,190) / (8,113.20 \times 1,190))$, reinforcing a high standard of production. These combined values result in an overall simulated OEE of 20.91%, indicating a more efficient operation compared to the wave-offset model. The findings suggest that targeted improvements in performance and availability could further enhance productivity, making process improvements a key area for future development in printing enterprises.

4.4.3. Comparison of Real-World and Simulated OEE Results

The comparison between real-world and simulated OEE results shows a close alignment between the two datasets, indicating the reliability of the model in reflecting actual performance. While slight variations exist, such as the model's wave-offset machine showing marginally higher quality (99.80% vs. 98.61%) and slightly lower availability (34.78% vs. 34.90%), the overall impact on OEE remains minimal. Similarly, the offset system maintains consistency across both real-world and simulated results, with only minor differences in performance and quality.

Table 1: Real world and Initial state of the model

No.	System	Machine	Availability	Performance	Quality	OEE
1.	Real world	Wave-offset	34.90%	20.87%	98.61%	7.18%
		Offset	73.55%	29.15%	98.09%	21.03%
2.	Model	Wave-offset	34.78%	20.80%	99.80%	7.22%
		Offset	73.00%	28.96%	98.89%	20.91%

The simulation results closely matched the real-world availability, performance, and quality and OEE data, indicating that the model reliably represents actual machine performance, as shown in Figure 3. The slight variations observed in the availability, performance, and quality metrics were within acceptable limits and could be attributed to the inherent variability in real-world operations. The overall OEE values exhibited a strong correlation between the simulated and real-world data, validating the accuracy of the simulation model. The correlation coefficient between the simulated and real-world OEE values was approximately 0.9623, indicating a strong positive linear relationship. These findings suggest that the model effectively captures

operational behaviors and can be a useful tool for analyzing and predicting equipment efficiency under varying conditions.

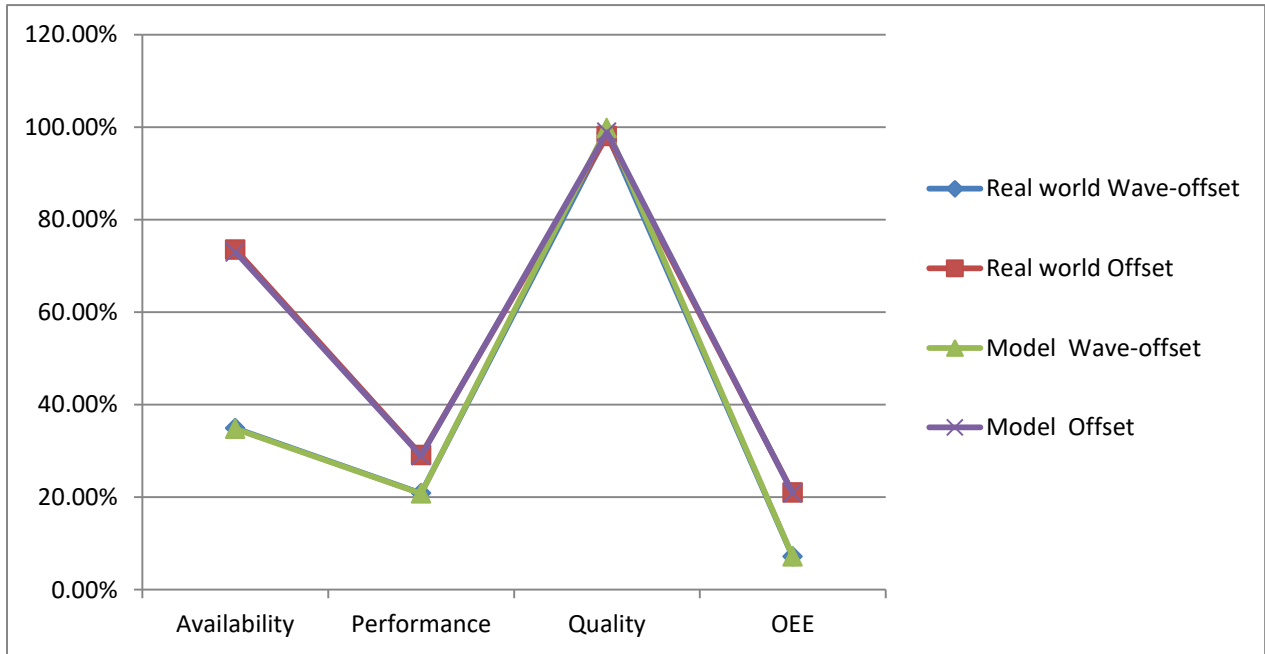


Figure 3: Plot of Initial Availability, Performance, Quality and OEE

4.5. Simulation Output Analysis

Based on the simulation output data, the mean time across 12 replications was approximately 8010.05 hours. The variance was approximately 21812.46 hours, and the standard deviation (the square root of the variance) was approximately 147.67 hours. These values indicate the degree of variation around the mean duration. The standard error, which shows the average error in estimating the mean, was approximately 42.63 hours. Using this standard error and a 95% confidence level, the confidence interval for the mean was approximately 8010.05 ± 132.44 hours, resulting in a range of 7877.61 to 8142.49 hours. The optimal number of replications required to meet the desired level of precision within a 95% confidence interval are computed as table 2.

Table 2: Number of Replications Computation

R	6	7	8	9	10
$t_{\frac{\alpha}{2}, R-1}$	2.447	2.447	2.365	2.306	2.262
$\left(\frac{t_{\frac{\alpha}{2}, R-1} S_0}{\varepsilon}\right)^2$	7.97	7.97	7.76	7.58	7.44

The smallest integer satisfying the error criterion $R \geq \left(\frac{t_{\frac{\alpha}{2}, R-1} S_0}{\varepsilon}\right)^2$ is $R = 8$. To meet the error criteria for a 95% confidence interval, the required number of observations is 7.76, which rounds up to 8. Since the initial replication size was 12, there is an excess of 4 replication ($8 - 12 = -4$). Therefore, a replication size of 8 is sufficient to meet the desired precision in the confidence interval estimate.

4.6. Potential Sources of Production Delays

4.6.1. Operating Speed

Operating speed was a crucial factor in production efficiency and potential delays. The wave-offset machine operates at 7,178 unite/hour of its design speed (12,000 unite/hour), while the offset machine operates at just 1,190 unite/hour of its design speed (3,000 unite/hour), translating to significant inefficiencies. These underperformances suggest considerable delays, extending production times. The wave-offset machine's underperformance contributes to around 40.18% $\left(\frac{12,000-7,178}{12,000}\right)$ delays, while the offset machine's inefficiency adds up to about 60.33% $\left(\frac{3,000-1,190}{3,000}\right)$ delays.

4.6.2. Machine Failure

Machine failures are significant contributors to production delays with machine breakdowns and the associated repair times. For the wave-offset machine, the total repair time over a 4-year period is 2,372.82 hours, which accounts for approximately 14.77% $\left(\frac{2,372.82}{16,060}\right)$ of the total delay. Similarly, the offset machine experiences a total repair time of 683.40 hours within the same period, contributing to around 4.26% $\left(\frac{683.40}{16,060}\right)$ of the delay.

4.6.3. Setup Time

Setup time was another critical source of production delays, which refers to the duration needed to prepare the raw materials before the production process begins. This time includes tasks such as identifying the required raw materials, raising store requisitions, extracting raw materials, preparing the row material and transporting them to the work area. The wave-offset machine has a setup time of 604.50 hours, and the offset machine requires 1243.48 hours, over a 4-year run length. The wave-offset machine's setup time accounts for approximately 3.76% ($604.50/16,060$) of the production delay, and the offset machine's setup time represents about 7.42% ($1,243.48/16,060$) of the delay.

4.6.4. Make Ready Time

The make ready time is the period required to prepare the printing machines for production, including tasks such as adjustments, and calibration to ensure optimal printing conditions. For the wave-offset and offset machines, make ready time encompasses aligning plates, setting ink levels, and conducting test runs to guarantee high-quality outputs. The wave-offset machine, make ready time is 6,438.07 hours, while the offset machine requires 2,067.61 hours over a 4-year run length, leading to high potential delays. The wave-offset machine's make ready time contributes to around 40.09% ($6,438.07/16,060$) of the total delay, while the offset machine's make ready time accounts for approximately 12.84% ($2,067.61/16,060$) delay.

4.7. Production Delays Redaction Strategies and Efficiency improvement

4.7.1. Scenario 1: Effects of Increasing Machine Capacity to 90% of Design Speed

Increasing the run speed of the wave-offset and offset machines to 90% of their design run speeds would significantly reduce production delays and enhance overall efficiency. Regular maintenance and fine-tuning can help improve machine operating speeds. Investing in operator training to ensure machines are used efficiently and optimizing the production schedule to balance workloads can also enhance performance and reduce delays.

The wave-offset machine, which actually operates at 7,178 unite/hour, would see its speed increase to 10,800 unite/hour (90% of 12,000 unite/hour). Similarly, the offset machine would experience a speed boost from 1,190 unite/hour to 2,700 unite/hour (90% of 3,000 unite/hour).

These improvements in machine run speed would likely lead to a considerable reduction in total production time, increase the percentage of production, and improve the overall operational efficiency of the manufacturing process as shown in figure 4 below.

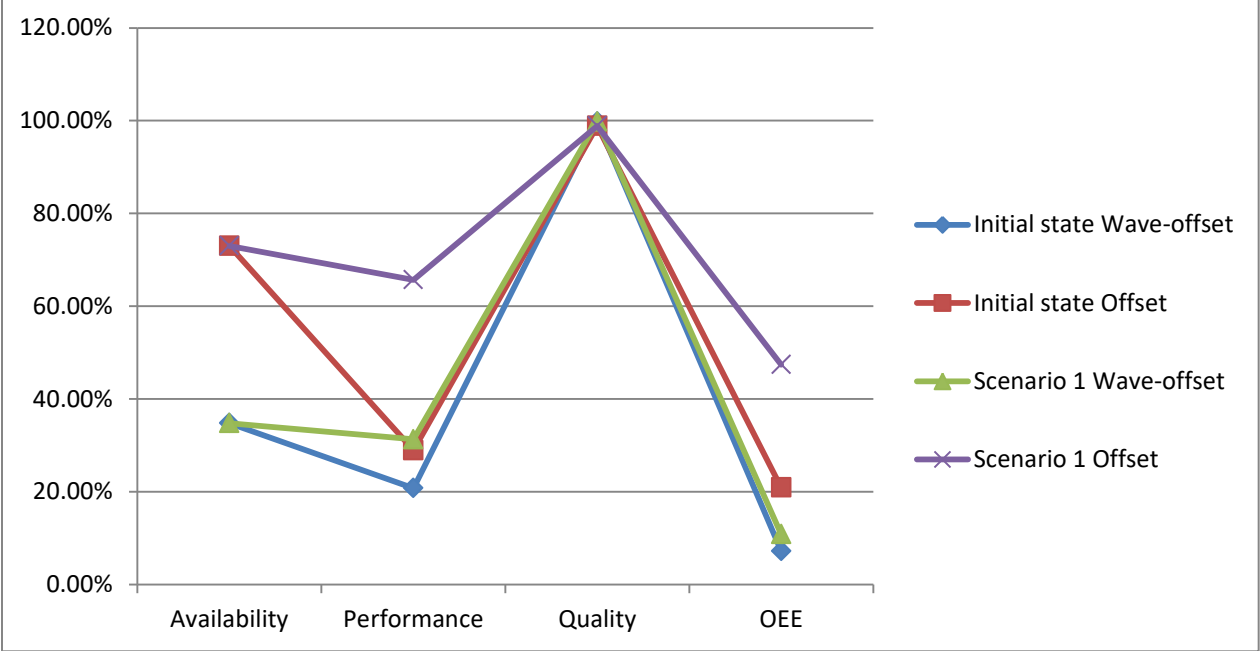


Figure 4: Plot of effects increasing machine capacity to 90% of design speed

4.7.2. Scenario 2: Effects of Reducing Repair Time by Half

Reducing the repair time for both the wave-offset and offset machines by half would have a substantial impact on minimizing production delays. Implementing a robust preventive maintenance program can help minimize machine breakdowns. This involves regularly inspecting and servicing machines to identify and address potential issues before they lead to failures. Training and certifying maintenance personnel ensure that they can perform repairs quickly and effectively, further reducing repair time. Conducting root cause analyses of machine failures can help identify and address underlying issues, preventing recurring problems. Additionally, having spare parts readily available and training operators to handle minor repairs can reduce downtime.

The wave-offset machine, this change would decrease the total repair time from 2,372.82 hours to 1,186.41 hours over a 4-year period, significantly reducing downtime and increasing machine

availability. Similarly, the offset machine's total repair time would be reduced from 683.40 hours to 340.43 hours. This reduction in repair time would enhance the overall efficiency and reliability of the machines, leading to more consistent production output and a decrease in unplanned stoppages that disrupt the manufacturing process as shown in figure 5 below.

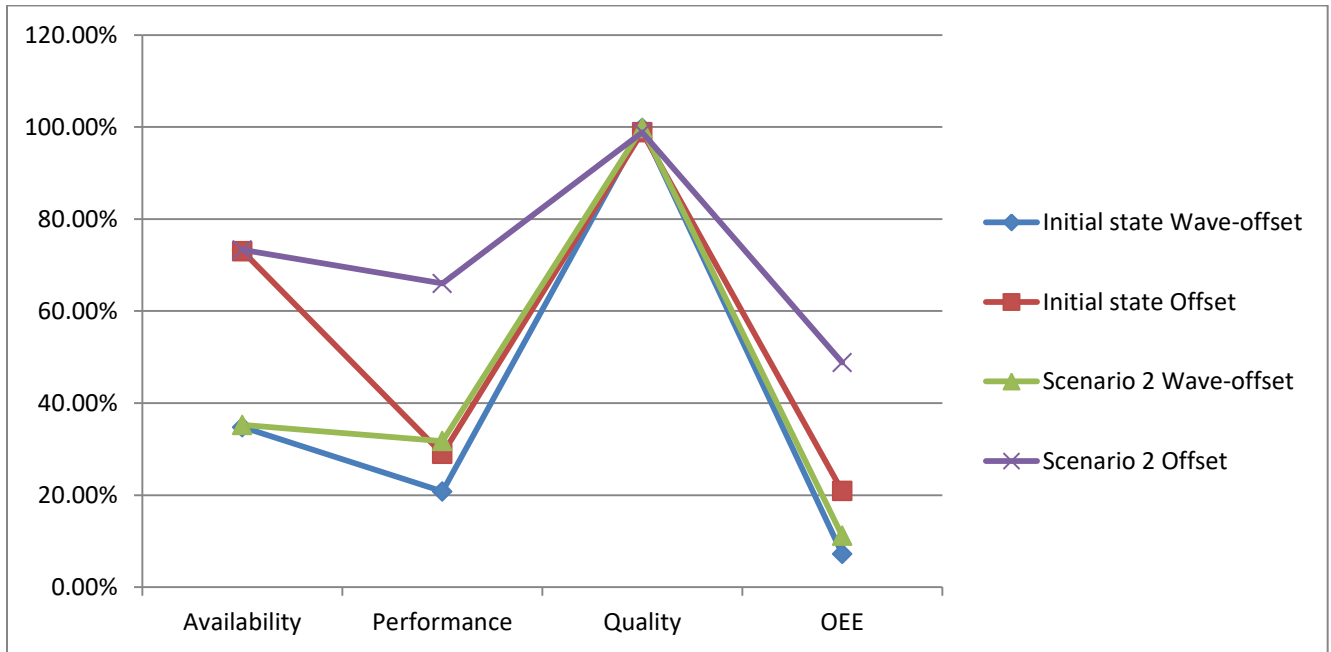


Figure 5: Plot of effects reducing repair time by half

4.7.3. Scenario 3: Effects of Reducing Setup Time by Half

Halving the setup time for the wave-offset and offset machines would greatly improve production efficiency by minimizing the time required to prepare the raw materials before the production process begins. Implementing standardized procedures and simplifying setup processes can significantly reduce setup time by minimizing complexity and ensuring consistency. Providing comprehensive training programs for operators and technicians can enhance their skills, enabling them to perform setups more efficiently. Pre-setup preparation, such as organizing and preparing necessary tools, materials, and information in advance, can streamline the setup process. Adopting lean manufacturing practices, like 5S, can improve workspace organization and efficiency, further contributing to the reduction of setup time.

The wave-offset machine's setup time would be reduced from 606.54 hours to 303.27 hours, while the offset machine's setup time would decrease from 1,264.26 hours to 632.13 hours over a

4-year run length as shown in figure 6 below. This reduction in setup time would streamline the production process, allowing for quicker transitions between different production runs and ultimately reducing the overall production delays. The increased efficiency in setup would also contribute to a more agile and responsive manufacturing operation.

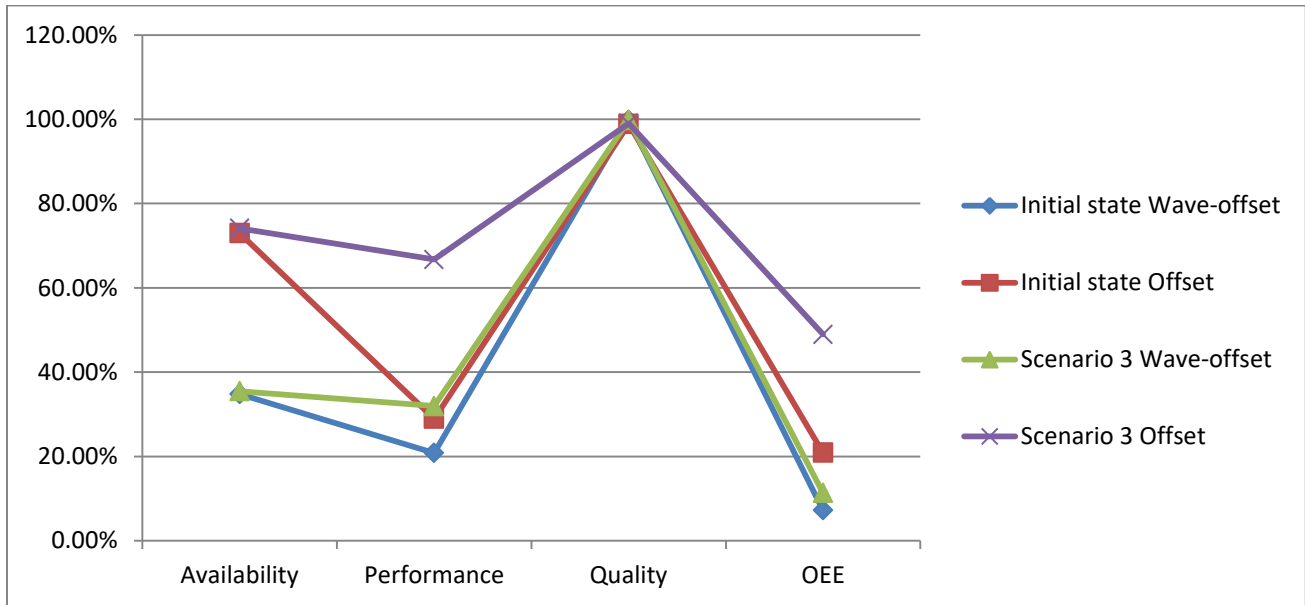


Figure 6: Plot of effects reducing setup time by half

4.7.4. Scenario 4: Effects of Reducing Make-ready Time by Half

Reducing the make-ready time for the wave-offset and offset machines by half would significantly enhance the overall operational efficiency of the printing process. Investing in automation and advanced technology can reduce manual interventions and speed up make-ready processes, leading to significant time savings. Developing Improved production schedules can minimize machine downtime between production runs, ensuring a more efficient operation. Fostering a culture of continuous improvement encourages operators to identify and implement make-ready time reduction opportunities. Enhancing communication and collaboration among production teams can ensure a smooth transition during make-ready activities, further reducing make-ready time.

The wave-offset machine's make-ready time would decrease from 6,602.95 hours to 3,301.48 hours, while the offset machine's make-ready time would be reduced from 2,036.56 hours to 1,018.28 hours over a 4-year period as shown in figure 6 below. This reduction in make-ready

time would shorten the period required to prepare the printing machines for production, allowing for faster adjustments, calibration, and test runs. As a result, the total production delays would be minimized, leading to a more efficient and productive printing operation with higher quality outputs and reduced downtime.

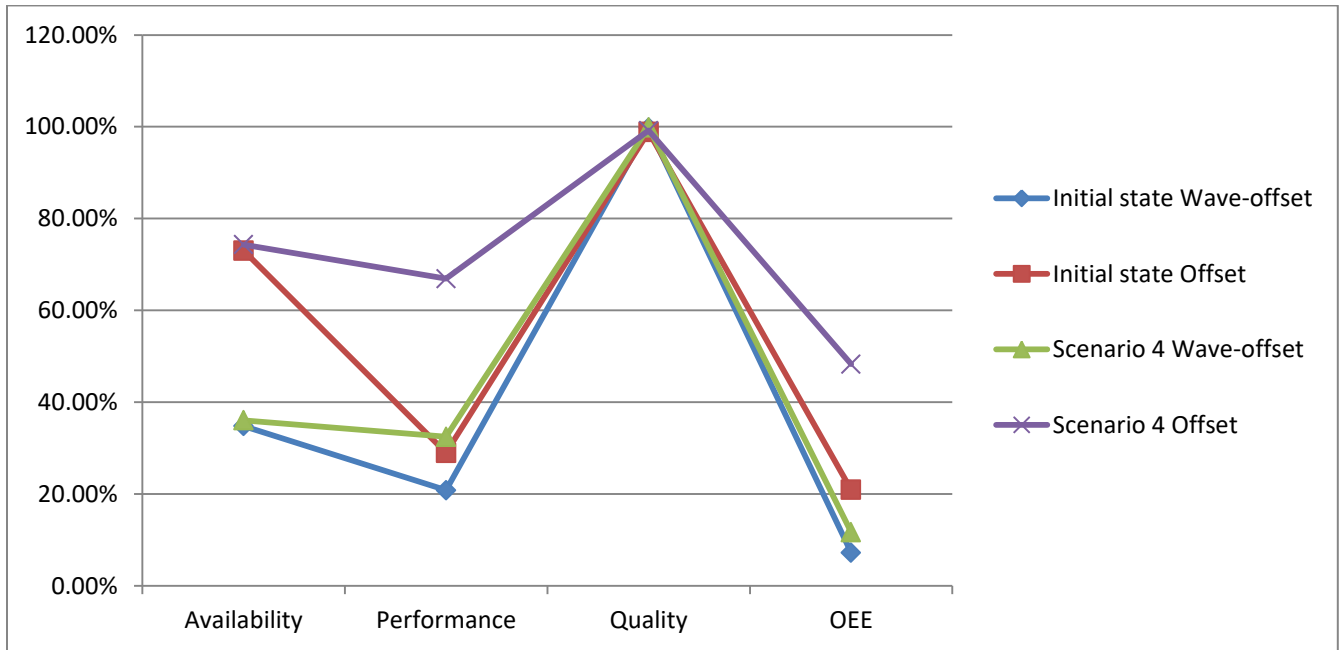


Figure 7: Plot of effects reducing setup time by half

4.7.5. Scenario 5: Effects of Reducing Machine Failures by Half

Reducing failures by half for both the wave-offset and offset machines can significantly improve production efficiency and minimize delays. This can be achieved by implementing failure prevention strategies, such as conducting detailed root cause analyses to identify recurring issues and addressing them proactively. Developing a robust predictive maintenance program based on data analysis ensures machines are regularly monitored and serviced to prevent unexpected breakdowns. Enhancing operator training equips personnel with the knowledge and skills to recognize early signs of machine failure and respond promptly. Additionally, investing in high-quality, durable components and ensuring an adequate supply of spare parts can reduce the likelihood of failures and minimize downtime when repairs are necessary.

Furthermore, fostering a culture of continuous improvement within the manufacturing process encourages teams to collaborate and innovate ways to enhance machine reliability. Reducing

machine failures not only decreases unplanned stoppages but also enhances the overall reliability and consistency of production output. By maintaining smooth operation and minimizing disruptions, the production process becomes more agile, responsive, and capable of achieving higher levels of efficiency and productivity.

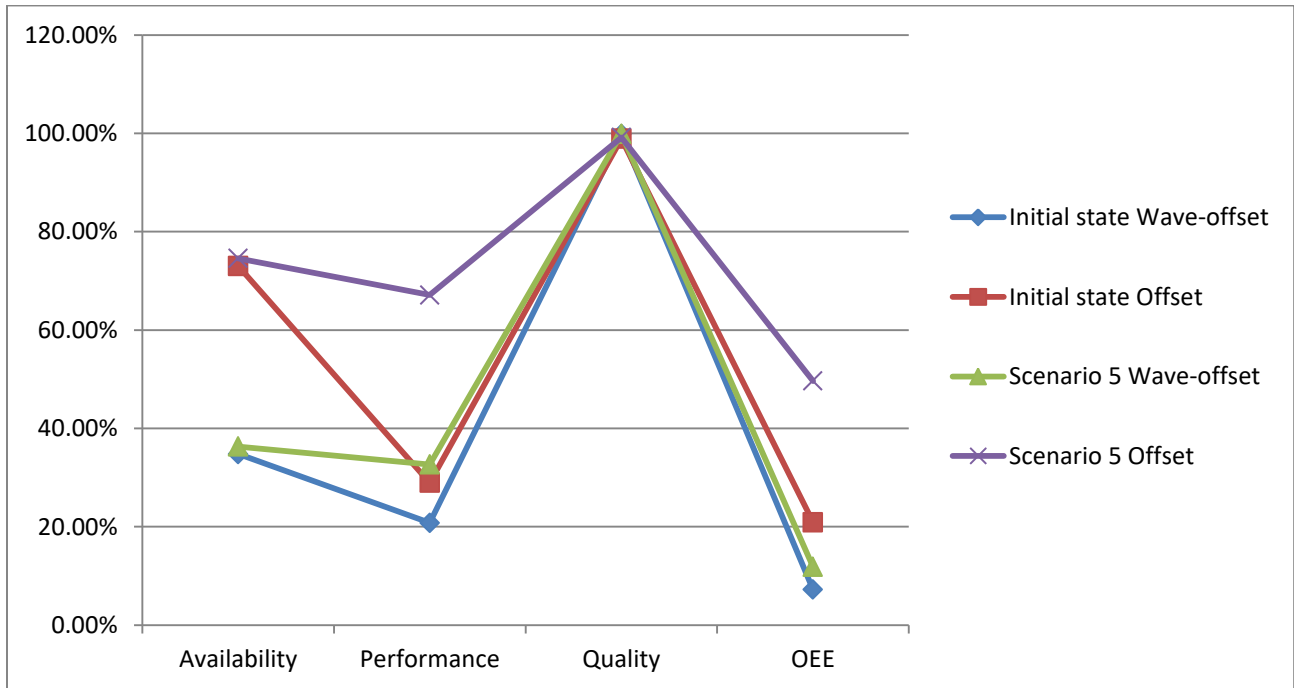


Figure 8: Plot of effects reducing Failures by half

Chapter Five

5. Conclusion and Recommendations

5.1. Conclusion

The operational efficiency of the printing process is significantly affected by several key factors, namely operating speed, machine failures, setup time, and make-ready time. The underperformance of both the wave-offset and offset machines due to lower operating speeds has been identified as a primary contributor to production delays, accounting for a considerable portion of the total delay. Machine failures and the resulting repair times further exacerbate these delays, with the wave-offset machine experiencing a higher percentage of downtime compared to the offset machine. Setup time and make-ready time also play critical roles in delaying production.

Table 3: Overall improvements in operational efficiency

No.	System	Machine	Availability	Performance	Quality	OEE
1.	Initial state	Wave-offset	34.78%	20.80%	99.80%	7.22%
		Offset	73.00%	28.96%	98.89%	20.91%
2.	Scenario 1	Wave-offset	34.78%	31.30%	99.80%	10.86%
		Offset	73.00%	65.70%	98.89%	47.43%
3.	Scenario 2	Wave-offset	35.27%	31.74%	99.80%	11.17%
		Offset	73.31%	65.98%	98.83%	48.80%
4.	Scenario 3	Wave-offset	35.49%	31.94%	99.80%	11.31%
		Offset	74.11%	66.70%	99.01%	48.94%
5.	Scenario 4	Wave-offset	36.06%	32.46%	99.87%	11.69%
		Offset	74.31%	66.88%	99.16%	48.28%
6.	Scenario 5	Wave-offset	36.29%	32.66%	99.87%	11.84%
		Offset	74.57%	67.12%	99.17%	49.64%

To enhance operational efficiency, several strategies can be employed, such as increasing machine capacity to 90% of design run speeds, reducing repair times by half through preventive maintenance programs, and cutting down both setup and make-ready times by half. These improvements would result in a more streamlined and responsive manufacturing operation,

ultimately leading to higher-quality outputs, increased production rates, and minimized production delays.

Implementing the proposed improvements specifically increasing machine speed to 90% of design capacity and halving repair, setup, and make-ready times would significantly decrease the total production delays across both wave-offset and offset processes. Originally, the combined delay time was 663.2 hours. Halving the repair times (95.5 hours total), setup times (96.8 hours), and make-ready times (470.9 hours) would result in a reduction of approximately 316.6 hours. This would bring total delays depressed to around 346.6 hours, representing a nearly 48% reduction in production downtime.

Strategically, the positive shift in OEE across scenarios further validates these interventions. For instance, in Scenario 5, the wave-offset machine's OEE rose to 11.84% (up from 7.22%) and the offset machine's to 49.64% (up from 20.91%). These improvements in availability, performance, and quality collectively ensure that future delays are less frequent and less severe. The OEE of the case company, when considering both the wave-offset and offset machines under the optimized Scenario is approximately 30.74%. Thus, the implementation of targeted operational changes offers a measurable and sustainable pathway toward enhanced production efficiency.

5.2. Recommendations

For the case company, implementing OEE as a performance measurement tool can significantly enhance performance measurement, bottleneck identification and operational efficiency. By systematically tracking availability, performance, and quality metrics, the company can identify areas for improvement, reduce downtime, and optimize resource utilization. Additionally, investing in workforce training and preventive maintenance can help streamline processes, minimize production delays, and improve responsiveness to market demands. Ensuring a culture of continuous improvement and data-driven decision-making will enhance competitiveness and long-term sustainability in the printing sector.

For researchers, future studies should focus on analyzing the long-term effects of different optimization strategies on machine performance. Investigating alternative materials and equipment designs that reduce maintenance frequency could also contribute to efficiency

improvements. Additionally, researchers could explore the impact of AI-driven predictive maintenance models in the printing industry, comparing their effectiveness against traditional methods. Examining workflow automation and human-machine collaboration strategies would provide valuable insights into increasing production speed without compromising quality. These studies would offer critical guidance for businesses looking to refine their operations using data-driven decision-making.

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Appendix 1:

Collected Data

1. Wave-offset (01/05/2017 – 30/06/2017 EC)

No	Job Type	Receipt Date	Arrival time	Inter arrival time	Number of failure	Repair Time	Setup time	Make ready time	Process Time	Production	Quality Fulfill
1.	Addis Zemen	01/05/2017	2:50	0			0.31	4.72	3.39	6583	Fulfill
2.	kelecha	01/05/2017	5:20	2.5			0.76	3.37	2.90	13851	Fulfill
3.	Al-Alem	02/05/2017	3:10	16.33	1	6.11	0.61	6.00	5.09	12910	Fulfill
4.	Addis Zemen	02/05/2017	7:20	4.17			0.98	3.50	2.95	17014	Fulfill
5.	Addis Zemen	03/05/2017	4:00	16.67			1.00	4.38	3.52	8550	Fulfill
6.	Herald	03/05/2017	8:30	4.5			0.97	4.32	2.64	9918	Fulfill
7.	Addis Admas	04/05/2017	3:20	16.83	1	2.59	0.39	5.12	2.23	13594	Fulfill
8.	Addis Zemen	04/05/2017	4:55	1.58			0.31	4.64	2.04	17271	Fulfill
9.	Addis Zemen	05/05/2017	4:35	15.67	1	4.16	0.22	6.65	1.91	12483	Fulfill
10.	Addis Zemen	06/05/2017	3:20	16.75			0.92	3.37	2.85	23256	Fulfill
11.	Herald	06/05/2017	8:50	5.5			0.03	4.33	2.68	9319	Fulfill
12.	Addis Zemen	07/05/2017	5:20	16.5			0.39	2.74	1.95	12397	Fulfill
13.	Herald	07/05/2017	7:00	1.67			0.66	5.34	2.47	31977	Fulfill
14.	Addis Zemen	08/05/2017	3:20	16.33	1	4.81	0.95	5.21	4.47	10174	Fulfill
15.	kelecha	08/05/2017	5:10	1.83			0.35	2.45	2.90	12226	Fulfill
16.	Herald	08/05/2017	7:25	2.25			0.06	3.23	1.06	9747	Fulfill
17.	Addis Zemen	09/05/2017	4:15	16.83			0.14	2.10	4.25	18810	Fulfill
18.	AlAlem	09/05/2017	7:35	3.33	1	1.06	0.49	5.72	2.48	11457	Fulfill
19.	Herald	09/05/2017	8:45	1.17			0.27	1.33	1.78	25137	Fulfill
20.	Addis Zemen	10/05/2017	3:50	16.08			0.48	2.78	3.56	24025	Fulfill

No	Job Type	Receipt Date	Arrival time	Inter arrival time	Number of failure	Repair Time	Setup time	Make ready time	Process Time	Production	Quality Fulfill
21.	Beresa	10/05/2017	5:20	1.5			0.75	2.36	3.48	22914	Not Fulfill
22.	Herald	11/05/2017	7:00	15.67	1	1.80	0.89	6.14	19.10	25992	Fulfill
23.	Books	12/05/2017	9:20	16.33			0.48	2.02	1.06	279239	Fulfill
24.	Policna Remjaw	17/05/2017	5:50	88.5			0.91	3.78	2.41	26676	Fulfill
25.	Herald	17/05/2017	7:10	1.33	1	5.89	0.07	6.44	3.00	18639	Fulfill
26.	Kelecha	18/05/2017	7:25	16.25			1.00	2.95	2.46	21460	Fulfill
27.	Policna Remjaw	19/05/2017	4:15	16.83	1	5.03	0.86	5.18	1.78	29754	Fulfill
28.	Policna Remjaw	22/05/2017	5:10	50.92			0.73	2.94	2.69	24880	Fulfill
29.	Addis Zemen	23/05/2017	7:25	16.25			0.82	3.26	2.18	8635	Fulfill
30.	Al-Alem	24/05/2017	8:50	17.42			0.83	2.94	4.67	32490	Fulfill
31.	Addis Admas	25/05/2017	5:20	16.5	1	0.77	0.55	4.21	2.61	12996	Fulfill
32.	Reporter	25/05/2017	7:00	1.67	1	5.95	0.47	5.79	2.18	31806	Fulfill
33.	Addis Lisan	26/05/2017	5:10	16.17			0.29	3.59	2.66	10260	Fulfill
34.	Addis Zemen	29/05/2017	7:25	54.25	1	3.54	0.68	5.68	3.16	25051	Fulfill
35.	Beresa	30/05/2017	4:15	16.83			0.55	5.35	2.13	30609	Fulfill
36.	Herald	01/06/2017	3:50	47.92			0.58	4.19	3.16	9576	Fulfill
37.	Addis Zemen	01/05/2017	5:25	-			0.64	5.02	2.09	20007	Fulfill
38.	Herald	02/05/2017	4:00	16.58	1	2.92	0.45	6.73	3.63	14107	Fulfill
39.	Herald	02/05/2017	8:20	4.33			0.53	3.66	3.16	18126	Fulfill
40.	Addis Zemen	03/05/2017	5:50	21.83	1	1.88	0.74	4.03	3.19	17784	Fulfill
41.	Addis Zemen	04/05/2017	5:20	16.75			0.79	3.71	2.09	20178	Fulfill
42.	Bekelecha	04/05/2017	7:55	2.58			0.19	5.00	3.65	19066	Fulfill
43.	Herald	05/05/2017	2:50	18.92			0.60	4.48	0.46	14193	Fulfill
44.	Wegheta	05/05/2017	5:20	2.5	1	4.06	0.66	5.38	2.11	11799	Fulfill
45.	Book	06/06/2017	4:35	490.25	1	1.32	0.44	25.56	22.16	254445	Fulfill

No	Job Type	Receipt Date	Arrival time	Inter arrival time	Number of failure	Repair Time	Setup time	Make ready time	Process Time	Production	Quality Fulfill
46.	Herald	13/06/2017	3:45	157.17			0.65	4.91	2.00	10516	Fulfill
47.	Addis Zemen	14/06/2017	7:50	16.08			0.40	3.22	3.74	15561	Fulfill
48.	Addis Zemen	15/06/2017	5:25	17.58			0.77	4.06	1.14	19494	Fulfill
49.	Herald	15/06/2017	7:35	2.17			0.83	2.24	3.19	17356	Fulfill
50.	Herald	16/06/2017	3:20	16.75	1	4.68	0.98	6.72	4.33	22230	Fulfill
51.	Reporter	17/06/2017	8:50	17.5			0.87	4.51	4.30	15133	Fulfill
52.	Addis Lisan	18/06/2017	5:20	16.5			0.20	4.11	3.39	14107	Fulfill
53.	Addis Zemen	18/06/2017	4:40	2.33	1	1.54	0.96	5.21	4.96	12910	Fulfill
54.	Wegheta	19/06/2017	7:50	17.17			0.31	4.53	3.86	20349	Fulfill
55.	Wegheta	20/06/2017	2:35	16.75			0.12	2.06	3.98	11713	Fulfill
56.	Kelecha	20/06/2017	7:20	4.75			0.41	4.46	1.92	25308	Fulfill
57.	Book	21/06/2017	5:25	16.08			0.37	23.40	19.60	13509	Fulfill
58.		26/06/2017			1	3.74					
59.	Herald	27/06/2017	2:55	113.5			0.61	4.74	3.13	12483	Fulfill
60.	Addis Zemen	27/06/2017	4:50	1.92			0.89	3.59	3.49	19494	Fulfill
61.	Herald	28/06/2017	5:20	16.5			0.30	5.80	2.45	20862	Fulfill
62.	Reporter	28/06/2017	5:40	0.33			1.00	4.48	3.94	17271	Fulfill
63.	Addis Lisan	29/06/2017	3:55	16.58			0.20	3.96	3.60	24538	Fulfill
64.	kelecha	29/06/2017	5:50	1.92	1	2.49	0.31	4.52	2.96	6583	Fulfill
65.	Addis Zemen	29/06/2017	9:20	3.5			0.76	3.43	2.32	22401	Fulfill
66.	Wegheta	30/06/2017	5:20	19.33			0.61	3.60	3.29	12910	Fulfill
67.	Al-Alem	30/06/2017	7:55	2.58			0.98	2.28	3.55	17014	Fulfill

2. Offset (01/05/2017 – 30/06/2017 EC)

No	Job Type	Receipt Date	Arrival time	Inter arrival time	Number of failure	Repair Time	Setup time	Make ready time	Process Time	Production	Quality Fulfill
1.	Ethiopian Seed Supply	01/05/2017	3:25	0			3.42	5.72	24.24	18281	Fulfill
2.	Guje Health Center	04/05/2017	4:15	48.25	1	4.46	4.37	6.69	30.08	24611	Fulfill
3.	Sidama Finance Bureau	07/05/2017		33			5.32	8.62	57.01	71892	Fulfill
4.		10/05/2017			1	1.46					
5.		11/05/2017			1	1.42					
6.	A.A City Vital Events	14/05/2017	7:35	84.58			1.74	4.59	11.99	12392	Fulfill
7.	Sidama Finance Bureau	15/05/2017	8:45	19.75			3.51	5.54	40.95	53848	Fulfill
8.	Addis Abeba Airport	19/05/2017	3:50	14.83	1	1.45	3.33	7.27	27.23	31384	Fulfill
9.	National Dialogue Commission	23/05/2017	5:20	71.33			5.03	7.35	47.48	56611	Fulfill
10.		24/05/2017			1	1.32					
11.	Addis Ketema Police	27/05/2017	7:55	40.92			2.69	3.95	23.75	31021	Not Fulfill
12.		29/05/2017			1	3.66					
13.	Gambella Fin. & Econ.	01/06/2017	5:20	60.33	1	0.65	2.83	6.83	46.09	52743	Fulfill
14.	Stasticstical Service	08/06/2017	3:40	91.67			2.41	2.57	36.94	32568	Fulfill
15.		12/05/2017			1	4.18					
16.	Shekiso City Landhold Office	13/06/2017	2:50	90.83			4.28	5.76	21.89	47612	Fulfill
17.		14/05/2017			1	4.53					
18.	A.A City Fire & Risk	15/06/2017	4:35	48.58	1	1.65	4.81	6.59	56.11	56327	Fulfill
19.	A.A Land Holding	21/06/2017	3:45	36.75	1	4.61	3.48	8.72	53.72	53153	Fulfill
20.	BSPE	28/06/2017	7:55	40.92			3.39	5.25	14.58	17444	Fulfill

Appendix 2:

Initial Model Simulation Output

8:00:54AM

Category Overview

June 12, 2025

Values Across All Replications

Model 1

Replicat 8 Time Hours

Key Performance Indicators

System

Ave

Number Out

1,629

Values Across All Replications

Model 1

Replicat 8 Time Hours

Entity

Time

VA Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	33.3861	0.62	32.59	34.395	0.00	57.991
wave offset real	4.4263	0.09	4.315	4.6338	0.00	73.984
NVA Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	5.8634	0.08	5.686	5.9945	0.00	8.9087
wave offset real	5.0312	0.08	4.906	5.1429	0.00	50.675
Wait Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	49.3467	15.72	26.94	79.144	0.00	426.40
wave offset real	5.9063	0.28	5.382	6.3170	0.00	81.990
Transfer Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	3.5263	0.05	3.436	3.6073	0.00	6.7138
wave offset real	0.4724	0.01	0.454	0.4833	0.00	0.9993
Other Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	0.04007	0.01	0.025	0.0555	0.00	3.4269
wave offset real	0.05384	0.01	0.037	0.0645	0.00	3.5779
Total Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	92.1626	15.54	69.04	121.30	0.580	456.78
wave offset real	15.8900	0.37	15.20	16.516	0.391	94.749

Other

Values Across All Replications

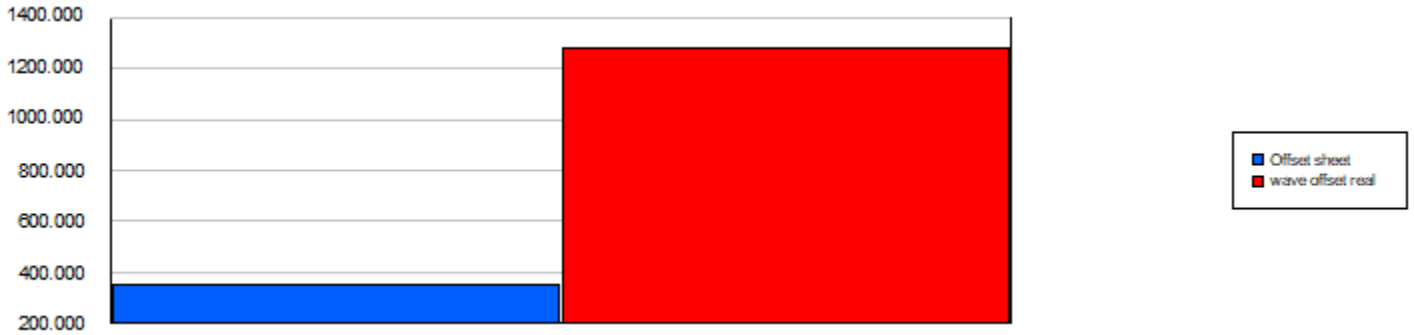
Model 1

Replicat 8 Time Hours

Entity

Other

Number In	Avera	Half	Minim um	Maxim um
Offset sheet	352.63	8.41	339.00	366.00
wave offset real	1279.63	26.51	1242.0	1328.0



Number Out	Avera	Half	Minim um	Maxim um
Offset sheet	350.38	8.62	335.00	363.00
wave offset real	1278.63	26.50	1241.0	1328.0

WIP	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset sheet	2.0285	0.39	1.454	2.7488	0.00	12.000
wave offset real	1.2651	0.02	1.232	1.2942	0.00	11.000

Values Across All Replications

Model 1

Replicat 8 Time Hours

Queue

Time

Waiting Time	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset make	0.9919	0.19	0.606	1.2884	0.00	18.176
Offset print.Queue	20.3943	7.70	9.616	34.452	0.00	265.20
Offset repaire.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Offset setup.Queue	28.9296	8.11	17.37	44.801	0.00	294.77
Wave offset make	3.2179	0.20	2.891	3.6712	0.00	77.150
Wave offset print.Queue	1.1666	0.12	1.025	1.4222	0.00	72.942
Wave offset	0.00513	0.01	0.00	0.0410	0.00	1.3648
Wave offset setup.Queue	1.7002	0.11	1.541	1.8979	0.00	48.474

Other

Number Waiting	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset make	0.02141	0.00	0.012	0.0287	0.00	3.0000
Offset print.Queue	0.4431	0.18	0.199	0.7667	0.00	7.0000
Offset repaire.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Offset setup.Queue	0.6277	0.19	0.358	0.9993	0.00	8.0000
Wave offset make	0.2485	0.01	0.231	0.2745	0.00	8.0000
Wave offset print.Queue	0.0903	0.01	0.077	0.1118	0.00	6.0000
Wave offset	0.00001	0.00	0.00	0.0001	0.00	1.0000
Wave offset setup.Queue	0.1315	0.01	0.116	0.1491	0.00	6.0000

Values Across All Replications

Model 1

Replicat 8 Time Hours

Resource

Usage

Instantaneous Utilization

	Avera	Half	Minim	Maxim	Minim	Maximu
			um	um	um	m
Offset machine	0.8069	0.02	0.759	0.8384	0.00	1.0000
Offset maintenance crew	0.00087	0.00	0.000	0.0011	0.00	1.0000
Offset oprator	0.1285	0.00	0.120	0.1362	0.00	1.0000
Wave offset machine	0.3900	0.01	0.378	0.3998	0.00	1.0000
Wave offset maintenance	0.00428	0.00	0.002	0.0049	0.00	1.0000
Wave offset oprator	0.4006	0.01	0.391	0.4138	0.00	1.0000

Number Busy

	Avera	Half	Minim	Maxim	Minim	Maximu
			um	um	um	m
Offset machine	0.8069	0.02	0.759	0.8384	0.00	1.0000
Offset maintenance crew	0.00087	0.00	0.000	0.0011	0.00	1.0000
Offset oprator	0.1285	0.00	0.120	0.1362	0.00	1.0000
Wave offset machine	0.3900	0.01	0.378	0.3998	0.00	1.0000
Wave offset maintenance	0.00428	0.00	0.002	0.0049	0.00	1.0000
Wave offset oprator	0.4006	0.01	0.391	0.4138	0.00	1.0000

Number Scheduled

	Avera	Half	Minim	Maxim	Minim	Maximu
			um	um	um	m
Offset machine	1.0000	0.00	1.000	1.0000	1.000	1.0000
Offset maintenance crew	1.0000	0.00	1.000	1.0000	1.000	1.0000
Offset oprator	1.0000	0.00	1.000	1.0000	1.000	1.0000
Wave offset machine	1.0000	0.00	1.000	1.0000	1.000	1.0000
Wave offset maintenance	1.0000	0.00	1.000	1.0000	1.000	1.0000
Wave offset oprator	1.0000	0.00	1.000	1.0000	1.000	1.0000

Values Across All Replications

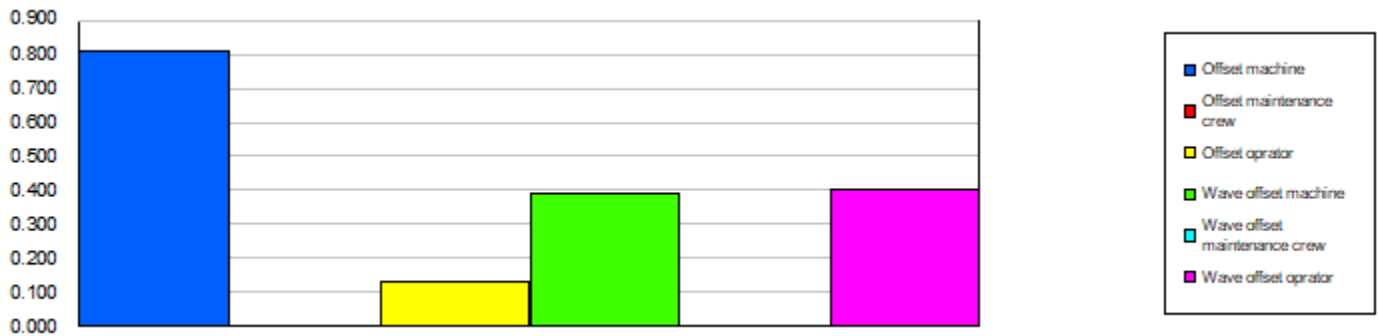
Model 1

Replicat 8 Time Hours

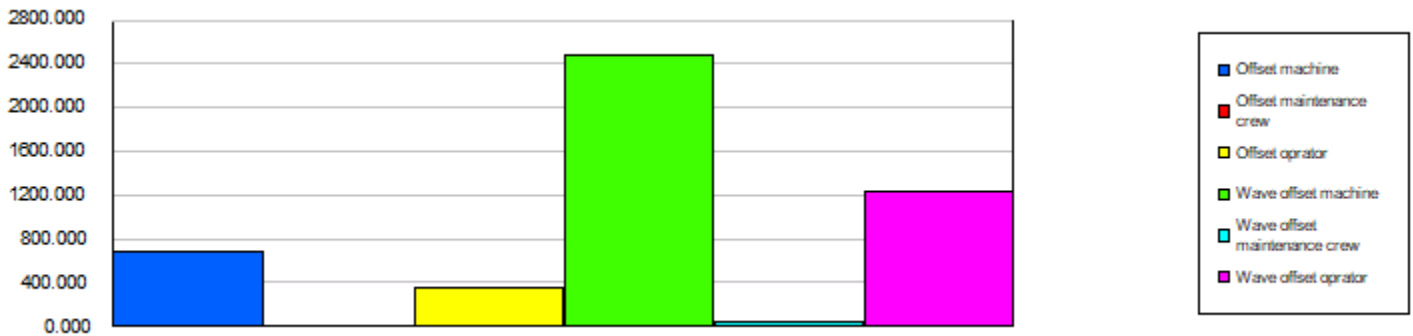
Resource

Usage

Scheduled Utilization	Avera	Half	Minimum	Maximum
Offset machine	0.8069	0.02	0.7597	0.8384
Offset maintenance crew	0.00087	0.00	0.0005	0.0011
Offset oprator	0.1285	0.00	0.1201	0.1362
Wave offset machine	0.3900	0.01	0.3782	0.3998
Wave offset maintenance	0.00428	0.00	0.0029	0.0049
Wave offset oprator	0.4006	0.01	0.3911	0.4138



Total Number Seized	Avera	Half	Minimum	Maximum
Offset machine	688.38	19.57	655.00	714.00
Offset maintenance crew	7.3750	1.67	4.0000	11.000
Offset oprator	344.50	9.74	328.00	358.00
Wave offset machine	2483.88	51.13	2403.0	2566.0
Wave offset maintenance	37.3750	6.70	26.000	45.000
Wave offset oprator	1242.00	25.64	1201.0	1283.0



Values Across All Replications

Model 1

Replicat 8 Time Hours

User Specified**Tally**

Interval	Avera	Half	Minim um	Maxim um	Minim um	Maximu m
Offset Bad part Time in	95.1365	18.94	63.82	132.13	22.48	397.67
Offset Good part Time in	8018.06	108.26	7867.	8200.2	-15	16015.
Offset repair Time in	1.9308	0.20	1.662	2.2864	0.580	3.4269
Wave offset Bad part Time in system	15.5514	2.15	12.31	20.786	2.510	50.295
Wave offset Good part Time in system	7864.01	142.17	7628.	8085.2	-2	16057.
Wave offset repair Time in system	1.8543	0.10	1.701	2.0436	0.391	3.5779