Degree project

UNIVERSITY OF SKÖVDE

Analyzing Reconfigurability and Sustainability Potentials of Production Flow using Simulation Tools

Master Degree Project in Virtual Product Realisation (Intelligent Automation)

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Abstract

This thesis examines the reconfigurability potential of high-volume engine-component production using simulation-based analysis and multi-objective optimisation. The cylinder block and cylinder head production lines at Aurobay Technologies were analysed as an industrial case, where a discrete-event simulation model was developed in FACTS Analyzer following a Design Science Methodology. The study compared the existing dedicated production layout with a reconfigured shared-flow alternative in which selected assembly and verification operations were integrated across both lines. Simulation-based multi-objective optimisation using NSGA-II was applied to explore trade-offs between throughput and lead time under realistic variations in processing times, buffer capacities, availability, and repair behaviour.

The results show that the dedicated baseline layout dominates the reconfigured alternative across most of the industrial operating envelope. While the reconfigured layout achieves lower lead time in limited low-to-medium throughput regimes, it consistently exhibits reduced throughput potential and is strictly dominated by the baseline layout at higher throughput levels. Matched operating-point comparisons confirm that local lead-time improvements from reconfiguration are offset by coordination losses and contention at shared operations, particularly in the cylinder block line. Consequently, the optimisation results do not support claims of overall superiority of the reconfigured layout.

The thesis presents a rigorous simulation-based evaluation of alternative production system configurations. The results clarify the conditions under which reconfigurable layouts enhance flow behaviour, as well as those in which dedicated configurations remain structurally superior. This contribution supports evidence-based decision-making without requiring physical experimentation.

Keywords: reconfigurable manufacturing systems, discrete event simulation, lead time reduction, simulation model, modular production, Aurobay, FACTS Analyzer, production flow optimisation

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Skövde, 2025

Jikku Mani

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1 Introduction

Modern manufacturing is characterised by increasing product variety, fluctuating demand, and the need to utilise existing resources as efficiently as possible. Production systems that were originally designed for stable, high-volume output now face pressure to operate with greater flexibility while maintaining performance levels. In such environments, the way products move through machining and assembly operations defined by routing logic, buffer structures, and equipment interactions plays a decisive role in determining system behaviour. Even small structural adjustments, such as merging flows or sharing operations, can reshape queue dynamics, alter utilisation patterns, and influence overall throughput (TH) and lead time (LT)(Diaz et al., 2020).

Engine component manufacturing is particularly sensitive to these effects due to its dependence on tightly coordinated sequences of parallel machines, inspection steps, and interdependent buffers. As product mixes evolve and operational conditions vary, conventional fixed layouts may struggle to maintain flow stability. This has created growing interest in exploring alternative configurations that reuse existing equipment in more adaptable ways. Reconfigurable flow strategies offer a potential pathway, but their real impact must be evaluated before implementation, as changes in routing can produce both positive and negative system-level consequences(Puik et al., 2017).

Simulation based analysis provides a controlled means of examining how production systems behave under such structural changes. By modelling alternative routing arrangements and testing them under varied operational assumptions, it becomes possible to study how LT, TH, and work distribution respond without disrupting ongoing production. This study applies that approach to investigate whether selective reconfiguration of key operations in cylinder block (CB) and cylinder head (CH) machining can support more flexible and efficient flows. The following sections outline the industrial background, research problem, objective, and research question that guided this investigation(Barrera Diaz et al., 2021).

1.1 Background

The company at the centre of this research is a powertrain manufacturer with a deep industrial lineage that has played a pivotal role in Sweden’s engine production history. Originating from the consolidation of Volvo Cars' and Geely Holding’s combustion engine divisions, it now operates as an independent entity focused on developing high efficiency propulsion systems for global markets. The firm’s formation marked a strategic shift transforming legacy combustion engine expertise into a platform for delivering next generation hybrid and low emission technologies. Its primary production base in Skövde, Sweden, has long been a cornerstone of European engine manufacturing, with operations spanning back over a century. Historically, this site supported high

volume production of internal combustion engines used in both passenger and commercial vehicles, including those developed under the Volvo brand. These engines were recognised for their reliability, precision engineering, and robust performance across diverse operating conditions (Aurobay, 2025).

Today, the organisation is channelling its legacy into the design and manufacture of advanced hybrid powertrains. This includes downsized, turbocharged engines with integrated electrification modules that aim to reduce emissions while maintaining performance standards. Besides putting things together, the company also performs complicated machining, combines thermal management systems, and ensures strict quality checks, all backed by automated inspection systems and tracking systems. It has production and engineering centres all around Europe and Asia, which lets it innovate in one place and respond quickly to supply chain needs in another. The company now places a strong focus on reusing existing infrastructure to accommodate shifting regulatory and market requirements, with a focus on modular upgrades rather than new installations. This includes adapting traditional engine lines to support hybrid assemblies, retooling machines for variable flexibility, and optimising workflows to reduce downtime and energy consumption. With sustainability embedded in its operational strategy, the firm continues to explore methods for minimising material waste, extending the lifespan of critical equipment, and improving energy efficiency throughout the production chain. It positions itself not merely as an engine producer but as a forward-thinking propulsion technology provider committed to offering solutions that balance legacy manufacturing strengths with emerging environmental and technical demands (Aurobay, 2025).

The REFUSE (Resource-Efficient Use and Development of Reconfigurable Machining Systems) project represents a wider collaborative research initiative between Swedish industry and academia. Its central vision is to develop sustainable and Reconfigurable Manufacturing Systems (RMS) that extend the useful life of existing production assets through intelligent redesign, modularisation, and digital decision support. By prioritising the reuse and adaptation of machinery instead of full replacement, it aims to reduce investment costs, lower embodied carbon emissions, and conserve materials contributing directly to circular-economy objectives and the United Nations' Sustainable Development Goals (SDG) 7, 9, and 13. The project brings together multiple industrial partners, including Aurobay, to explore practical pathways for transforming conventional manufacturing into adaptive, resource-conscious production networks. This thesis was embedded within the REFUSE project, using Aurobay's engine manufacturing plant as a case study to investigate how the CB and CH lines could be reconfigured to accommodate future variations in demand and product mix. Through this collaboration, it aimed to foster a paradigm shift in how factories evolve over time from static, equipment-driven systems towards flexible, data-informed, and sustainable manufacturing environments capable of supporting future propulsion technologies (Project REFUSE - ASSAR Innovation, 2025).

1.2 Aim

The aim of this research was to evaluate how production flow reconfiguration influences the trade-off between LT and TH in the CB and CH production systems, using simulation-based analysis and multi-objective optimisation (MOO). The study focused on comparing an existing dedicated layout with a reconfigured shared-flow alternative to understand how structural changes affect system performance across different operating conditions, without introducing new production resources.

1.3 Research Problem

The central problem in this study was the limited flexibility of the CB and CH production lines, which were originally designed for dedicated, high-volume manufacturing. While these lines ensured stable TH, they exhibited limited adaptability to variations in product mix, demand, and equipment availability. As a result, the industrial impact of reconfiguring these production flows remained uncertain and required systematic evaluation.

Although simulation had been applied in production planning, its role in systematically evaluating production-flow reconfiguration strategies in engine manufacturing remained underexplored. This study therefore investigated how flow simulation and optimisation could be used to analyse the trade-off between LT and TH resulting from reconfiguration, without relying on physical trial and error.

While reconfigurability and simulation have been studied independently, limited research has quantitatively examined shared-flow routing strategies in high-volume engine production using simulation-based multi-objective optimisation (SMO). This gap restricts evidence-based decision-making regarding when and under what operating conditions reconfiguration provides practical benefits at Aurobay.

1.4 Research Objective

To address the research problem, the study aimed to:

1. Model the existing CB and CH production flows to identify processes suitable for reconfiguration.

2. Develop simulation models in FACTS Analyzer for both the current baseline and Reconfigured line.

3. Apply optimisation to evaluate trade-offs between LT and TH.

4. Examine how selective reconfiguration, without introducing additional production resources, influences LT, TH, and flow behaviour across different operating conditions.

1.5 Research Question

This investigation was guided by the central research question:

"How does production flow reconfiguration affect the trade-off between lead time and throughput when evaluated using simulation-based optimisation?"

This research question reflected both operational and strategic priorities in production engineering and was positioned within a design science framework. It addressed the problem of limited adaptability in high-volume production systems by examining how reconfiguration of production flows influences the trade-off between LT and TH, rather than assuming simultaneous improvement of both objectives.

The study employed simulation-based analysis and MOO as a decision-support artefact to systematically evaluate how structural changes affect system performance across different operating conditions. Through the iterative development, demonstration, and analytical evaluation of baseline and reconfigured scenarios, the research generated evidence-based insights into when and under what conditions reconfiguration alters the feasible operating envelope of complex manufacturing systems.

In this way, the work contributes both to practical industrial decision-making and to the academic understanding of simulation-based optimisation as a design science artefact for analysing performance trade-offs in production systems.

1.6 Industrial and Confidentiality Limitations

Due to confidentiality agreements with Aurobay and the sensitive nature of its production information, certain operational details could not be disclosed in this thesis. This includes exact cycle times, station names, production rates, and business-related performance figures that belong to Aurobay's internal systems. Detailed factory layouts, machine drawings, and control algorithms used in the plant were also omitted or presented only in simplified form to comply with the company's non-disclosure rules. Any references to internal software, supplier data, or business strategies were described in general or anonymous terms to protect company privacy. These restrictions did not affect the reliability or validity of the research findings; they only limited the level of technical detail that could be shown publicly. All modelling and analysis work in this study followed Aurobay's data-handling and confidentiality policies to maintain both academic integrity and industrial trust.

1.7 Structure of the Report

This report is structured to progress systematically from problem formulation to simulation-based evaluation and validated conclusions. Chapter 1 introduces the industrial background, research problem, aim, objectives, research question, and contextual constraints, including confidentiality limitations and the connection to the REFUSE project. Chapter 2 establishes the theoretical foundation by defining the CB and CH production context, key performance indicators, reconfigurability concepts, discrete-event simulation (DES), and SMO. Chapter 3 presents a conceptual study grounded in Principle 15 to analyse the behavioural effects of server flexibility under controlled conditions. Chapter 4 reviews relevant literature to identify research gaps and position the study within existing work. Chapter 5 describes the research methodology based on Design Science Methodology, detailing data collection, model development, optimisation design, and validation strategy. Chapter 6 reports the industrial simulation and optimisation results for the baseline and reconfigured layouts, including matched operating-point comparisons and walkthrough validation. Chapter 7 discusses sustainability implications strictly in terms of operational efficiency and responsible industrial decision-making. Chapter 8 critically discusses the findings in relation to theory and industrial relevance, while Chapter 9 outlines the study's limitations. Chapter 10 proposes directions for future research, Chapter 11 addresses ethical considerations, and Chapter 12 concludes the thesis by summarising the main findings and contributions.

Figure 1 illustrates the overview of the research workflow, showing how the study progressed through a structured sequence from problem identification to validated evaluation. The workflow begins with identifying flow-related challenges and uncertainty regarding reconfiguration impacts, followed by a conceptual study to establish theoretical expectations of flexibility effects. These insights informed the design of baseline and reconfigured simulation artefacts, which were developed using industrial data and analysed through comparative simulation experiments. SMO was then applied to explore trade-offs between TH and LT across a broad operating envelope. The workflow concludes with verification, validation, and analytical evaluation, ensuring that the resulting simulation artefact provides a rigorous and transparent decision-support basis for assessing production-flow reconfiguration under realistic industrial constraints.

Problem Identification Flow challenges and limited adaptability in the CB and CH production lines are identified, including long lead times, high work-in-progress, and uncertainty regarding the performance impact of production-flow reconfiguration.
• **Conceptual Foundation** A controlled conceptual study is conducted to analyse how server flexibility influences lead time, throughput, and work-in-progress under idealised conditions, providing a theoretical reference for later industrial evaluation.
• **Literature Review** Research on reconfigurable manufacturing systems, production-flow simulation, lead-time reduction, and simulation-based multi-objective optimisation is synthesised.
• **Research Methodology** Design Science Methodology structures the study through problem definition, requirement specification, development of baseline and reconfigured simulation artefacts, simulation and optimisation, validation, and analytical evaluation.
• **Data Collection & System Design** Industrial process data, reliability information, routing logic, and layout constraints are used to construct simulation models representing both the existing and reconfigured production flows.
• **Baseline Simulation Model** The existing CB and CH production flows are modelled in FACTS Analyzer, verified for logical correctness, and qualitatively validated through expert assessment of throughput–lead-time behaviour.
• **Reconfigured Shared-Flow Model** Selected feasible operations are reorganised into a shared-flow structure, while all other modelling assumptions are held constant to enable a fair and controlled comparison.
• **Comparative Simulation Experiments** Both layouts are simulated under identical experimental conditions, and performance indicators including lead time, throughput, work-in-progress, utilisation, and flow behaviour are analysed.
• **Simulation-Based Multi-Objective Optimisation** NSGA-II is applied to both layouts to identify Pareto-optimal solutions and analyse dominance patterns and trade-offs between throughput and lead time.
• **Verification and Evaluation** Model verification, replication-based consistency checks, expert evaluation and walkthrough validation.
• **Sustainability Evaluation** Results are interpreted from a sustainability perspective, demonstrating how simulation-based evaluation supports resource-efficient decision-making by assessing reconfiguration potential without physical investment or production disruption.

Figure 1 Overview of the Research Workflow

2 Frame of Reference

This chapter establishes the theoretical and industrial foundation for analysing reconfiguration of CB and CH production lines. It first outlines the functional role and manufacturing characteristics of CB and CH to define the system context. The core performance indicators TH, LT, and WIP are then introduced to explain how flow behaviour is evaluated and compared between baseline and reconfigured layouts. The chapter proceeds to discuss reconfigurability and its key dimensions, followed by the role of simulation and the rationale for using FACTS Analyzer as the primary environment for modelling and optimisation. Building on this, the principles of optimisation in manufacturing, SMO, NSGA-II, and Pareto optimality are described to frame how trade-offs are identified and interpreted. Finally, the concepts of circularity and sustainability are defined and linked to infrastructure reuse and digital experimentation,

providing the theoretical basis for arguing how the proposed reconfiguration can contribute to more efficient and sustainable engine production.

2.1 Cylinder Head and Cylinder Block in Engine Manufacturing

The CB and CH represent the two principal components of an internal combustion engine, forming its structural and functional core. At the Skövde facility, these components are manufactured on dedicated, high-volume lines designed for precision, repeatability, and reliability. The CB line performs extensive machining and assembly operations to create the engine's foundation, integrating cylinders, oil passages, and coolant channels that ensure mechanical strength and thermal stability.

Figure 2 The cylinder block component suggested for the reconfigured flow.

Figure 2 illustrates a typical CB proposed for the reconfigured flow. It represents the lower section of the engine, machined to exact tolerances to support the reciprocating assembly and withstand high dynamic loads. The CH line, positioned above the CB in final assembly, combines machining, assembly, marking, and verification processes in a compact and coordinated sequence. It includes rigorous dimensional checks and leak testing to secure combustion chamber accuracy and ensure operational durability.

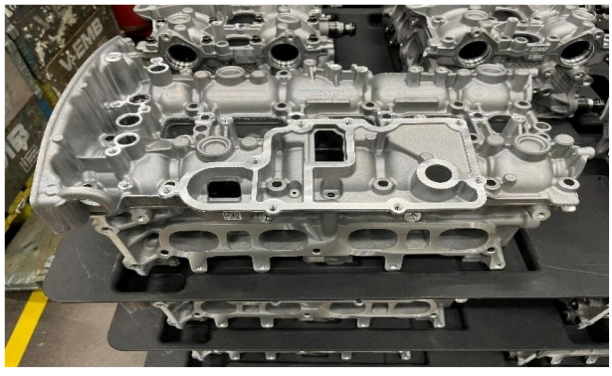

Figure 3 The cylinder head component suggested for the reconfigured flow.

Figure 3 shows a representative CH used in the reconfigured flow. This upper component contains the combustion chambers, intake and exhaust ports, and integrated coolant and lubrication passages, all requiring high-precision machining and surface finishing. Both production lines currently focus on Generation 3 engine variants, where maintaining consistent quality and performance is critical. Stability across operations is achieved through buffer management, automated inspections, and parallel machine configurations that balance TH among stations. The structural and operational differences between the CB's extended machining chain and the CH's compact flow highlight their respective reconfiguration potentials explored in this study.

2.2 Reconfigurability and Its Importance

Reconfigurability refers to a production system's capacity to alter its structure or operational flow when conditions change, without requiring major redesign or long interruptions. In high-volume machining lines, even small variations in processing time, equipment availability, or demand patterns can propagate into long queues and unstable performance. A system that can adjust routing, reassign workloads, or temporarily redistribute operations is therefore more capable of maintaining stable TH while preventing excessive lead-time growth. This adaptability is especially critical in environments where product families share similar process characteristics but operate on lines that were originally designed as independent flows (Lameche et al., 2017).

Its importance becomes clear when examining how rigid flows behave. When each product type follows a fixed route with limited interaction between lines, bottlenecks tend to persist and cannot be relieved without structural changes. Reconfigurability introduces the possibility of redirecting selected operations through alternative stations, allowing the system to smooth flow during periods of imbalance. As a result, queue lengths decrease, the utilisation of critical resources becomes more balanced, and overall variability is reduced. This creates a more predictable production environment in which performance disturbances do not escalate into system-wide delays (Koren & Shpitalni, 2010).

The advantages also extend to long-term operational efficiency. By enabling selective reuse of existing machinery, reconfigurable layouts reduce the need for new equipment and allow capacity to be expanded or contracted without major capital investment (Bortolini et al., 2018). Such systems handle fluctuations more effectively, recover faster from disruptions, and support continuous improvement strategies by exposing where flexibility delivers the highest performance gains. In machining-intensive operations, this means that the system can maintain competitive cycle times while avoiding the excessive WIP levels that usually accompany rigid, fixed-path designs (Segerstedt et al., 2020).

In this thesis, reconfigurability was examined through the controlled introduction of shared operations between two lines that traditionally operated independently. Although the full configuration of the facility is not disclosed, the study focused on a limited set of stations whose functional similarity allowed selective integration. This targeted modification enabled the production flow to

shift dynamically when one-line experienced higher workload, demonstrating how even minimal structural adjustments can relieve bottlenecks, shorten LTs, and stabilise TH.

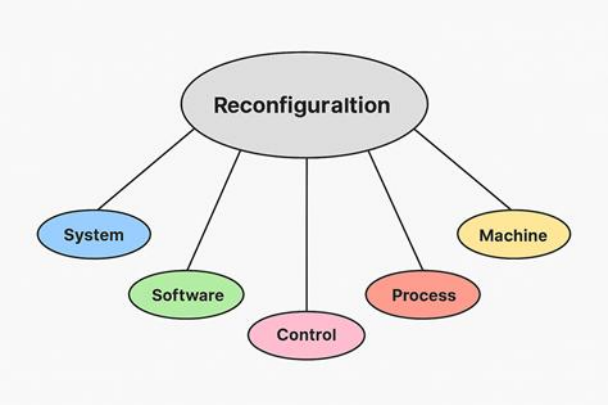

Figure 4 Key Dimensions of Reconfigurability in Manufacturing Systems

Figure 4 illustrates the key dimensions of reconfigurability in manufacturing systems, showing that adaptability arises from five interconnected aspects such as system, machine, process, control, and software. Together, these dimensions enable a production system to be rapidly adjusted in structure, functionality, and operation in response to changing product demands or manufacturing conditions.

2.3 Throughput

TH refers to the number of completed units, such as CH or CB, that exit the production system within a specified time frame, typically expressed in units per hour or per shift. It is a core metric used to quantify production system performance, reflecting the system's ability to maintain flow and meet output targets under varying operational conditions. TH is used to compare baseline and reconfigured production scenarios, allowing a quantitative evaluation of how layout changes affect overall system efficiency. While maximizing TH is a common objective, it must be pursued in harmony with quality standards, equipment limitations, and sustainability goals. An unbalanced drive for elevated TH may result in augmented LT, excessive buffering, and elevated WIP levels.

The relationship between TH, LT, and WIP is described by Little's Law, a fundamental principle in queuing theory:

$$LT = \frac{WIP}{TH} \; or \; equivalently \; TH = \frac{WIP}{LT} \quad (Equation\ 1)$$

Where:

LT is the average lead time (in time units),

WIP is the average number of parts in the system,

TH is the average throughput (in parts per time unit).

This relationship highlights that TH is not an isolated indicator it is dynamically linked to how much inventory is circulating and how long it takes to process each unit. Improvements in TH must therefore consider the broader system behaviour, especially bottlenecks and flow imbalances. TH serves as a decision support parameter for evaluating reconfigurable system designs. Enhancements in TH are only considered meaningful when achieved without compromising operational stability or inflating LT.

2.4 Lead Time

LT is treated as a central performance indicator for evaluating how efficiently the production system progresses from the initiation of processing to the completion of finished units. It represents the cumulative span in which a part is subject to machining, inspection, transportation, queuing, and any pauses arising from resource constraints or availability issues. In the production environment analysed, LT is particularly critical because the processes under investigation involve high precision operations, multiple interdependent stages, and stringent quality requirements. The value of LT lies in its ability to reveal the responsiveness of the system (Spindler et al., 2021). Longer durations often indicate hidden inefficiencies, such as uneven station loads or imbalances in buffer management, whereas shorter durations suggest smoother coordination across the flow. LT is therefore not viewed merely as a time measure but as an operational lens through which the adaptability and stability of the system are assessed. It serves to highlight whether resources are synchronised effectively, whether queues and idle times are kept under control, and whether the overall system is capable of maintaining continuity under varying conditions. Reducing LT directly supports more reliable planning, quicker order fulfilment, and improved usage of existing infrastructure. LT is positioned as both a diagnostic tool and a benchmark against which the effectiveness of reconfiguration strategies is evaluated (Cuatrecasas-Arbós et al., 2015).

2.5 Work In Progress

WIP is treated as a central indicator for evaluating how production flow responds to different reconfiguration strategies. It represents the collection of items that have entered the production system but are not yet completed whether under processing, waiting in queues, or held in intermediate buffers. It acts as a dynamic measure of how efficiently the system balances operational flow, resource availability, and buffer capacity. High WIP levels often indicate congestion, typically arising from bottlenecks, imbalanced workflows, or poor coordination between stations. Excessively low WIP can signal idle resources or insufficient TH, leading to underutilisation and delayed output. An optimised WIP level ensures that the line remains both responsive and stable, avoiding extremes that disrupt synchronisation across operations. Within the simulation experiments, WIP served as a key performance metric for analysing the fluidity of production under alternative layouts and routing rules. Its behaviour was

shown to be shaped by process times, buffer capacities, machine availability, and variability in input rates. Because of its sensitivity to both upstream and downstream changes, WIP provided valuable insights into how design modifications such as reconfigurable routing or flexible station assignments altered overall system dynamics.

2.6 Simulation and Its Applications

Simulation has long been a fundamental technique in production engineering for evaluating system behaviour under varied operational conditions without disrupting real manufacturing. It allows engineers to represent complex interactions between machines, buffers, operators, and materials, and to assess the consequences of structural or operational changes before they are implemented physically. Through simulation, parameters such as TH, LT, WIP, and buffer utilisation can be analysed in a risk-free digital environment, providing a rigorous foundation for optimisation and decision-making. This is particularly important in high-volume manufacturing environments where production operates continuously and simulation-based analytical evaluation modifications cannot be introduced without causing downtime, uncertainty, or operational risk. When systems are tightly coupled and operate near capacity, even small layout or routing changes can produce unpredictable effects, making direct physical testing impractical. Simulation therefore becomes the only feasible method for examining alternative configurations and understanding their impact on system performance under controlled, repeatable, and non-disruptive conditions.

A wide range of simulation tools has been developed to support such analysis. Arena, Simul8, AnyLogic, Tecnomatix Plant Simulation, and FlexSim are among the most commonly used platforms (Kovbasiuk et al., 2021). These tools differ in their focus, with some being better suited for discrete-event logic and others providing strong integration with hybrid or agent-based models. Arena and Simul8 are widely applied in logistics and process optimisation, while AnyLogic supports multi-method modelling and hybrid dynamics. Tecnomatix Plant Simulation is often employed in automotive and high-volume production settings, offering powerful 3D visualisation and control-logic integration. The selection of a tool typically depends on the purpose of the study, data availability, and the degree of model transparency required (Kovbasiuk et al., 2021). At Aurobay, for instance, Siemens Plant Simulation has already been used to create detailed production models of the CH and CB lines, providing an established platform for high-fidelity shop floor analysis.

In this study, the FACTS Analyzer software served as the primary simulation environment. The selection was guided by Aurobay's strategic interest in using the tool for internal research and process improvement, ensuring industrial relevance and data consistency. From a methodological standpoint, it provided integrated features for discrete-event modelling, optimisation, and performance analysis, allowing dynamic evaluation of production flow and system flexibility. Compared with general-purpose simulation packages, the

platform offered higher compatibility with large-scale factory layouts and supported scenario testing aligned with the study's reconfiguration objectives (A. Ng et al., 2007). FACTS Analyzer was therefore selected not only for organisational compatibility but because its EPT-based abstraction and automatic model generation aligned directly with the study's goal of exploring reconfiguration at a conceptual yet operationally realistic level.

2.6.1 FACTS Analyzer

The FACTS Analyzer is a simulation tool designed to improve factory conceptual design by integrating model abstraction, input data management, and optimisation. Conventional simulation techniques are frequently employed in the later phases of design, resulting in inefficiencies and increased expenses. Its goal is to put simulations ahead of other tasks, so that decisions can be made early on about how to best set up factories before important design decisions are made.

Simulation is often acknowledged as an effective method for examining intricate production systems. Its adoption in early design phases is limited due to the complexity of simulation tools, which often require specialized knowledge (A. H. C. Ng et al., 2011). Mehrabi et al (2000) highlight that Factory managers typically rely on external consultants, leading to delays and increased costs. FACTS Analyzer addresses this issue by providing an easy-to-use platform that allows decision makers to create, analyse, and optimise factory layouts without extensive simulation expertise. One of its core innovations is the Effective Processing Time (EPT) based aggregation, which simplifies simulation modelling. This method combines variations in cycle time, machine breakdowns, and repair times into a single distribution, reducing complexity while maintaining accuracy (A. Ng et al., 2007). It supports model abstraction, enabling designers to focus on essential system behaviours rather than intricate details. According to (A. H. C. Ng et al., 2011) its automated model generation feature allows users to quickly sketch conceptual factory layouts and convert them into simulation models. These models are stored in a neutral format, ensuring compatibility with various simulation software. Another key feature is parallel simulation and optimisation, which enhances computational speed. Integrated simulation-driven optimisation helps identify the best factory configurations based on performance metrics, making it as an efficient tool for factory decision making (A. Ng et al., 2007). In this thesis, both the simulation modelling and the MOO were conducted entirely within the FACTS Analyzer environment.

2.7 Optimisation in Manufacturing Systems

In this thesis, optimisation is not used as a secondary analysis step but as the primary mechanism for understanding system behaviour under competing performance requirements. The manufacturing system under study exhibits multiple feasible operating conditions rather than a single clearly optimal configuration. Because system performance emerges from the interaction of

routing logic, buffering, variability, and resource sharing, it is not possible to determine the effects of reconfiguration through isolated scenario testing or average performance measures alone. Optimisation is required to systematically explore how the system behaves across a wide range of feasible configurations (de Alcantara et al., 2025).

Within FACTS Analyzer, optimisation is implemented by automatically generating alternative system configurations and evaluating them through repeated simulation runs. Rather than manually defining a limited number of scenarios, the optimisation process searches the configuration space in a structured and reproducible manner. Each configuration is assessed using identical simulation conditions, ensuring that performance differences are attributable to structural changes in the system rather than inconsistent assumptions or stochastic noise. This approach allows the analysis to move beyond anecdotal comparisons and towards evidence-based evaluation of system behaviour (Amaran et al., 2016).

The relevance of optimisation lies in its ability to reveal performance limits and trade-offs that are not visible through conventional simulation studies. A single simulation run, even when carefully calibrated, only represents one operating point. Optimisation exposes the full range of achievable operating conditions and clarifies which regions of performance are feasible, dominated, or unattainable under the system's constraints. This is particularly important for reconfiguration analysis, where structural changes may improve performance in some regions while degrading it in others. Optimisation, as implemented in FACTS Analyzer, provides a systematic search process that balances exploration and evaluation, making it possible to assess a large configuration space within practical computational limits.

It enables a fair comparison between baseline and reconfigured layouts under equivalent conditions and provides a transparent basis for assessing whether reconfiguration alters the achievable performance space. Rather than assuming that reconfiguration is beneficial, optimisation allows this assumption to be tested rigorously against simulated system behaviour. In doing so, optimisation supports the design science orientation of the research by demonstrating the utility and limitations of the proposed system changes through structured evaluation rather than isolated performance claims (Amaran et al., 2016).

2.8 Simulation-Based Multi-Objective Optimisation

SMO is widely used to analyse manufacturing systems that show complex behaviour, randomness, and competing performance measures. Unlike analytical optimisation, which depends on simplified mathematical equations, SMO evaluates system performance by repeatedly running a DES model. This makes it possible to observe how the system actually behaves over time, including the effects of variability, machine failures, queues, and resource interactions. For real manufacturing systems, where such effects strongly influence performance, this approach provides a more realistic and reliable

basis for analysis than deterministic optimisation methods (Mourtzis et al., 2014) .

Optimising manufacturing systems almost always involves multiple performance measures that conflict with each other. Measures such as LT, TH, and WIP are closely linked, and improving one often causes deterioration in another. Traditional optimisation approaches usually deal with this by combining all objectives into a single value using weights or constraints. Although this simplifies the mathematics, it hides the real trade-offs between objectives and forces subjective choices about what should be prioritised(de Alcantara et al., 2025). SMO avoids this problem by treating each objective separately and producing a set of Pareto-optimal solutions. These solutions show the full range of feasible trade-offs, allowing system behaviour to be analysed more transparently (Diaz et al., 2020) .

The value of SMO becomes especially clear in discrete-event manufacturing systems, where system behaviour depends on the sequence and timing of events rather than smooth, continuous processes. Effects such as blocking, starvation, congestion, and shifting bottlenecks cannot be captured accurately using analytical models that assume steady-state or average behaviour. DES allows these effects to be modelled explicitly, while the optimisation layer explores how changes in system configuration influence performance. By combining simulation and optimisation in a single framework, SMO ensures that all candidate solutions are evaluated under the same stochastic conditions, making comparisons fair and consistent (Blake & Ali, 2011) .

An additional advantage of SMO lies in its ability to handle large and combinatorial decision spaces. In manufacturing systems that incorporate routing flexibility, shared resources, or reconfigurable layouts, the number of feasible system configurations grows rapidly, making exhaustive evaluation infeasible. Traditional simulation studies often rely on manually selected scenarios, which risks overlooking relevant regions of the solution space. SMO addresses this limitation by embedding a population-based optimisation algorithm within the simulation environment, enabling systematic exploration of alternative configurations without restricting analysis to a small set of predefined cases (Diaz et al., 2020) .

SMO enables simultaneous evaluation of multiple configurations within a single simulation model, avoiding the need to construct and validate separate models for each alternative(Diaz et al., 2020). This is particularly relevant in industrial contexts where decision-making time is limited and rapid assessment of configuration alternatives is required. Diaz et al (2020) shows that SMO not only identifies Pareto-optimal solutions but also provides insight into the structural consequences of reconfiguration, such as how changes in routing or buffering affect the achievable balance between LT, TH, and WIP.

Compared with rule-based tuning or heuristic adjustments, SMO provides higher transparency and scientific rigour. Heuristic approaches often depend on expert judgement and local improvements, which makes results difficult to

reproduce or generalise. Analytical optimisation, on the other hand, usually requires strong simplifying assumptions that remove important sources of variability. SMO combines the strengths of both approaches by using formal optimisation algorithms together with high-fidelity simulation models. This produces results that are both structured and grounded in realistic system behaviour, increasing confidence in the conclusions drawn from the analysis (Mourtzis et al., 2014)

In manufacturing research, SMO is therefore increasingly viewed as a decision-support approach rather than a tool for identifying a single best solution. Instead of delivering one optimal configuration, SMO reveals the shape and limits of the feasible performance space. Pareto fronts make it possible to see whether changes to a system expand, shift, or restrict the achievable trade-offs between objectives. This perspective is particularly important when studying system reconfiguration, where flexibility does not automatically lead to better performance and must be evaluated carefully in relation to measurable outcomes (Diaz et al., 2020) .

In this thesis, SMO is used as the main analytical framework for comparing alternative manufacturing system configurations under consistent simulation conditions. Each configuration is evaluated using the same stochastic inputs, simulation horizon, and replication settings, ensuring methodological consistency throughout the analysis. By applying SMO, it becomes possible to assess how reconfiguration affects the structure of performance trade-offs, rather than assuming uniform improvement across all performance measures. The use of SMO supports the design science orientation of the research. The simulation model functions as a purposeful artefact, while SMO provides a systematic method for evaluating its behaviour and usefulness.

2.9 NSGA-II Algorithm

NSGA-II is used as the optimisation engine within the simulation-based optimisation framework implemented in FACTS Analyzer. The algorithm is applied to search for alternative routing and buffering configurations of the manufacturing system by repeatedly executing the DES model and evaluating the resulting performance in terms of LT, TH, and WIP. Each candidate solution generated by NSGA-II represents a specific system configuration, and its performance is assessed directly through simulation rather than analytical approximation. This ensures that the optimisation process is fully grounded in observed system behaviour under realistic operating conditions(Bensmaine et al., 2011).

NSGA-II belongs to the class of evolutionary MOO algorithms and is specifically designed to handle problems where objectives conflict and no single optimal solution exist. Instead of requiring predefined weighting factors to combine objectives, NSGA-II works by identifying a set of Pareto-optimal solutions. This is particularly important for manufacturing systems, where assigning fixed weights to LT, TH, or WIP would introduce subjective bias and risk masking

important trade-offs. By avoiding weight-based aggregation, NSGA-II allows the optimisation to reflect the natural structure of the problem rather than forcing artificial priorities.

The algorithm operates by maintaining a population of candidate solutions that evolves over successive generations. In each generation, solutions are evaluated using the simulation model, and their objective values are compared using a process known as non-dominated sorting. Solutions are grouped into fronts based on Pareto dominance, where solutions in the first front are not dominated by any other solution, and subsequent fronts represent increasing levels of dominance. This ranking mechanism ensures that solutions offering better trade-offs are retained and propagated through the optimisation process(Deb et al., 2002).

To prevent the optimisation from converging prematurely to a narrow region of the solution space, NSGA-II incorporates a crowding-distance mechanism. This measure estimates how close a solution is to its neighbours in objective space and favours solutions located in less crowded regions of the Pareto front. As a result, the algorithm maintains diversity among solutions and produces a well-distributed representation of the trade-off space. For manufacturing analysis, this is essential because it allows different operating regimes to be examined rather than focusing on a single local optimum(Deb et al., 2002).

NSGA-II is particularly well suited to discrete-event manufacturing systems because it does not rely on gradient information or smooth objective functions. Manufacturing performance measures derived from simulation are often noisy, non-linear, and discontinuous due to stochastic effects such as machine failures, queue interactions, and blocking. Gradient-based or deterministic optimisation methods struggle under these conditions, whereas NSGA-II remains robust because it evaluates solutions based on relative dominance rather than exact functional forms. This makes it appropriate for optimisation problems where performance emerges from complex event interactions rather than explicit equations(Bouazza et al., 2025).

FACTS Analyzer implements NSGA-II as its primary MOO algorithm because of its proven reliability in simulation-based manufacturing studies and its compatibility with DES outputs (A. H. C. Ng et al., 2012). The algorithm can directly use simulation variables as decision parameters and simulation results as objective values, allowing seamless integration between the optimisation engine and the DES model. This avoids the need for manual data transfer or external optimisation tools, which would increase modelling effort and introduce additional sources of error. The tight integration between NSGA-II and the simulation environment ensures that each optimisation iteration is evaluated consistently and efficiently.

Alternative optimisation methods available in FACTS Analyzer were reviewed but not selected for this study. Several of these methods, such as Differential Evolution, Particle Swarm Optimisation, CMA-ES, and NEWUOA, are designed

for single-objective or smooth deterministic problems and would require combining LT, TH, and WIP into a single weighted function. This would hide the trade-offs between performance measures and introduce subjective weighting choices. Other options, including Latin Hypercube Sampling, Full Factorial Design, and Sequential Bifurcation, are sampling or screening techniques rather than optimisation algorithms and therefore do not converge towards Pareto-optimal solutions. NSGA-II was selected because it directly supports SMO, handles stochastic DES outputs reliably, and produces a well-distributed Pareto front without objective aggregation. Given the large configuration space and the high computational cost of repeated simulation runs, NSGA-II provides a practical and well-suited optimisation approach for this study.

NSGA-II plays a major role in enabling systematic and unbiased exploration of the configuration space. Rather than testing a small number of manually selected scenarios, the algorithm allows a large number of feasible configurations to be evaluated under identical simulation conditions. This supports a fair comparison between baseline and reconfigured layouts and ensures that conclusions are based on the structure of the Pareto front rather than isolated performance points(Deb et al., 2002).

The use of NSGA-II contributes directly to the scientific value of the thesis by making trade-offs explicit. The resulting Pareto fronts provide evidence of how reconfiguration affects the balance between LT, TH, and WIP, and whether any reconfigured solutions are competitive with the baseline under comparable operating conditions. This aligns with the design science orientation of the research, where the goal is not to claim universal improvement but to rigorously evaluate the behaviour and limits of alternative system designs. By enabling this form of analysis, NSGA-II functions not merely as a computational tool but as a core analytical mechanism that underpins the credibility and interpretability of the thesis results. (Barrera Diaz et al., 2021).

2.10 Pareto Optimality and Pareto Front

In MOO, system performance cannot be described by a single best solution because improvements in one measure often led to deterioration in another. Pareto optimality provides a structured way to address this by identifying solutions that represent the best achievable compromises. A solution is Pareto-optimal when no other feasible solution performs better in all objectives at the same time. The set of all such non-dominated solutions forms the Pareto front, which represents the boundary of achievable system performance under given constraints.

In manufacturing systems, Pareto fronts are particularly relevant because performance measures such as LT, TH, and WIP are tightly coupled through flow behaviour, buffering, and resource utilisation. Changes intended to improve one aspect of the system often have indirect consequences elsewhere. The Pareto front captures these interdependencies by showing the range of

feasible operating conditions rather than forcing the analysis towards a single performance target.

In this thesis, Pareto fronts are generated as the direct output of SMO process and are used throughout the analysis as the primary basis for performance evaluation. They are first introduced in the optimisation results to visualise the feasible trade-off space of both the baseline and the reconfigured production layouts. Each point on the Pareto front corresponds to a complete system configuration evaluated through DES, including routing logic, buffer settings, stochastic processing times, and machine availability. The Pareto fronts represent realistic and achievable operating states rather than theoretical optima.

The relevance of Pareto analysis in this study lies in its ability to support fair and meaningful comparison between alternative production layouts. Rather than comparing isolated performance values or average results, the Pareto fronts make it possible to assess how the entire performance space changes when the system is reconfigured. By analysing the relative position, overlap, and dominance relationships between the Pareto fronts, it becomes possible to determine whether reconfiguration improves performance across a broad range of operating conditions or only in limited regions.

2.11 Circularity in Manufacturing

Circularity in manufacturing refers to the design and operation of production systems that preserve the functional value of resources such as materials, components, and equipment over extended periods, thereby avoiding linear patterns of use that culminate in disposal. Rooted in circular-economy principles, the concept emphasises strategies such as reuse, refurbishment, remanufacturing, and lifetime extension to reduce waste generation and mitigate the environmental burden associated with industrial activity (Carlsen & Bruggemann, 2022). Within production engineering, circularity is not limited to material flows; it also encompasses the reuse and adaptation of manufacturing infrastructure, recognising that a substantial share of industrial environmental impact is embedded in machinery, tooling, and production assets themselves.

This infrastructure-oriented perspective on circularity is closely aligned with research on RMS, where modularity, scalability, and convertibility enable existing equipment to be adapted to changing production requirements rather than replaced (Koren et al., 2018). From this standpoint, circularity operates as both an environmental and a technical principle: environmentally, it reduces the need for new resource extraction and equipment manufacturing; technically, it supports the redeployment and continued utilisation of assets across evolving product mixes. A circular manufacturing system is therefore characterised by its capacity to reassign functions, extend equipment lifetimes,

and sustain productive performance without repeated cycles of reinvestment and disposal.

In this thesis, circularity is explicitly operationalised at the level of production infrastructure rather than material recovery or closed-loop material flows. The proposed reconfiguration of the CB and CH lines does not involve the introduction of new machinery; instead, existing inspection, verification, and handling operations are selectively shared and reallocated between the two lines. By integrating shared operations and exploiting unused or underutilised capacity, the study demonstrates how reconfiguration can extend the functional lifetime of current assets and improve utilisation within an automotive engine manufacturing context. This contribution should therefore be understood as a conceptual and operational demonstration of infrastructure-level circularity through reconfiguration, rather than a quantitative assessment of environmental impact or life-cycle performance,

2.12 Sustainability

Sustainability in production systems encompasses the long-term integration of environmental, economic, and social performance considerations into manufacturing operations. Environmentally, sustainability focuses on lowering energy consumption, reducing emissions, minimising waste, and improving the efficiency of resource use throughout the product and system lifecycle. Economically, it relates to maintaining competitiveness through efficient operations, reduced operational losses, and responsible investment strategies that avoid unnecessary material and capital expenditure. Socially, sustainability incorporates system design features that support worker safety, knowledge development, adaptability, and equitable working conditions (Balaji et al., 2022). Within manufacturing research, sustainability is increasingly viewed as a systems-level condition rather than an isolated performance metric, where processes, layouts, equipment configurations, and operational policies are assessed not only for their immediate output effects but also for their long-term resource implications and resilience. The growing emphasis on sustainability has led to greater reliance on digital evaluation tools, as simulation and optimisation allow alternative designs to be examined without generating waste, consuming physical resources, or interrupting production (Spindler et al., 2021). Sustainable production systems are therefore characterised by reduced variability, stable flow characteristics, balanced utilisation, and efficient resource handling attributes that contribute directly to lower energy consumption and reduced operational losses. In this sense, sustainability provides a theoretical framework for understanding how manufacturing systems can enhance performance while advancing environmental responsibility and long-term operational robustness.

Within this thesis, sustainability is operationalised by assessing whether targeted reconfiguration combined with SMO can reduce LT, stabilise TH, and lower WIP without introducing additional machinery or conducting disruptive physical trials on the shop floor. The use of FACTS Analyzer and the NSGA-II

algorithm enable alternative layouts and routing strategies to be evaluated entirely in a digital environment, preventing scrap generation, downtime. By demonstrating that existing equipment can be rearranged to achieve smoother flow, better utilisation, and more predictable system behaviour, the study links operational performance improvements directly to reduced resource waste and enhanced system resilience. In doing so, the proposed reconfiguration approach aligns with the core definitions of sustainability by showing how performance optimisation and environmental responsibility can be achieved simultaneously through informed, simulation-driven decision-making.

3 Conceptual Framework for Server Flexibility in Production Systems

The conceptual study was developed to analytically explore how server flexibility influences fundamental production-system behaviours, TH, LT, and WIP, under controlled simulation conditions. This step was necessary before applying reconfiguration strategies to the industrial CB and CH system. The study draws upon two core theoretical foundations.

The simulation-based analytical evaluation modelling approach was influenced by prior research at Aurobay. Hidemyr (2023) presents a virtual-commissioning framework that highlights how structured digital environments support systematic industrial experimentation through standardised modelling and iterative validation. This methodological orientation shaped the construction of controlled conceptual scenarios used in this study. Second, Pegden (2015) defines Principle 15 as the formal description of server flexibility, the capability of a resource to process multiple part types or operations dynamically without being restricted by dedicated routing. Principle 15 also demonstrates that flexibility improves flow stability by reducing queue imbalances and distributing workload adaptively (Pegden, 2015).

Together, these works provided both the modelling discipline and the theoretical reason for analysing flexible versus dedicated routing structures prior to the industrial case.

3.1 Principle 15 Reference Design Logic

The original formulation of Principle 15 involved a simulation comparing system performance under flexible and dedicated server configurations. In this setup, entities followed an exponential inter-arrival distribution and were processed using a triangular distribution of service times. When flexibility was enabled, entities were dynamically routed to the least loaded server, promoting balanced utilisation. Under a dedicated configuration, routing relied solely on compatibility, disregarding real-time load conditions. Figure 5 illustrates this dedicated server routing, in which each entity type is restricted to its assigned

server, resulting in uneven workload distribution and visible queue accumulation at Server 1 while Server 2 remains underutilised.

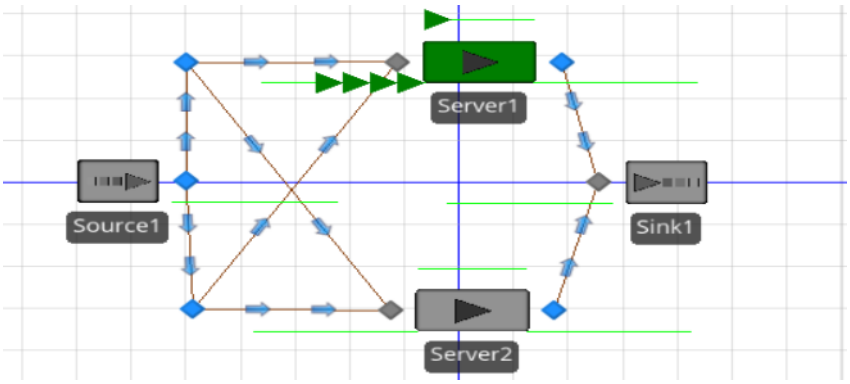

Figure 5 Dedicated Server Routing with Imbalanced Load Distribution

3.2 Conceptual Models

Three conceptual models were constructed, each representing a different operational condition that mirrors real manufacturing behaviour balanced flow, processing-time imbalance, and availability variability.

3.2.1 Model 1: Original Principle 15 Based System with Adjusted Inter Arrival Time

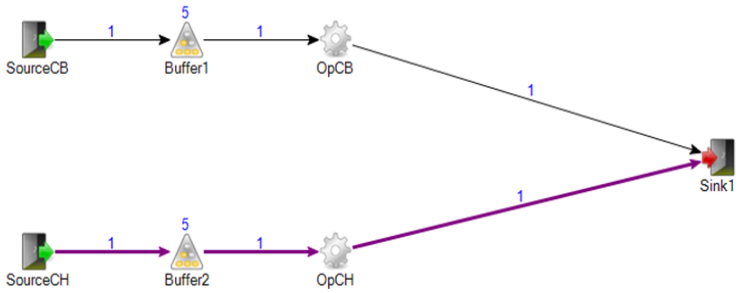

Figure 6 Original Flow Configuration for Cylinder Block and Cylinder Head

Figure 6 illustrated the initial dedicated flow of the CB and CH lines, this model reproduced the baseline CB or CH configuration, where each product followed its own path and converged at a shared sink. Arrivals were exponential, and service times were triangular. The flexible configuration allowed both servers to process both part types.

Key Findings:

- With large buffers, flexibility reduced LT and WIP while maintaining similar TH.

- With small buffers, flexibility continued to stabilise queues and reduce waiting times despite capacity constraints.

- The system exhibited smoother utilisation distribution across both servers in all conditions.

Table 1 summarises the simulation outcomes for a large-buffer system, Table 2 reported the corresponding results when buffer capacity was reduced. Each table compared the original and flexible configurations in terms of production stability, flow continuity, and utilisation balance.

Table 1 Effect of server flexibility under large buffer capacity (50 units)

Model Type	TH	LT	WIP	Buffer Occupancy (%)
Original	597.4	500.7	83.13	84
Flexible	598.3	466.9	77.67	76

Under large-buffer conditions, the flexible configuration achieved smoother flow and lower congestion while maintaining a stable production rate. Balanced workload distribution prevented queue build-ups and improved utilisation across both servers.

Table 2 Effect of server flexibility under small buffer capacity (5 units)

Model Type	TH	LT	WIP	Buffer Occupancy (%)
Original	598.5	71.5	11.88	~99
Flexible	598.4	69.6	11.57	~95.9

With smaller buffers, the flexible setup continued to outperform the original, maintaining coordinated flow and shorter waiting periods despite limited storage. Even under restricted capacity, the system remained stable and responsive, validating the behavioural advantage of moderate flexibility.

3.2.2 Model 2: Imbalanced Processing Time Configuration

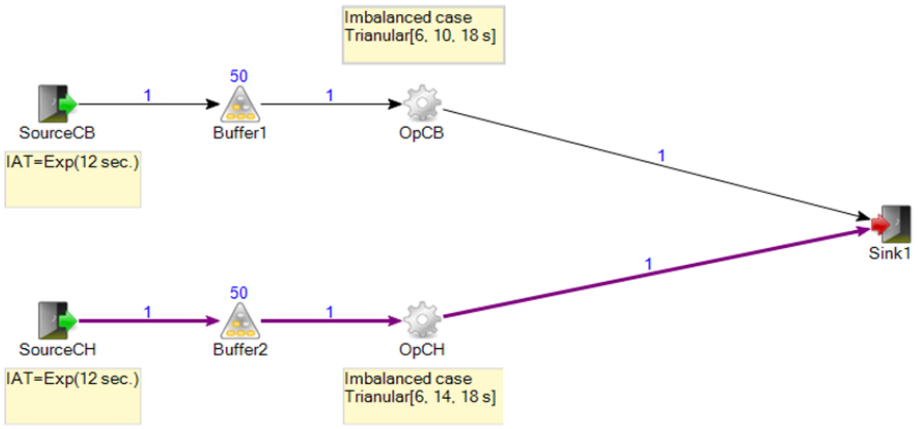

Figure 7 Dedicated Flow with Asymmetric Processing Time Configuration

Figure 7 illustrated the dedicated CB and CH lines operating with unequal processing times, representing an intentionally imbalanced flow condition. Here, CB and CH lines were intentionally assigned different processing times to emulate asymmetric workloads. Two configurations were compared, fixed routing versus flexible redirection between the lines.

Key Findings:

- In large-buffer conditions, CH experienced severe congestion under dedicated routing, while CB remained underutilised.
- Flexibility redistributed workload, dramatically reducing LT variation between the two product flows.
- Under small buffers, flexible routing maintained higher stability and minimised idle time without altering input rates.

Table 3 Effect of flexibility under imbalanced processing times (large buffer = 500 units) summarised the results under a large-buffer scenario, whereas Table 4 presented the outcomes for a reduced-buffer condition.

Table 3 Effect of flexibility under imbalanced processing times (large buffer = 500 units)

Model Type	TH	LT_CB (s)	LT _CH (s)	Buffer Occupancy _ CB (%)	Buffer Occupancy _CH (%)
Original	583.58	109.72	6232.70	1.63	98.40
Flexibility Enabled	598.98	548.92	527.87	8.90	8.60

With large buffers, the dedicated configuration produced severe congestion in the CH line due to its longer process chain, leaving the CB line underutilised. Enabling flexibility redistributed workload between the two servers, greatly reducing delay variation and improving flow balance across both streams.

Table 4 Effect of flexibility under imbalanced processing times (small buffer = 5 units)

Model Type	TH	LT_CB (s)	LT_CH (s)	Buffer Occupancy _ CB (%)	Buffer Occupancy _CH (%)
Original	583.80	53.50	76.10	100.00	70.20
Flexibility Enabled	598.36	66.30	66.30	90.30	90.10

When buffer capacity was restricted, the flexible configuration maintained higher stability and TH by dynamically rerouting parts and balancing utilisation between the CB and CH lines. The improvement was particularly visible under constrained conditions, where the system self-adjusted to limit idle time and congestion without altering input rates.

3.2.3 Model 3: Availability Constrained Configuration with Constant Processing Time

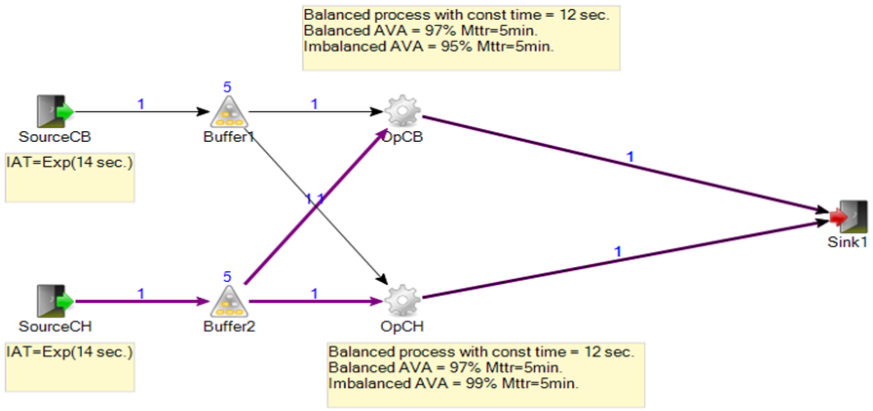

Figure 8 Simulation Model of Shared Flow under Availability Constraints and Fixed Processing Time

Figure 8 illustrated the simulation setup used to examine how flexibility influenced performance when machine reliability varied. This model varied machine availability while keeping processing time constant. Balanced (97 – 97%) and imbalanced (95 –99%) availability pairs were tested under both large and small buffers.

Key Findings:

- With balanced availability, flexibility sharply reduced LT and WIP with no loss of TH.
- Under imbalanced availability, flexibility prevented bottleneck formation by rerouting parts away from temporarily unavailable servers.
- Queue lengths remained evenly distributed even with downtime effects.

Table 5 summarised the balanced-line results, and Table 6 presented the corresponding outcomes for the imbalanced-line condition.

Table 5 Effect of flexibility under balanced availability conditions

Model Type	Buffer Size	TH (units /day)	LT (min)	WIP	Buffer Occupancy _ CB (%)	Buffer Occupancy _ CH (%)
Original	50	513.2	108.74	15.5	14.9%	13.0%
Flexibility Enabled	50	513.2	57.39	8.18	6.47%	6.37%
Original	5	513.3	48.4	6.9	51.45%	51.3%
Flexibility Enabled	5	513.3	36.4	5.2	34.4%	34.3%

Under balanced conditions, the flexible configuration achieved a noticeable reduction in waiting time and buffer usage while maintaining the same production rate. By enabling shared access between servers, the system adapted to temporary unavailability without causing starvation or idling, leading to a smoother and more continuous flow.

Table 6 Effect of flexibility under imbalanced availability condition

Model Type	Buffer Size	TH (units/ day)	LT (min)	WIP	Buffer Occupancy _ CB (%)	Buffer Occupancy _ CH (%)
Original	50	513.2	121.5 (173.4, 69.6)	17.3 (12.4, 4.96)	22.9%	8.2%
Flexibility Enabled	50	513.4	56.3	8.0	6.3%	6.23%
Original	5	513.3	48.4 (53.6, 43.7)	6.9 (3.8, 3.1)	58.5%	44.9%
Flexibility Enabled	5	513.3	35.6	5.1	33.2%	33.0%

In the imbalanced case, where the CB and CH lines operated under unequal availabilities, the flexible model maintained stable TH and significantly reduced queue imbalances. Allowing parts to reroute dynamically minimised the impact of machine downtime, balanced utilisation across both lines, and prevented over-saturation of any single buffer.

3.3 Theoretical Synthesis and Design Relevance

Across all three models, flexibility consistently improved internal flow behaviour, reducing LT, lowering WIP, and balancing utilisation while having minimal effect on overall TH in high-availability conditions. These behavioural patterns align with Pegden's Principle 15 and confirm that the value of flexibility lies in flow stability, not raw capacity increase.

The three models collectively represent balanced, imbalanced, and availability-constrained manufacturing environments. Their results provide a reliable theoretical baseline for interpreting how flexibility could influence the real CB and CH system. They also demonstrate conditions where flexibility may be most impactful, particularly when workloads differ between product types or when machine availability fluctuates.

The conceptual study therefore establishes clear expectations before industrial evaluation: flexible routing should improve synchronisation, reduce queue-induced delays, and enhance the robustness of flow benefits directly relevant to RMS.

3.4 Conceptual Optimization Performance Patterns

Figures 9 and 10 present the optimisation patterns derived from the conceptual Models 2, where the dedicated and flexible server configurations were systematically tested across different buffer levels, process-time settings, and availability scenarios.

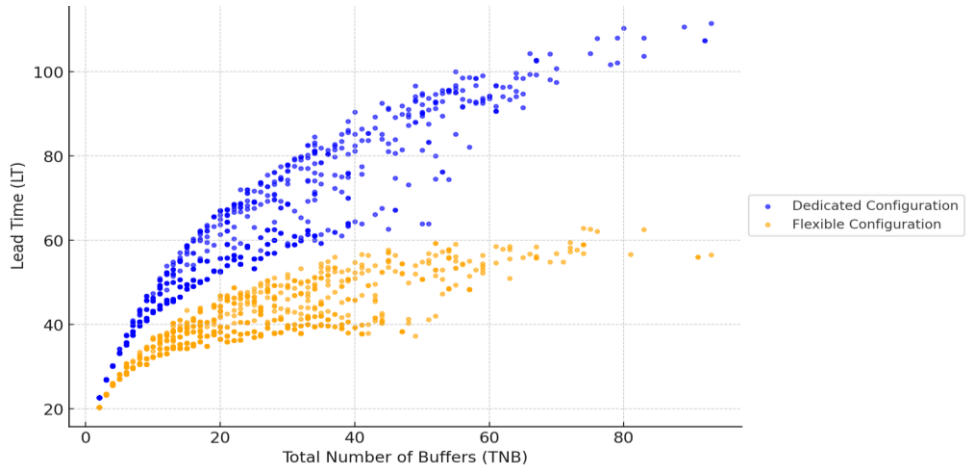

Figure 9 Optimisation Results for Model 2: Trade-off between Total Number of Buffers and Lead Time for Dedicated and Flexible Machine Configurations

The optimisation comparisons confirm the theoretical results:

- Flexible systems occupy the lower-left region of the TNB and LT space, indicating shorter LT for similar buffer counts.
- Dedicated systems exhibit longer LTs and unstable utilisation distribution.
- The flexible system's Pareto frontier shows steep LT reduction at low buffer levels, reflecting efficient buffer utilisation through workload reassignment.

These patterns validate the systemic advantage of flexible routing mechanisms and form a conceptual reference against which industrial reconfiguration results will later be assessed.

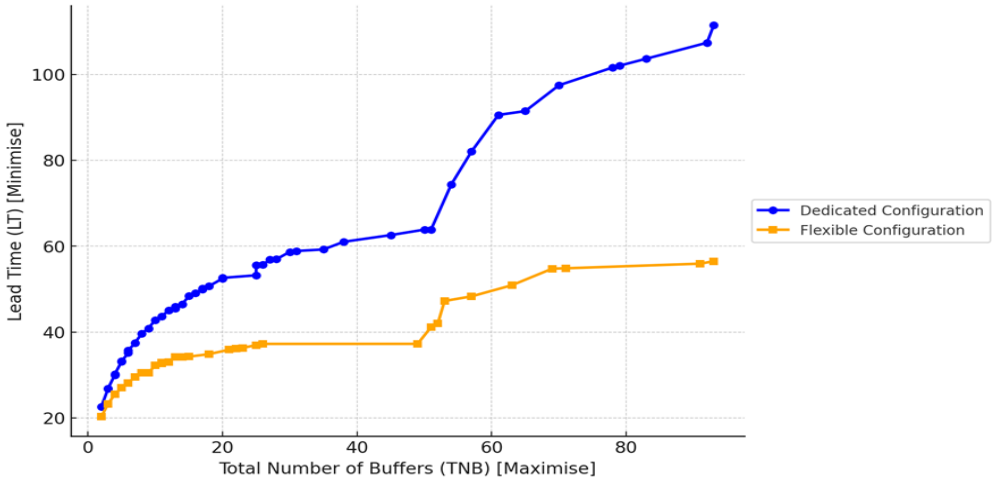

Figure 10 Pareto-Optimal Solutions for Model 2: Non-Dominated Trade-off between Total Number of Buffers and Lead Time for Dedicated and Flexible Machine Configurations

Flexibility improves LT performance primarily by reducing buffer occupancy and stabilising flow, particularly in systems with large buffers. Since TH remains statistically unchanged across all conceptual models, removing excessive buffering is key to realising these improvements. When buffer capacity is tightened, flexibility can still yield further LT reductions, but it does not result in any additional TH gains. This outcome aligns with Pegden's Principle 15 and reflects that flexibility enhances internal flow efficiency rather than increasing system capacity.

It is important to note that this conclusion is not universally generalisable. In systems characterised by high variability such as those with low availability levels (around 80%) and long MTTR the expected LT improvements may not hold. Under such unreliable conditions, flexibility may introduce secondary inefficiencies or fail to compensate for frequent downtime. For the Aurobay case examined in later chapters. The system operates at relatively high availability (above 95%).

3.5 Synthesis of Conceptual Study Findings

The conceptual study demonstrates that:

- Flexibility reduces LT and WIP consistently under all modelled conditions.
- TH remains largely unchanged, confirming that flexibility enhances efficiency, not maximum capacity.
- Benefits are strongest when processing times or availability levels are imbalanced.

These behaviours provide theoretical justification for the reconfiguration strategies later applied to the CB and CH production lines.

4 Literature Review

Prior research has demonstrated that production-flow reconfiguration can be an effective mechanism for influencing LT while preserving TH performance in complex manufacturing systems. Studies evaluating alternative production configurations have shown that reorganising machine groupings, modifying routing structures, or adjusting stage compositions redistributes congestion and waiting times, thereby improving flow efficiency when assessed under realistic operating conditions (Puik et al., 2017;Renna, 2024). In these works, DES was used to evaluate baseline and reconfigured configurations under identical demand and availability assumptions, revealing that LT reductions were achieved primarily through improved balance between stages rather than through additional capacity. This evidence is directly relevant to the present thesis, where selective reconfiguration of CB and CH flows is investigated as a means to improve responsiveness without compromising stable throughput.

In high-volume automotive production with a wide product mix, reconfiguration has shown clear benefits. Simulation-based studies of mixed-model and automotive assembly lines report that redistributing operations across stations can improve system performance. Introducing controlled routing flexibility reduces flow disturbances caused by variations in processing times and product mix. At the same time, TH remains stable across different operating scenarios (Altemeier et al., 2010). These studies relied on discrete-event models to capture blocking and starvation effects that emerge after structural changes, showing that LT was reduced by smoothing load imbalances across parallel resources. Such findings are relevant to CB and CH production, where variability and equipment availability similarly affect tightly coupled flow lines.

The value of simulation for analysing flow-level changes has also been demonstrated in engine production contexts. Studies focusing on engine assembly systems used DES to evaluate structural adjustments at constrained

stages and showed that LT decreased as bottlenecks were relieved and waiting times redistributed, while overall TH remained within acceptable limits (Blake & Ali, 2011). Comparable simulation-based investigations in process-intensive manufacturing environments, including pharmaceutical, food-processing, and glass production systems, confirmed that layout modifications validated through simulation reduced internal transport delays and queue accumulation, leading to shorter LT without sacrificing production output (Spindler et al., 2021; Grenzfurtner et al., 2025; Mendoza-Ortega et al., 2025). These results support the use of simulation as a credible method for evaluating reconfiguration effects before implementation in high-volume systems.

Routing flexibility has been identified as a particularly effective lever for LT reduction in production systems with parallel or partially shared resources. Research introducing alternative routing options demonstrated that allowing products to access compatible capacity reduced waiting times and queue lengths by alleviating local congestion, resulting in substantial LT improvements while maintaining TH levels (Pinilla & Prinz, 2003). Similar observations were reported in multi-model production lines, where limited routing flexibility improved flow stability by distributing workload more evenly across available resources under fluctuating demand (Altemeier et al., 2010). These findings directly support the relevance of shared-flow routing in CB and CH lines, where compatible operations may be selectively integrated to reduce congestion effects.

Beyond scenario-based comparisons, several studies have applied SMO to systematically explore the trade-off between LT, TH, and WIP across reconfiguration alternatives. In these works, DES was embedded within an optimisation loop to evaluate large sets of configuration variants, revealing Pareto-optimal regions where LT was reduced without unacceptable TH loss (Diaz et al., 2020; Barrera-Diaz et al., 2023; Yegul et al., 2017b). The results demonstrated that improvements in LT were achieved by redistributing flow and buffering rather than by increasing nominal capacity, while TH was preserved through balanced utilisation of resources. These findings are directly aligned with the present thesis, which similarly evaluates reconfiguration outcomes by analysing the LT–TH trade-off rather than assuming universal improvement.

Further empirical evidence reinforces the necessity of simulation-driven evaluation when assessing structural changes. Studies on material-flow modelling showed that queue interactions, blocking, and starvation effects arising from reconfiguration can only be reliably captured through DES, particularly in systems with high utilisation and limited buffering (Carl May et al., 2024). Additional simulation-based analyses confirmed that reallocation of machines and rebalancing of production stages reduced LT and stabilised TH under variable operating conditions, supporting the industrial feasibility. (Butrat & Supsomboon, 2022b; Okuyelu et al., 2024). These contributions demonstrate that simulation enables consistent comparison of baseline and reconfigured flows under controlled assumptions, which is essential for evidence-based decision-making.

Across the reviewed literature, LT is consistently treated as an indicator of congestion and flow inefficiency rather than as an isolated performance measure. Studies linking LT to inventory accumulation and process monitoring showed that reductions in LT reflected improved flow continuity and reduced waiting, while TH stability was preserved through controlled release and balancing strategies (Cuatrecasas-Arbós et al., 2015). Simulation-based assessments under uncertainty further demonstrated that LT improvements could be achieved without TH degradation when structural changes were evaluated holistically rather than locally (Spindler et al., 2021). These findings support the interpretation framework adopted in this thesis, where changes in LT are analysed alongside TH behaviour to assess the practical value of reconfiguration.

5 Research Methodology

This study adopted the DSM as the principal research framework to assess and enhance the reconfigurability of the CB and CH production systems. The DSM emphasised the systematic and iterative development of a purposeful artefact namely, a SMO in FACTS Analyzer to address the identified industrial challenge (Johannesson & Perjons, 2021).

It provided a structured and practical approach that combined scientific rigour with industrial applicability. The methodology enabled the creation, demonstration, and qualitative validation of a simulation-based artefact, which was analytically evaluated under operationally realistic simulated conditions rather than through theoretical reasoning alone. In doing so, it bridged the gap between conceptual design and simulation-based analytical evaluation, making it well suited for exploring how reconfiguration strategies influence production performance (Johannesson & Perjons, 2021).

The research followed a simulation-based analytical evaluation approach grounded in a positivist and realist philosophical stance, treating the manufacturing system as an objective and measurable entity. The study evaluated the performance of the developed simulation artefact across systematically varied operational conditions to assess design trade-offs.

5.1 Research Design and Rationale

The research was guided by the Design Science Methodology (DSM), motivated by the need to improve production adaptability and sustainability without significant investments in new infrastructure. Rather than relying on purely theoretical assumptions, the study adopted a design science approach in which a simulation-based artefact was constructed and analytically evaluated under operationally realistic simulated conditions.

Several methodological alternatives were considered. A qualitative case study could have provided rich insights into organisational change processes, but it would not have supported systematic, reproducible analysis of LT and TH trade-

offs across alternative system configurations. Empirical experimentation on the shop floor could have produced real-world data but was impractical due to cost, risk of disruption, and limited access. Purely mathematical optimisation models were also evaluated but deemed less suitable, as they would have oversimplified the stochastic and event-driven nature of production flow behaviour. For these reasons, DSM was selected because it supports structured development, demonstration, and analytical evaluation of artefacts, enabling both scientific rigour and industrial applicability (Johannesson & Perjons, 2021).

The research requirements were defined through engineering consultations, supported by operational data and literature on RMS. The simulation model was designed to reflect the system constraints, including task dependencies, failure behaviour, buffer limitations, and machine availability. The study followed a positivist and realist stance (Johannesson & Perjons, 2021), viewing the production system as an objective reality that can be represented through DES and evaluated using controlled simulation-based analysis. FACTS Analyzer enabled reproducible simulation of both baseline and reconfigured scenarios, ensuring industrial relevance while remaining consistent with qualitative expert-based validation constraints. This design ensured that the research addressed both an industrial problem and a methodological contribution to the field of production system reconfigurability.

5.2 Data Collection

To ensure the development of a valid and context-specific simulation model, a multi-layered data collection strategy was implemented. This strategy drew upon empirical fieldwork, technical documentation, and engineering expertise. The combined evidence base was crucial for accurately capturing both the structural configuration and the dynamic behaviour of the CB and CH production systems within the simulation environment.

5.2.1 Quantitative and Technical Input Data

To construct a realistic and empirically grounded simulation model, four primary categories of quantitative data were collected from operational documentation and engineering sources: process times, machine availability, MTTR, and buffer capacities. In addition to these, routing logic information was gathered to understand the flow behaviour across stations. These formed the core numerical inputs required to represent the temporal dynamics and flow constraints of the CB and CH production systems. Table 7 summarises the key quantitative input parameters used for constructing the simulation model, outlining their data sources, explanations, and specific modelling applications. Each of these parameters was systematically validated in collaboration with the engineers to ensure both technical accuracy and contextual relevance.

Table 7 Quantitative Input Parameters and Their Simulation Applications

Parameter	Data Source	Explanation	Modelling Application
Operation Specific Process Times	Excel datasets	Operation level machining, assembly, and verification durations were provided in either fixed or triangular distributions.	Integrated directly into FACTS Analyzer as activity duration profiles for each station.
Machine Availability	Reliability logs from engineering team	Machines were reported with varying availabilities. Downtime scenarios were based on realistic MTTR.	Availability percentages were applied to resources to simulate stochastic failures and recovery cycles, affecting TH reliability.
MTTR	Maintenance engineering estimates and standard Aurobay settings	A nominal MTTR value of 1 minute was used across all failure events unless otherwise specified, reflecting typical repair duration.	MTTR was used in conjunction with availability to model breakdown repair cycles in station behaviour, ensuring flow disruption realism.
Buffer Capacities and Usage	Layout files (L/J/O Plant showcase models) and flowcharts	Buffers were dimensioned based on physical layout constraints.	Buffer capacity was varied in scenarios to test congestion effects, queue dynamics, and flow stability.
Routing Logic	Engineer consultations, Flow diagrams	2 routing strategies: 1) Fixed path flow with dedicated resources, and 2) Shared routing with reconfigurable station access and conditional routing rules.	Used to simulate baseline vs. reconfigured layouts, with dynamic task assignments and shared resource logic to test reconfigurability benefits.

5.2.2 CAD Models and Visual Layout Data

The three physical plant layout schematics including J, L, and O Plants were examined to extract machine locations, operation sequences, transport

pathways, and buffer configurations. The CB line comprised 31 operations ranging from OP10 (initial assembly) to OP220 (final verification), with several parallel machine groups used for TH balancing. The CH line consisted of 24 operations, including early-stage marking (OP10), assembly (OP20), leak testing (OP140), and verification (OP150). Compared to the CB layout, the CH system was more compact, integrating several operations within shared zones and reducing transport distances.

A key task in the reconfiguration study involved classifying operations according to their suitability for shared use, reuse, or dedicated retention. This classification was carried out through engineering consultations and detailed flow analysis. Product-specific operations were kept as dedicated and excluded from reconfiguration. Reused operations represented stations that could be functionally repurposed for both CB and CH flows, while common operations were those already present in both systems. This classification formed the operational basis for identifying reconfigurable candidates. Table 8 highlights which operations are new, reused, or common between the CB & CH, identifying OP10, OP20, OP150, and OP220 as key candidates for reconfigurable integration.

Table 8 Classification of Operations for Reconfigurable Layout Integration

Operation Code	Cylinder Block	Cylinder Head	Marked as NEW	Marked as Reuse	Marked as Common CB/CH
OP10	✓	✓	✕	✕	✓
OP20	✕	✓	✕	✓	✓
OP150	✕	✓	✕	✓	✓
OP220	✓	✕	✕	✓	✓
OP30–130	✓	✓	✓	✕	✕
OP140	✕	✓	✓	✕	✕
OP160–210	✓	✕	✓	✕	✕
OP170	✓	✕	✓	✕	✕

5.2.3 Empirical Observations and On-Site Validation

Comprehensive on-site observations were conducted across multiple days at Skövde facility. These observations aimed to capture operational behaviours typically underrepresented in static schematics or process spreadsheets but crucial for accurately modelling flow characteristics, bottlenecks, and human-machine interactions. Several key phenomena were systematically observed and recorded. Persistent queue build-up was noted near CB OP160 to OP220, especially at verification and inspection stations, with these bottlenecks linked to asynchronous upstream processes and limited buffer capacity in the CB line. Material transport between stations was predominantly managed using Automated Guided Vehicle (AGVs) and shuttle conveyors, with occasional

delays caused by path congestion or manual prioritisation of urgent batches, thereby influencing LT variability.

Buffer utilisation patterns showed that while certain buffers such as those before CB OP100 and CH OP140 operated below capacity, others like CB OP130 and CB OP160 were frequently saturated, indicating suboptimal buffer allocation. These insights informed layout refinements in the reconfigured model. Operators were frequently observed performing manual overrides to bypass standard sequencing during minor stoppages or part shortages. Flexible operator allocation was common, particularly during shift transitions, where personnel moved between stations based on production demand. These adaptive behaviours, absent from the original static routing logic, were incorporated into the simulation to reflect dynamic shop-floor responsiveness more accurately.

5.2.4 Engineering Consultations and Scenario Inputs

A series of workshops and iterative consultation sessions were conducted with the simulation and manufacturing engineering teams. These consultations were essential for validating both the logic underpinning the simulation model and the technical feasibility of the reconfigurable flow scenarios. The discussions addressed layout planning, equipment availability, space utilisation, and production continuity under the proposed shared-flow configurations. Through these sessions, the engineers evaluated how reconfiguration could be implemented without disrupting ongoing production. As summarised in Table 9, the engineering team provided detailed assessments of machine-reuse opportunities and operational compatibility. Their input formed the industrial foundation for developing the shared-flow simulation scenarios, ensuring that the model accurately represented both practical opportunities and real operational challenges.

Table 9 Key Outcomes from Engineering Discussions

Aspect	Details Provided by Engineers
Machine Reuse Strategy	Machines from multiple cells specifically J, L, and O Plants were identified for strategic reuse in both CB and CH operations. This reuse formed the physical basis for Shared flow modelling.
Operations Enabled for Reuse	Operations such as OP10 (Marking and Assembly), Op20 (Assembly), OP50, OP60, OP90, OP110, OP115, OP140, OP150, OP160, and Op220 were evaluated for reuse potential based on machine compatibility and process logic.
Shared Operation Justification	Engineers confirmed that OP10, OP220 of CB were functionally similar across and OP10, OP20, OP150 of CH lines and thus feasible for multi resource allocation in a reconfigured layout.
Facility Constraints	A total floor space of 3000 m² was available for reconfigurable deployment in the O Plant, requiring efficient layout planning. Special purpose machines, measurement stations, and logistic zones had to be accommodated within this space.

Flow and Layout Planning	The team proposed reusing 2 existing zones in O Plant for consolidated operations. These zones were historically used for CH machines and provided adequate access to logistics corridors and utilities.
Challenges Noted	Risk of line stoppages during machine relocation and setup. Buffer reshuffling required to manage flow synchronisation. Interruption in sequencing unless routing flexibility was ensured.
Simulation Scenario Basis	These constraints and opportunities formed the foundation for the modelled scenarios, differentiating baseline from Shared flow architectures. Simulation logic was adjusted to reflect this transition precisely.

5.3 System Design Architecture

5.3.1 Model Assumptions and Constraints

It was assumed that the plant operates on a continuous three-shift schedule each week, reflecting the actual industrial practice. For each station, the major inputs included process time, MTTR, and machine availability, which were modelled as stochastic parameters based on reliability data. Shared operations were represented explicitly, meaning the same process could be executed by multiple machines across CB and CH. Transport times and operator behaviour were kept standardised to maintain tractability. Constraints were imposed by buffer capacities, floor space availability, and routing rules.

5.3.2 Baseline Flow Configuration

The original production architecture consisted of 31 and 24 sequential operations, respectively. These operations collectively represented the complete production sequence from initial assembly to final verification. Only a targeted subset of these operations was included in the architectural visualisation to maintain clarity and focus. Listing all operations would have unnecessarily increased complexity without contributing to understanding the reconfiguration potential. Only those processes identified by experienced manufacturing engineers as technically feasible for reallocation were highlighted.

The selected operations comprised Assembly and Verification Operations of both lines. They were included in the system diagrams to highlight key reconfigurable stages instead of showing every process in detail.

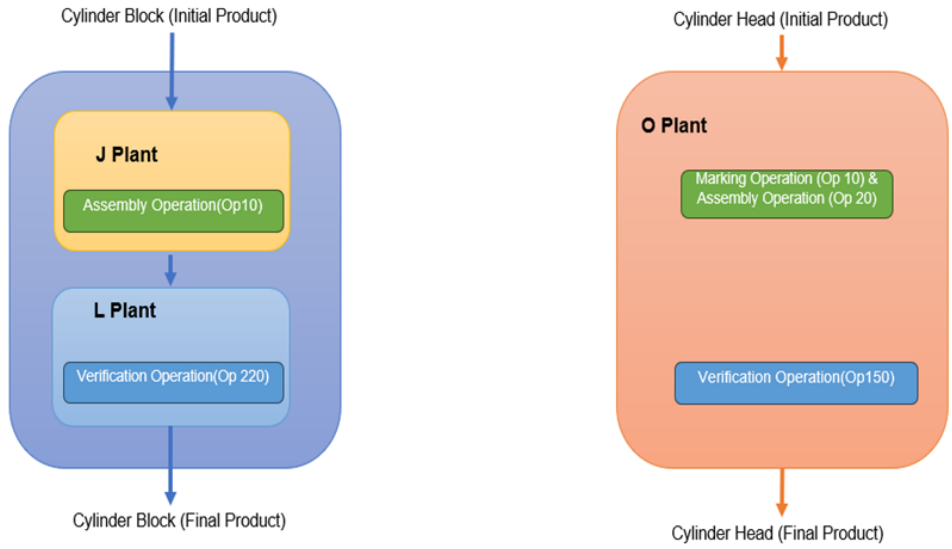

Figure 11 Simplified Plant Locations Within Factory

Figure 11 presents the baseline production structure in which each product followed a fixed, dedicated path through distinct plant facilities. The CB was processed within the J Plant for Assembly (OP10), before being transferred to the L Plant for final Verification (OP220). The CH line operated primarily within the O Plant, where it underwent Marking (OP10), Assembly (OP20), and Verification (OP150). This representation illustrated the rigid separation between production lines and the lack of cross-resource utilisation.

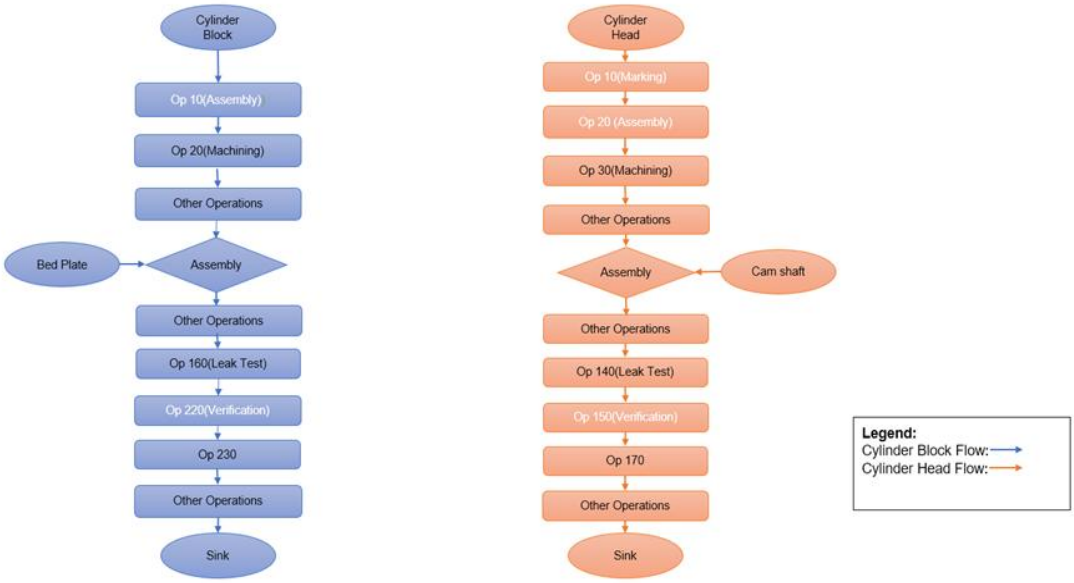

Figure 12 Flow Diagram of Cylinder Block & Cylinder Head

Figure 12 provides a detailed flow diagram depicting the original, product-specific operation sequences. The CB production began with an assembly stage (OP10), continued through machining and other intermediate operations,

underwent Leak Testing (OP160), and concluded with Verification (OP220). The CH process followed a parallel but separate structure, beginning with Marking (OP10) and Assembly (OP20), progressing through Machining (OP30), Leak Testing (OP140), and Verification (OP150).

5.3.3 Reconfigured Architecture

The reconfigured architecture introduced a Shared Flow strategy designed to enhance system flexibility by integrating selected operations across plants and products. This approach transformed the traditional layout into a semi-integrated structure that allowed dynamic resource allocation between CB and CH lines (Mehrabi et al., 2000).

Figure 13 illustrates this shared configuration, where the J Plant became capable of performing both CB Assembly (OP10) and CH Marking and Assembly (OP10 and OP20). Similarly, the L Plant was adapted to handle Verification operations for both CB (OP220) and CH (OP150). The O Plant maintained its core role as a processing unit but now participated in supporting shared operational interactions through coordinated routing rules.

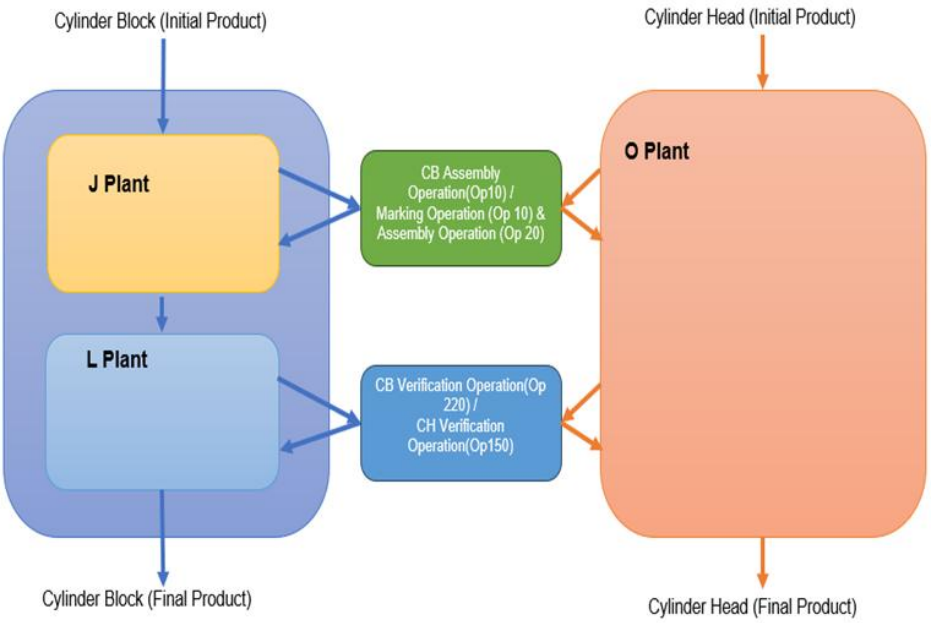

Figure 13 Simplified Plant Locations Within Factory

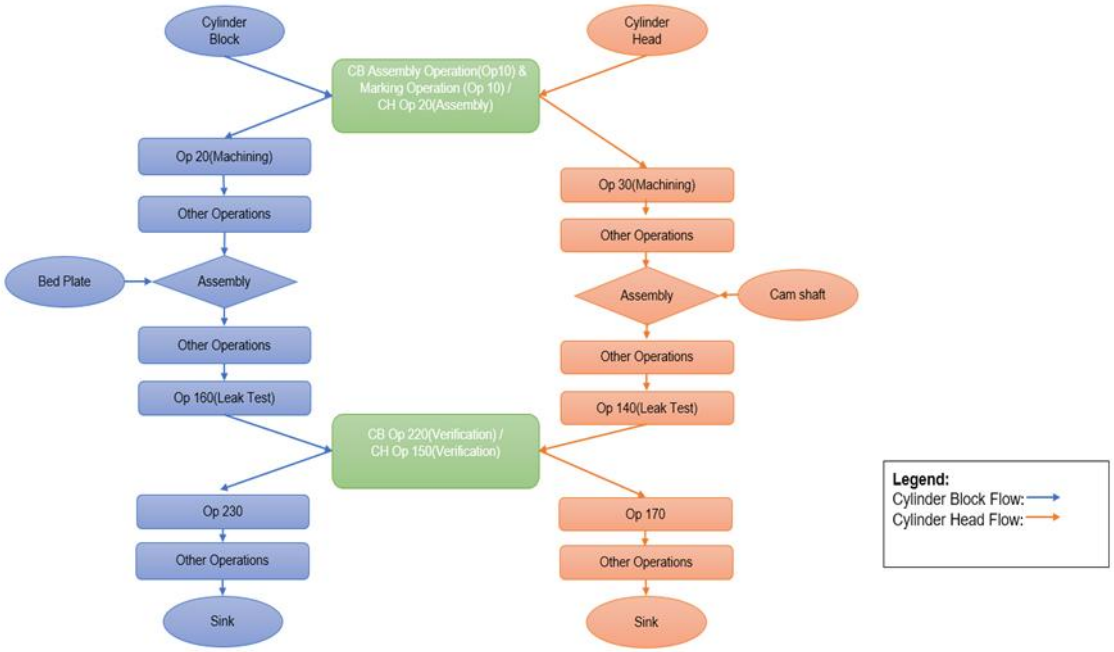

Figure 14 Flow Diagram of the Reconfigured Shared Flow

Figure 14 visualises the modified process logic. The CB's OP10 and CH's OP10 and 20 were reallocated to a common assembly unit, facilitating efficient use of resources and reducing idle capacity. Verification tasks (OP150 for CH and OP220 for CB) were consolidated into a shared verification cell, eliminating duplication while maintaining product-specific quality checks. All other operations such as machining, leak testing, and specialised sub-assemblies remained dedicated to preserve technical and geometric integrity. This shared configuration supported higher operational responsiveness by enabling dynamic routing based on availability and demand. If a verification machine for CH became unavailable, CB verification tasks could temporarily occupy the shared resource without interrupting production.

Reconfiguration triggers were aligned with real-world industrial drivers. The first was demand fluctuation, where variable production volumes necessitated quick scaling without retooling. The second was product variant introduction, reflecting the automotive sector's shift towards multiple configurations within the same engine family. The third was equipment availability, as unplanned breakdowns often caused bottlenecks in rigid systems. The shared flow model addressed these issues by introducing redundancy and flexibility within critical process stages. The modelled simulation scenarios compared both dedicated and shared configurations under identical operational constraints. The dedicated configuration followed the fixed routing structure described earlier, while the shared configuration applied flexible routing logic with adjustable buffer capacities and resource sharing. These configurations provided the empirical basis for analysing TH, LT, and utilisation performance under different operating conditions.

5.4 Implementation

The implementation phase involved the development of executable DES models for the baseline and reconfigured CB and CH systems, followed by their integration into a MOO framework using NSGA-II. All optimisation results are therefore derived exclusively from the simulation artefacts implemented in FACTS Analyzer version 3.1.7, developed on a Windows 11 system (Intel Core i5-1135G7, 16 GB RAM, Intel Iris Xe Graphics).

5.4.1 Simulation Model Implementation

Process times, MTTR values, buffer capacities, station availability, routing orientation, operation placement, and flow sequences were obtained directly from the engineering teams. These data were imported into FACTS Analyzer using Excel-based input mapping and CAD-derived positional information.

Whenever uncertainties or mismatches arose, consultations were conducted with simulation and operations engineers to verify data correctness. No undocumented or unauthorised parameter adjustments were introduced.

The baseline model was constructed by creating all CB and CH operations in their original order, connecting them sequentially, and applying FIFO dispatching rules. Once all data were mapped, the baseline simulation was executed to verify that the model reproduces expected production behaviour (Appendix 4).

The reconfigured scenario was then developed within the same model structure by implementing shared-flow logic (Appendix 5). OP10, OP20, OP150, and OP220 were defined as shared resources, and additional routing paths were introduced only where reconfiguration was technically feasible. Buffer allocations were adjusted as necessary to support cross-line access. All modifications strictly followed engineering drawings and technical feasibility assessments.

Both the baseline and reconfigured scenarios were simulated for a total of 6 production days, including a 1-day warm-up period to remove transient variability. Each scenario was executed using 20 independent replications generated through FACTS Analyzer's automatic random-seed control. Key output metrics, including LT, TH, utilisation, and WIP, were collected using FACTS Analyzer's plant-output module and internal logging tools. The resulting datasets were exported in structured CSV format for subsequent analysis.

5.4.2 Optimisation Implementation

The optimisation phase was implemented by coupling the previously developed simulation models of the baseline and reconfigured CB and CH systems with the NSGA-II optimiser available in FACTS Analyzer. The purpose was to evaluate

system performance across variations in operational parameters that were explicitly defined within the model.

For each optimisation run, FACTS Analyzer generated candidate system configurations by varying selected parameters related to buffer capacities, processing times, machine availability, and MTTR. Each candidate configuration was automatically executed as a DES, and the resulting performance metrics were recorded. This procedure allowed the optimisation to capture the combined effects of parameter interactions such as blocking, starvation, and bottleneck shifts without relying on analytical approximations.

The primary optimisation objectives were:

1. Minimise LT, representing the system's ability to reduce waiting times and cycle delays.

2. Maximise TH, reflecting efficient utilisation of capacity and material flow.

WIP was monitored as a supporting performance indicator but was not treated as an optimisation objective. The following decision variables were selected and they represent realistic variations in machining environments while allowing the optimisation to evaluate the robustness of reconfiguration:

- Buffer capacities (1–60 units):
  Ranging from constrained (1) to generous (60) levels, enabling exploration of how buffering interacts with flow stability during reconfiguration.
- Processing-time ranges:
  - 50–60 s for single operations
  - 200–220 s for CH parallel groups
  - 280–320 s for CB parallel groups

  These ranges represent natural machining variability due to tool wear, load differences, and tolerance adjustments without distorting station characteristics.
- Availability levels (90–100%):
  Captures normal to high system uptime while avoiding unrealistic degradation.
- MTTR values (0–10 minutes):
  Model's variations in operator responsiveness and corrective maintenance delays, which strongly influence blocking patterns.

These ranges were selected to maintain physical realism while giving NSGA-II the freedom to explore layout sensitivity under diverse operational conditions.
The optimisation used the internal NSGA-II configuration of FACTS Analyzer, with the following settings:

- Population size: 50

- Maximum evaluations: 10,000
- Crossover probability: 0.8 (SBX crossover, distribution index 20)
- Mutation probability: 1.0 (scaled per variable)
- Mutation distribution index: 2
- Tournament size: 2
- Non-dominated archive: Enabled

These parameters were selected to balance exploration and convergence. The high mutation probability ensures adequate diversity across a large decision space, while SBX crossover preserves structure in promising solutions. The population size and evaluation limit were chosen to remain computationally feasible given the six-day simulation horizon, one-day warm-up, and 20 replications per candidate.

Both the baseline and reconfigured layouts were optimised using identical settings, ensuring a fair comparison. FACTS Analyzer executed each candidate solution and returned LT and TH values, which NSGA-II used to update the evolving Pareto front. Optimising across realistic variations in availability, MTTR, processing times, and buffering ensured that reconfiguration was evaluated not only in ideal conditions but across an entire operational envelope.

5.4.3 Comparison Method for MOO Results

To enable a valid and scientifically grounded comparison between the baseline and reconfigured system layouts, the optimisation outcomes are evaluated using a matched operating-point approach. This method is appropriate when Pareto fronts differ in shape, scale or distribution, and when direct point-to-point comparison risks producing misleading or invalid conclusions. By ensuring that solutions are compared only under equivalent operating conditions, matched operating-point analysis provides a transparent and defensible basis for interpreting trade-offs between objectives.

The NSGA-II algorithm generates sets of non-dominated solutions that represent different trade-offs between TH and LT. Points on one front do not necessarily correspond to similar operating conditions on another. For example, a baseline solution may achieve high TH but with a long LT, while a reconfigured solution may prioritise flow stability at a lower TH. Directly comparing such unrelated points would not represent the true performance differences of the underlying system designs.

The matched operating-point approach avoids this problem by aligning comparison conditions. This ensures that differences in LT or TH reflect the effect of the layout configuration rather than arbitrary differences between the

shapes of the fronts.The comparison goal is to evaluate the relative performance of the two system layouts by comparing LT at equal TH levels within the operational TH range, and to assess TH at equal LT levels as supplementary analysis across the overlapping portion of the fronts.

5.4.4 Matched Throughput Comparison

The primary analytical method compares LT performance at the same TH values. TH levels are selected from the overlapping region of the two Pareto fronts or from points where one layout provides exclusive solutions at a given operating level. For each TH value:

1. The corresponding LT value is identified on each Pareto front.

2. LT values are compared directly.

3. The configuration yielding the lower LT is regarded as superior under that specific operating condition.

This method directly addresses the main research objective, as it tests whether the reconfigured layout provides shorter LT at the TH levels that the plant realistically operates within.

5.4.5 Matched Lead-Time Comparison

A matched LT comparison is also applied to provide additional insight into global trade-off behaviour. In this analysis, TH values are compared at identical LT levels within the overlapping LT range of the two fronts. This reveals which layout delivers higher TH for the same process duration and clarifies the overall dominance pattern across the wider optimisation landscape. Although this comparison is informative, it is used only as secondary support because the main industrial question concerns LT performance at realistic TH values rather than the absolute TH limits of either layout.

The matched operating-point approach ensures that both systems are compared under equivalent conditions, making the evaluation methodologically valid and directly aligned with industrial practice. Because the comparison criteria are explicit and repeatable, the analysis becomes transparent while clearly revealing whether performance differences arise from the configurations themselves rather than from the shape of the Pareto fronts.

Matched TH comparison is used as the primary method, as it most directly corresponds to the industrial requirement of improving LT without reducing TH below operationally acceptable levels. Matched LT comparison is used as supporting analysis to contextualise the broader trade-off structure between the two layouts.

5.5 Validation of Simulation model

Validation was conducted to establish the credibility and analytical reliability of the developed simulation artefact rather than to empirically validate system-level performance outcomes. Due to the abstraction level of the model and industrial confidentiality constraints, full quantitative validation of the complete production system against real operational data was neither feasible nor methodologically meaningful.

In line with Design Science Methodology, validation therefore focused on walkthrough-based verification of correct model implementation, logical consistency, and industrial plausibility of the simulated behaviour. The validation strategy combined systematic inspection of model logic and event sequencing with structured expert walkthrough evaluation of the baseline configuration. Confidence interval analysis of selected Pareto solutions was applied solely to assess the precision of simulated performance estimates, not to perform statistical hypothesis testing or to validate optimisation dominance (Law, 2015;Carson, 2003; Sargent, 2013)

5.5.1 Verification Procedure

Verification was conducted to confirm that the baseline simulation model was correctly implemented and executed according to its specified logic prior to validation and evaluation. In line with established DES practice, verification focused on internal correctness rather than empirical comparison with production outputs. The procedure concentrated on logical consistency, event sequencing, and numerical stability of the implemented model. Process-time parameters, MTTR values, availability settings, routing rules, and buffer capacities were cross-checked against engineering specifications and consultation inputs provided by Aurobay. Model behaviour was systematically inspected using FACTS Analyzer's animation and event-trace functionality as part of a structured walkthrough of the simulation logic. This inspection verified correct entity routing, absence of deadlocks, stable queue behaviour, and consistent triggering of breakdown, repair, and restart events. Multiple test runs were executed under identical settings to confirm repeatability and stable model execution.

5.5.2 Walkthrough-Based Expert Validation Procedure

The baseline simulation model was validated using a structured, walkthrough-based expert evaluation approach. This form of validation is appropriate when the artefact represents a complex industrial system and when direct quantitative validation against full-scale operational data is not feasible.

Quantitative validation using real production data was not possible due to industrial confidentiality constraints. Detailed datasets required for statistical validation such as machine availability logs, disturbance records, and buffer state histories could not be disclosed or published. As a result, expert-based

walkthrough validation was adopted as the primary method for assessing model credibility.

Five domain experts were selected for the validation: three Aurobay manufacturing engineers with direct shop-floor experience of the CB and CH lines, one process planner responsible for layout and scheduling decisions, and one academic simulation researcher. The number of experts was intentionally limited, as qualitative validation prioritises depth and relevance of expertise over sample size. The available pool of experts with detailed system knowledge is inherently limited, and additional participants would not increase analytical validity.

The evaluation focused on four validation aspects:

1. system behaviour and flow logic,
2. reconfiguration logic feasibility,
3. realism of the TH and LT relationship, and
4. industrial usefulness.

These aspects were selected because they directly reflect the purpose and abstraction level of the simulation model. Other criteria were excluded as they were either outside the scope of the model or could not be reliably assessed within the available data and system representation.

Each expert independently rated each aspect using a three-level ordinal scale: Confirmed (2), Partially Confirmed (1), and Needs Adjustment (0). Expert agreement was calculated using a normalised weighted scoring approach:

$$\text{Agreement (\%)} = \frac{2N_c + 1N_p + 0N_n}{2N} \times 100 \quad (Equation\ 2)$$

where N_c, N_p, and N_n denote the number of Confirmed, Partially Confirmed, and Needs Adjustment ratings, respectively, and $N = 5$. This method preserves the ordinal nature of expert judgement while providing a transparent and reproducible consensus measure.

Walkthrough validation was applied only to the baseline model, as it represents the existing production system for which experts have direct operational experience (Miles et al., 2020).

5.5.3 Confidence Interval Analysis of Selected Pareto Solutions

The optimisation process in this thesis produces a set of Pareto-optimal solutions rather than a single deterministic outcome. Each Pareto solution represents a system configuration evaluated through DES under stochastic conditions, including random machine failures, variable processing times, and

queue interactions. As a result, the performance values obtained from simulation are estimates affected by random variability.

To quantify the reliability of these estimates, confidence interval (CI) analysis based on the student-t distribution is applied. The objective of this analysis is not to compare Pareto solutions statistically or to perform hypothesis testing, but to assess the precision of the estimated mean performance values associated with selected Pareto solutions. This provides transparency regarding the uncertainty inherent in SMO results and supports credible interpretation of the Pareto analysis (Carson, 2003).

The student-t distribution is appropriate when the true population variance is unknown and the number of simulation replications is limited. In this study, each selected Pareto solution for both base line and reconfigured line is evaluated using 20 independent simulation replications. Since the number of replications is below 30, the t-distribution provides a more conservative and statistically valid estimate of uncertainty compared with the normal distribution. A 95% confidence level is used throughout the analysis (Carson, 2003).

For each performance measure, the confidence interval is calculated as:

$$\bar{x} \pm t_{1-\alpha/2,\, n-1} \cdot \frac{s}{\sqrt{n}} \quad (Equation\ 3)$$

$\bar{x}$ is the sample mean obtained from n simulation replications, s is the sample standard deviation, n is the number of replications (here $n = 20$), and $t_{1-\alpha/2,\, n-1}$ is the critical value from the student-t distribution with $n - 1$degrees of freedom.

At a 95% confidence level, this interval indicates that there is a 95% probability that the true mean system performance lies within the reported bounds.

CI analysis is not applied to the Pareto front as a whole, since Pareto solutions are not independent samples and therefore do not satisfy the assumptions required for inferential statistical testing. Instead, three representative Pareto solutions are selected for each production layout: a low, a medium, and a high operating point along the Pareto front.

These points are chosen to represent different regions of the feasible performance space rather than extreme or optimal cases. The low point reflects operation under lower throughput conditions, the medium point represents intermediate operation, and the high point corresponds to operation near the upper throughput region. Selecting three Pareto points balances analytical clarity and coverage of operating regimes. Analysing more points would add redundancy without improving insight, while analysing fewer points would fail to capture variability across the performance space.

In SMO, Pareto analysis identifies trade-offs between competing objectives, while confidence interval analysis complements this by quantifying the robustness of individual Pareto solutions. These methods allow both structural performance trade-offs and stochastic variability to be evaluated. This strengthens the scientific credibility of the optimisation results and supports design science evaluation by demonstrating not only what performance is achievable, but also how reliable those estimates are under stochastic conditions.

6 Industrial Results

This chapter reports the performance outcomes obtained from the simulation-based evaluation and optimisation of the baseline and reconfigured CB and CH production layouts. System behaviour is examined through DES to quantify the objectives at plant and line levels. The optimisation results characterise the trade-off between TH and LT using Pareto-optimal solutions derived from the simulation model. The credibility of the simulation artefact is supported through Walkthrough-Based Expert Validation Procedure for the baseline configuration and CI analysis of selected pareto points. All numerical values are taken directly from executed simulation and optimisation runs, and all figures represent outputs generated by FACTS Analyzer and the optimisation environment.

6.1 Simulation of Baseline

Table 10 Simulation Results of the baseline production system

Metric	Plant	CB Line	CH Line
Throughput (units/day)	114.99	54.36	60.63
Lead Time (s)	3484	3838	3167
WIP (units)	120.30	57.95	53.36
Produced Parts (total)	13 799	6523	7 276

Table 10 shows the results Obtained from the simulation of baseline model. Plant-level TH is higher than the two individual lines, with CH producing slightly more units than CB. LT values for the plant, CB and CH fall within the same general range, with CB being the fastest and CH slightly slower. WIP is highest at plant level, while CB and CH hold similar but lower inventory levels.

Total produced parts follow the same pattern, with the plant output exceeding both lines and CH producing more than CB.

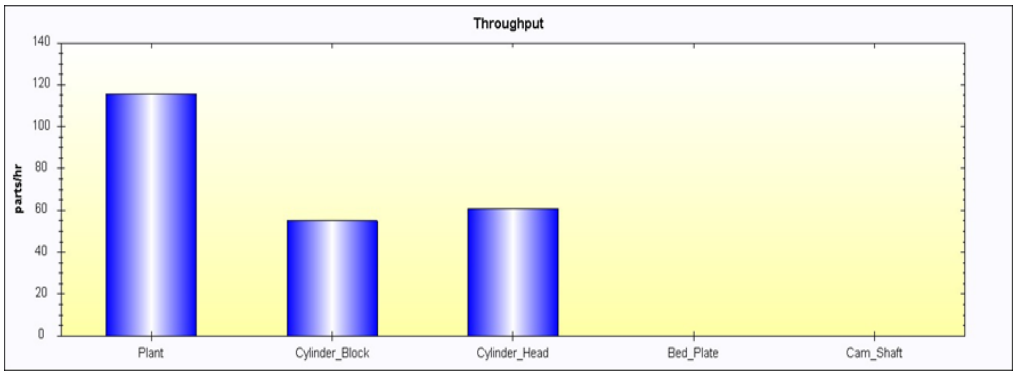

Figure 15 Throughput of the Baseline Production System

Figure 15 illustrates the TH performance of the overall plant during the simulation of baseline model. The CB and CH lines both achieve noticeably lower TH than the plant, with the two lines displaying similar output patterns.

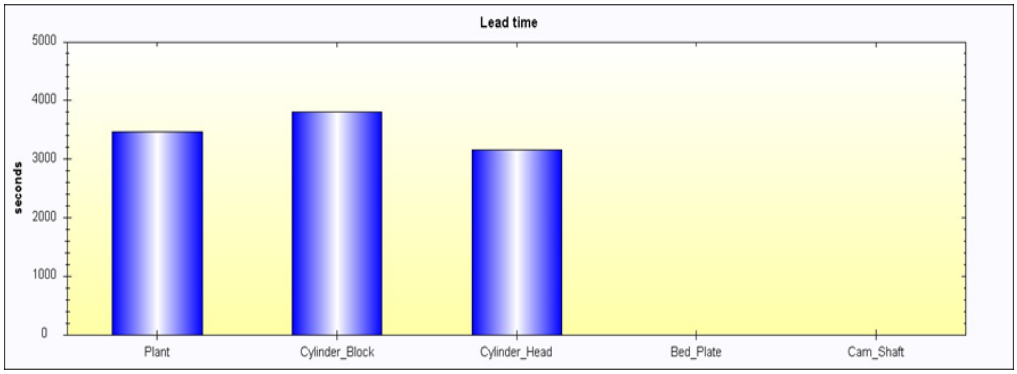

Figure 16 Lead Time of the Baseline Production System

Figure 16 presents LT values for the baseline during the simulation of baseline model. The plant-level LT lies within the same order of magnitude as the individual production lines. Among the lines, the CB exhibits the highest LT, while the CH shows a lower value, indicating moderate variation between line-specific processing durations under baseline conditions.

6.2 Simulation of the Reconfigured Line

Table 11 Simulation Results of Reconfigured line

Metric	Plant	CB Line	CH Line
Throughput (units/day)	102.62	51.33	51.29
Lead Time (s)	3210	3628	2791
WIP (units)	100.9	51.70	39.78

Produced Parts (total)	12 315	6 160	6 154

Table 11 summarises the results obtained during simulation of reconfigured line model. Plant-level TH remains higher than either line, following the same pattern as in the baseline case. LT values differ more noticeably between the two lines, with CH showing a shorter processing duration than CB. WIP is lowest on the CH line, higher on the CB line, and highest at plant level. The total number of produced parts follows the same distribution, with the plant output exceeding both lines and CH and CB delivering nearly identical totals.

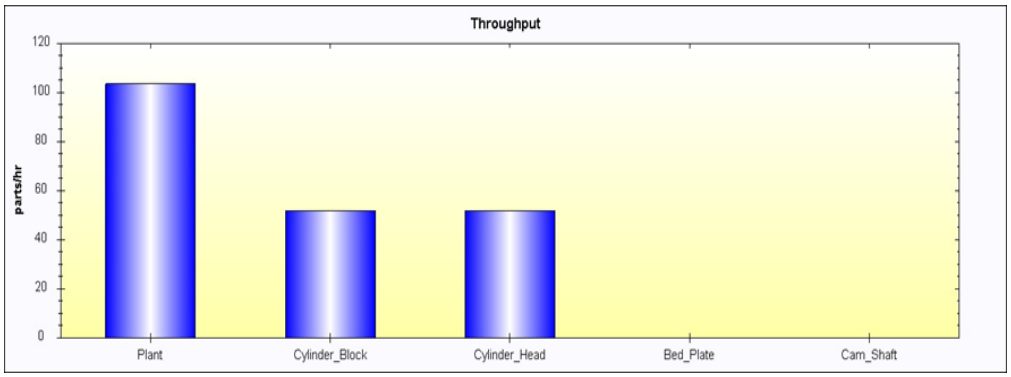

Figure 17 Throughput of the Reconfigured Production System

Figure 17 illustrates the plant's TH distribution during the simulation of reconfiguration line model. The CB and CH lines display identical TH, with both bars reaching the same height.

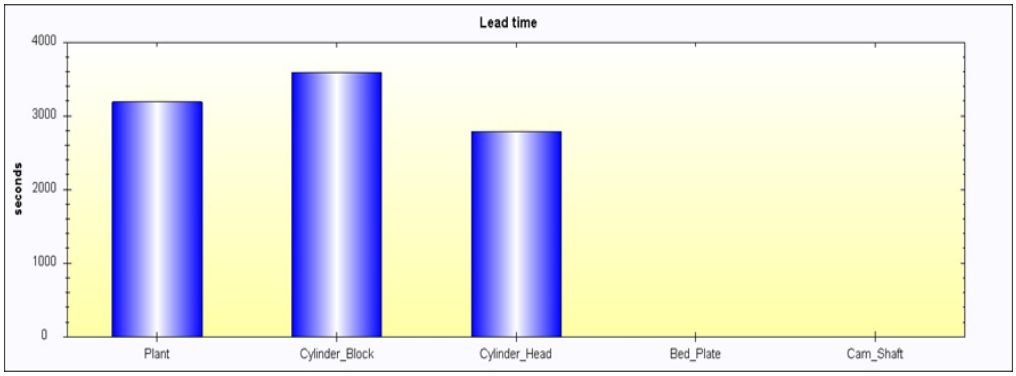

Figure 18 Lead Time of the Reconfigured Production System

Figure 18 presents the LT distribution of reconfiguration line during simulation of reconfigured line model. A notable reduction in LT is observed at the plant level compared to the baseline. The CH line continues to maintain a relatively low and stable LT, while CB LT slightly increased.

6.3 Simulation Comparison of Baseline and Reconfigured Metrics

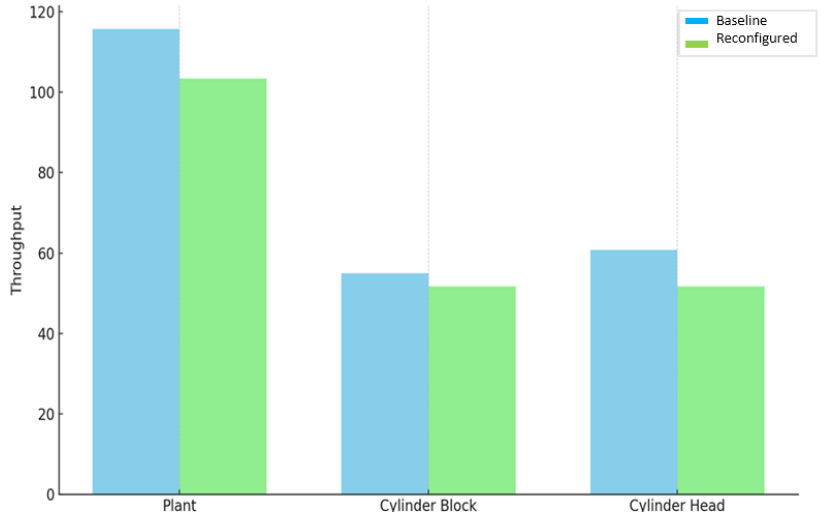

Figure 19 Comparison of Throughput before and after Reconfiguration during simulation

Figure 19 represents a comparative analysis of TH across the plant, CB, and CH lines under the simulation of baseline model and simulation of reconfigured line model. The plant shows a visibly higher TH in the baseline layout, with the reconfigured bar positioned lower. Both the CB and CH lines follow the same pattern, where the baseline layout maintains slightly higher TH than the reconfigured layout.

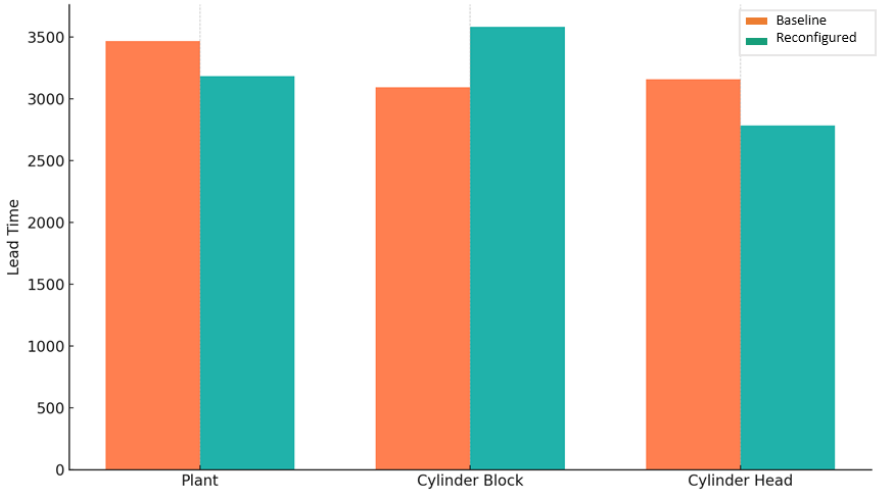

Figure 20 Comparison of Lead Time Before and after Reconfiguration during simulation

Figure 20 represents a comparative analysis of LT across the plant, CB, and CH lines under the simulation of baseline model and simulation of reconfigured line model. At plant level, the reconfigured layout shows a lower bar height, indicating shorter LT compared to the baseline. For the CB line, LT is higher the reconfigured layout, showing an increase relative to the original layout. The CH

line displays the opposite pattern, with the LT is noticeably lower in the reconfigured layout.

6.4 Walkthrough Validation of Simulation Results

The simulation outputs were further analysed through the walkthrough validation framework to ensure the credibility and reliability of the obtained results. This procedure provided a structured basis for interpreting the model's performance under baseline scenario.

6.4.1 Walkthrough-Based Expert Validation of the Baseline Model

The expert-based validation produced strong consensus that the baseline simulation artefact realistically represented the behaviour of the production system and provided meaningful analytical value. Table 12Table 12 summarises the consensus levels obtained from expert evaluations.

Table 12 Expert Consensus on Qualitative Validation of the Simulation Artefact

Validation Aspect	Confirmed (2)	Partially Confirmed (1)	Needs Adjustment (0)	Agreement (%)
System Behaviour and Flow Logic	4	1	0	90%
Reconfiguration Logic Feasibility	3	2	0	80%
Throughput–Lead-Time Relationship	4	1	0	90%
Industrial Usefulness	5	0	0	100%

System behaviour and flow logic achieved 90 % agreement, confirming that simulated queues, resource utilisation, and flow dynamics closely reflect observed shop-floor behaviour. Reconfiguration logic feasibility achieved 80 % agreement, indicating that shared operations were considered technically feasible within existing equipment constraints, with abstraction effects acknowledged. The TH and LT relationship achieved 90 % agreement, reflecting expert confirmation that increased TH accompanied by moderately higher LT and WIP is realistic under elevated load conditions. Industrial usefulness achieved 100 % agreement, demonstrating unanimous confidence in the artefact as a decision-support tool for evaluating future reconfiguration scenarios.

6.5 Optimisation Results

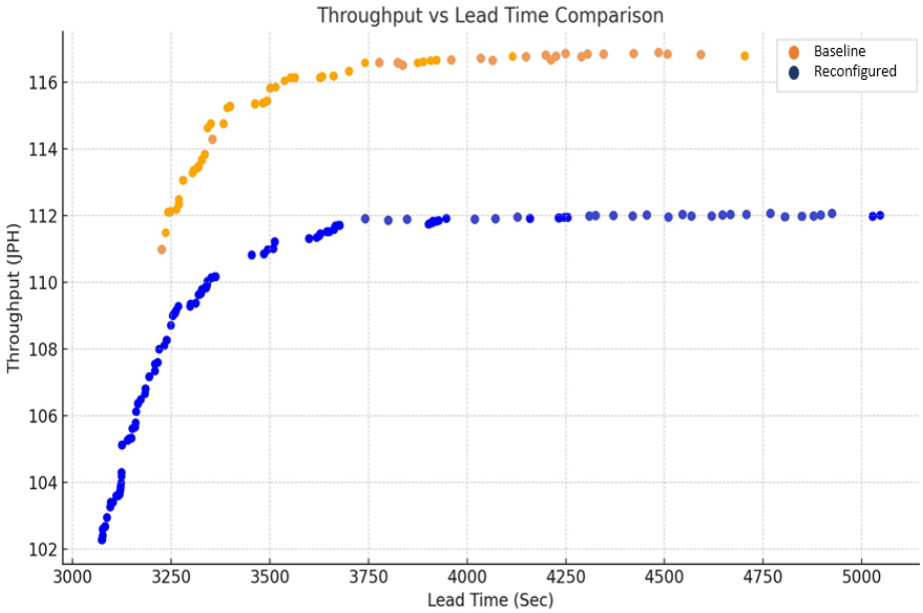

Figure 21 Optimisation results of possible improvement on Throughput vs Lead time

Figure 21 presents the non-dominated TH and LT solutions generated by NSGA-II for both the baseline and reconfigured layouts using the decision-variable ranges and optimisation settings. Each point represents a single evaluated candidate within the 10000-evaluation search process.

For the baseline layout, the optimiser produced Pareto-optimal solutions with:

- TH: approximately 112–117 units/day
- LT: approximately 3150–4650 s

For the reconfigured layout, NSGA-II identified Pareto-optimal solutions with:

- TH: approximately 102–112 units/day
- LT: approximately 3050–5100 s

The resulting distribution shows two clear patterns:

1. **Lower-LT region:** dominated by the reconfigured solutions, indicating that selective sharing of OP10, OP20, OP150 and OP220 enables shorter LT under multiple combinations of availability, MTTR, process-time variation and buffer levels.

2. **Upper-TH region:** dominated by the baseline layout, confirming that the dedicated flow preserves slightly higher maximum TH when pushed to its limits.

Both fronts exhibit considerable spread and diversity, reflecting the large decision space created by the selected parameter ranges (buffers 1–60 units, process-time variability, availability 90–100%, MTTR 0–10 min). The clustering indicates reduced dispersion of Pareto solutions within the explored parameter ranges, highlighting how optimisation reveals structured trade-off patterns beyond isolated deterministic simulation runs.

6.5.1 Matched Operating-Point Comparison of Pareto Solutions

During the analysis of the optimisation results, it became evident that the Pareto fronts of the baseline and reconfigured layouts occupy different regions of the trade-off space, with several solutions existing in non-overlapping domains. Under these conditions, inferential statistical tests were deliberately excluded, as Pareto-optimal solutions are not independent samples and violate the assumptions required for parametric testing.

The comparison is structured around two explicit goals. The primary goal is to evaluate whether the reconfigured layout reduces LT at the same TH levels, as this directly reflects the plant's operational requirement to improve flow without sacrificing production rate. The secondary goal is to compare TH at equal LT levels to understand the broader trade-off structure and determine which layout provides superior output for the same process duration. Both comparisons rely exclusively on the overlapping regions of the two Pareto fronts to ensure that all matched points represent valid and equivalent operating conditions.

6.5.2 Matched Throughput Comparison (Equal TH Levels)

Table 13 shows the LT of the baseline and reconfigured layouts at identical TH levels, using only non-dominated solutions from the NSGA-II Pareto fronts. The selected TH levels reflect the plant's operational TH window, where reconfiguration is expected to influence flow behaviour. For each TH value reported, the corresponding LT was extracted directly from the Pareto solutions of each layout. If a layout did not contain a Pareto solution at the specified TH level, it was reported as having no feasible matched solution for that operating point. This approach prevents invalid comparisons between different regions of the trade-off space and ensures that LT differences are interpreted under equivalent output conditions.

Using this procedure, the reconfigured layout provides feasible solutions in the range 102–112 units/day with LT values between 3050 and 3500 s, while the baseline layout provides feasible solutions from 112–116 units/day with LT

values between 3230 and 3540 s. This distribution shows that the two fronts intersect at 112 units/day, while each layout dominates different operating regions outside that point.

Table 13 Lead Time at Equal Throughput Levels

Throughput (units/day)	**LT Reconfigured (s)**	**LT Baseline (s)**	**Difference (s)**	**Better Layout**
102	3050	–	Reconfigured only	Reconfigured
103	3075	–	Reconfigured only	Reconfigured
104	3085	–	Reconfigured only	Reconfigured
105	3100	–	Reconfigured only	Reconfigured
106	3125	–	Reconfigured only	Reconfigured
107	3150	–	Reconfigured only	Reconfigured
108	3200	–	Reconfigured only	Reconfigured
109	3250	–	Reconfigured only	Reconfigured
110	3300	–	Reconfigured only	Reconfigured
111	3400	–	Reconfigured only	Reconfigured
112	3500	3230	+400 (Reconfigured slower)	Baseline
113	–	3290	Baseline only	Baseline
114	–	3345	Baseline only	Baseline
115	–	3440	Baseline only	Baseline
116	–	3540	Baseline only	Baseline

Across 102–111 units/day, only the reconfigured layout provides feasible Pareto solutions, indicating that it achieves lower LT operation within this TH region. At 112 units/day, both layouts are feasible and the baseline layout achieves a lower LT. Above 112 units/day, only the baseline layout provides feasible high-TH Pareto solutions, showing that it retains an advantage when maximising output is prioritised over lead-time reduction.

6.5.3 Matched Lead-Time Comparison

Table 14Table 14 presents the TH values of both layouts at equal LT levels selected from the overlapping region of the two Pareto fronts (3050–4700 s). This comparison enables a direct assessment of output performance under equivalent process durations and complements the matched TH analysis presented earlier. For each LT value listed in Table 14, the corresponding TH was obtained by selecting the closest non-dominated Pareto solution available for each layout. If no feasible solution existed at a given LT level, the corresponding layout was reported as having no matched solution. This selection procedure ensures that the TH differences arise from comparable operating conditions on the Pareto fronts rather than from unrelated regions of the objective space.

Table 14 Throughput at Equal Lead-Time Levels

Lead Time (s)	TH Reconfigured	TH Baseline	Difference	Better Layout
3050	102.0	–	Reconfigured only	Reconfigured
3100	105.0	–	Reconfigured only	Reconfigured
3150	106.7	–	Reconfigured only	Reconfigured
3200	108.0	–	Reconfigured only	Reconfigured
3250	109.0	112.5	Baseline +3.5	Baseline
3300	110.0	113.2	Baseline +3.2	Baseline
3350	110.6	114.0	Baseline +3.4	Baseline
3400	111.0	114.6	Baseline +3.6	Baseline
3450	111.3	115.0	Baseline +3.7	Baseline
3500	112.0	115.5	Baseline +3.5	Baseline
3600	111.9	116.2	Baseline +4.3	Baseline
3800	111.8	116.8	Baseline +5.0	Baseline
4000	111.8	117.0	Baseline +5.2	Baseline
4300	111.7	116.9	Baseline +5.2	Baseline

4700	111.6	116.6	Baseline +5.0	Baseline

For every matched LT level, the Baseline layout consistently delivers higher TH, confirming its advantage as a high-output configuration. These high-TH solutions occur in a region of the objective space that extends beyond the plant's typical operating conditions. The reconfigured layout provides lower-TH solutions at the same LT levels but offers locally favourable LT behaviour within a limited low-to-medium TH regime.

6.5.4 Confidence Interval Analysis of Selected Pareto Solutions

CI analysis was conducted for three representative Pareto solutions of both the baseline and reconfigured production layouts. Each configuration was evaluated using 20 independent simulation replications, and 95% confidence intervals were calculated using the student-t distribution (Carson, 2003).

Table 15 Baseline layout: confidence interval results for selected Pareto solutions (n = 20)

Pareto level	Mean TH	Std dev TH	95% CI TH	Mean LT	Std dev LT	95% CI LT
Low	112.11	0.225	[112.00, 112.21]	3230	45.66	[3208.64, 3251.36]
Mid	114.76	0.663	[114.45, 115.07]	3345	82.88	[3306.22, 3383.78]
High	116.80	0.506	[116.56, 117.04]	3540	86.69	[3499.43, 3580.57]

Table 15 shows the CI analysis of the baseline layout in which TH confidence intervals are narrow across all Pareto regions, indicating stable output performance under stochastic variability. LT exhibits wider confidence intervals at the medium operating point, reflecting increased sensitivity to congestion effects under intermediate load conditions.

Table 16 Reconfigured layout: confidence interval results for selected Pareto solutions (n = 20)

Pareto level	Mean TH	Std dev TH	95% CI TH	Mean LT	Std dev LT	95% CI LT
Low	102.28	1.186	[101.73, 102.84]	3050	70.94	[3016.81, 3083.19]
Mid	107.17	1.348	[106.54, 107.80]	3150	58.37	[3122.69, 3177.31]

High	112.02	1.314	[111.40, 112.63]	3500	68.64	[3467.89, 3532.11]

Table 16 shows the CI analysis of the of the reconfigured layout in which TH confidence intervals are consistently wider than those of the baseline layout, suggesting greater sensitivity to stochastic effects introduced by the reconfigured routing structure. LT variability increases substantially at the high Pareto operating point, indicating reduced flow stability under higher throughput conditions.

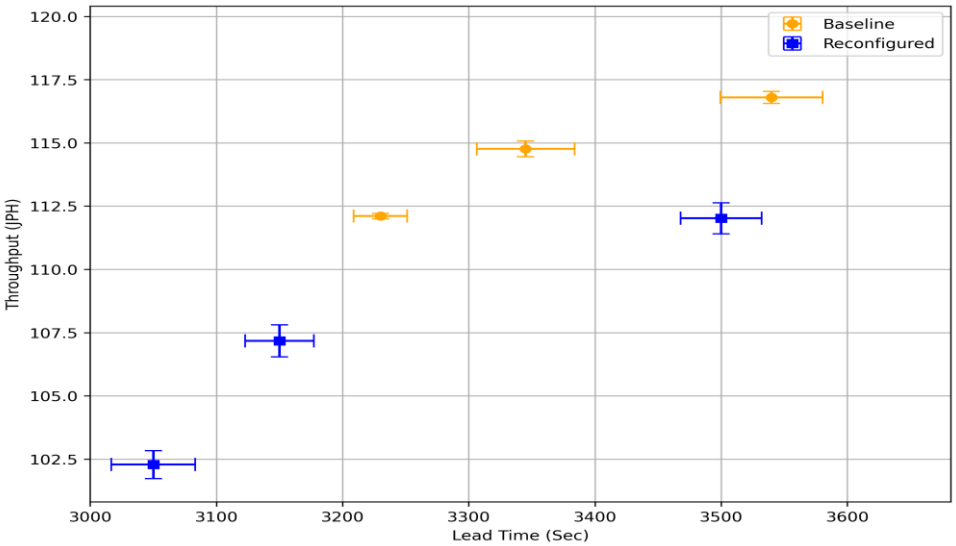

Figure 22 Throughput–Lead Time Trade-off with 95% Confidence Intervals

The Figure 22 shows selected Pareto-optimal operating points for the baseline and reconfigured production layouts, plotted in terms of TH and LT. Each point represents the mean value obtained from 20 simulation replications, while the horizontal and vertical bars indicate the corresponding 95% confidence intervals based on the student-t distribution. The visualisation highlights differences in performance stability and variability between the two layouts across low, medium, and high operating regions.

The CI widths are reasonable given the stochastic nature of the system and the use of 20 replications. Narrow intervals indicate reliable mean estimates, while wider intervals highlight operating regions where performance is more sensitive to variability. The confidence intervals do not serve as hypothesis tests between layouts. Instead, they indicate the precision of the estimated performance values and support cautious interpretation of observed differences in the Pareto analysis.

7 Sustainability

This study demonstrates sustainability impacts through measurable improvements in operational performance achieved via simulation-based analysis and optimisation. Sustainability is addressed strictly in terms of efficiency, economic robustness, and responsible industrial decision-making. The results show that meaningful sustainability-relevant outcomes can be evaluated at the system level using digital models before physical changes are introduced.

From an environmental perspective, the simulation and optimisation results indicate that reductions in LT and WIP can be achieved at selected operating points without increasing production capacity or adding new equipment. Shorter LT and lower congestion imply reduced idle running, fewer blocking events, and more stable machine utilisation, which in turn lowers indirect energy consumption associated with non-value-added operation. By avoiding capacity expansion and additional infrastructure, the evaluated scenarios also prevent environmental impacts typically linked to new machine installation and supporting systems. These outcomes support SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action) by demonstrating how digital optimisation can improve industrial efficiency while limiting unnecessary resource use.

Economic sustainability is reflected in the study's demonstration that performance trade-offs between TH, LT, and WIP can be analysed and improved through operational redesign rather than capital investment. Even where the baseline production line dominates the reconfigured alternative on the Pareto front, the results remain economically relevant by identifying feasible operating regions, exposing system sensitivity to availability, repair times, and buffer sizing, and clarifying the cost implications of flexibility. The ability to evaluate these effects through simulation reduces financial risk and supports informed decision-making, aligning with SDG 8 (Decent Work and Economic Growth) (Carlsen & Bruggemann, 2022).

Within the context of the REFUSE project, the contribution of this thesis lies in providing qualitative, decision-oriented evidence rather than conceptual sustainability claims. The work demonstrates how simulation and MOO can be used to assess efficiency, robustness, and performance stability under realistic industrial constraints and confidentiality limitations. Sustainability is therefore addressed through validated analytical methods that support responsible industrial planning rather than through assumed environmental benefits. The study adheres to responsible engineering and research ethics by limiting sustainability claims to what can be directly supported by simulation outputs.

8 Discussions

The results of this study reveal a clear distinction between the behaviour observed in the conceptual models and the performance of the industrial CB–CH production system. While the conceptual optimisation results (Figures 9 and 10) demonstrate that flexible routing can reduce LT under controlled and idealised conditions, the industrial simulation and optimisation results (Figure 21) consistently indicate that the baseline layout dominates the reconfigured layout across most of the feasible operating envelope.

The simulation results already indicate this dominance. Under identical simulation settings, input parameters, and replication conditions, the baseline layout achieves a higher plant-level TH (114.99 units/day) than the reconfigured layout (102.62 units/day). Because processing times, machine availability, MTTR, and buffer configurations were held constant, this reduction in TH cannot be attributed to parameter changes. Instead, it arises directly from the structural consequences of reconfiguration, specifically the introduction of shared assembly and verification operations between the CB and CH lines.

In the baseline configuration, the two production lines operate with dedicated verification and assembly resources, allowing local variability to be absorbed within each line. The reconfigured layout removes this decoupling by introducing shared stations, which increases coordination requirements and exposes both flows to mutual interference. As utilisation rises, these shared resources become contention points, increasing waiting times and blocking effects. This reduces the system's ability to sustain high output rates, thereby lowering achievable TH despite unchanged nominal capacity.

Line-level simulation results further explain this outcome. The CH line benefits from reconfiguration due to its shorter and more compact process chain, showing reduced LT and lower WIP under shared routing. In contrast, the CB line exhibits increased LT in the reconfigured layout, primarily due to contention at shared verification stages. Given the CB line's longer and more complex processing sequence, delays at shared resources propagate upstream, amplifying flow disruption and reducing effective TH at the plant level. Local improvements in one line are offset by degradation in the other, preventing system-level performance gains.

The optimisation results reinforce the simulation findings. The Pareto front of the baseline layout dominates that of the reconfigured layout across medium-to-high TH regions. At equal TH levels within the overlapping feasible range, the baseline layout consistently achieves equal or lower LT. Many reconfigured Pareto points are therefore strictly dominated, providing neither TH nor lead-time advantages.

The contrast with the conceptual study is instructive rather than contradictory. The conceptual models assume symmetric servers, balanced process chains, and simplified routing logic. Under these assumptions, flexibility improves flow

synchronisation without affecting TH. The industrial CB and CH system, however, it is characterised by heterogeneous process chains, uneven bottleneck placement, and tightly constrained verification operations. In such a system, flexibility improves responsiveness at lower load levels but introduces coordination losses that limit scalability under high utilisation.

Walkthrough-based expert validation supports the major findings by confirming that the simulated behaviour, queue formation, blocking effects, and TH and LT time trends matches industrial expectations for the baseline system. Confidence intervals were used only to describe variability across replications for selected solutions, not to claim statistical superiority or to validate optimisation dominance.

9 Limitations

The scope of this research was confined to simulation-driven analysis and did not include physical implementation or live production trials. While the developed models in FACTS Analyzer accurately represent the operational logic and performance trends of CH and CB production systems, they remain abstractions of reality. Factors such as operator fatigue, maintenance scheduling, and micro-level variations in material flow were simplified to maintain computational tractability.

The study employed deterministic assumptions for certain routing and buffer parameters, whereas actual shop-floor behaviour is subject to stochastic variations. The model did not incorporate detailed energy or cost accounting due to the absence of continuous resource metering at the line level. The evaluation of sustainability therefore focused on qualitative indicators such as equipment reuse and process efficiency rather than precise carbon or energy balances.

The selection of operations for reconfiguration was limited to those verified as technically viable within the existing plant layout and data availability. Alternative configurations are particularly those requiring new tooling, automation upgrades, or redesign of logistics paths were excluded. Consequently, the results represent potential performance improvements achievable within current resource boundaries rather than guaranteed industrial outcomes.

These limitations define the scientific boundaries of the research and provide direction for future work involving hybrid validation, energy metering, and pilot-scale reconfiguration trials.

10 Future Work

This study offered valuable directions for future research and artefact enhancement. In accordance with the DSM, further work should focus on

refining the simulation-driven artefact through iterative development, real-world data integration, and cross-domain validation. Future studies should incorporate real-time data acquisition and sensor integration to overcome the current reliance on static simulation inputs. Establishing connectivity with the Manufacturing Execution System (MES) or factory data layer would enable continuous data exchange between the physical and digital systems. This enhancement would transform the current simulation model into a near real-time digital twin capable of adaptive feedback control, dynamic scheduling, and predictive optimisation.

Addressing the deterministic assumptions made in this study also represents an important research avenue. Future work should include stochastic variations in routing logic, operator availability, and machine reliability to more accurately capture shop floor uncertainty. Introducing probabilistic modelling and agent-based simulation could enhance the model's realism and allow better generalisation of performance outcomes. To overcome the absence of energy and resource tracking, subsequent studies should integrate detailed energy metering and environmental data collection. Embedding metrics such as energy consumption, carbon intensity, and equipment utilisation efficiency within the simulation environment would allow quantitative evaluation of the sustainability benefits arising from reconfiguration. These data-driven insights would strengthen the environmental credibility of the framework and align with industrial sustainability objectives.

Expanding the modelling scope beyond the selected shared would provide a more comprehensive understanding of system-level reconfigurability. Future research could test additional hybrid configurations that include auxiliary subsystems such as material handling, inspection, or rework loops. Such exploration would reveal new combinations of reconfigurable pathways and contribute to the scalability assessment of the proposed approach.

11 Ethical Considerations

This research adhered strictly to recognised ethical standards, ensuring transparency, data protection, inclusivity, and responsible societal impact. All simulation inputs were derived from anonymised and non-sensitive operational data, including generalised layout and process information from Aurobay. No personal, employee-specific, or proprietary production details were accessed, thereby maintaining both industrial confidentiality and academic integrity.

The simulation models were developed entirely within the FACTS Analyzer platform, ensuring that all configuration assumptions, behavioural logic, and performance metrics were traceable, reproducible, and well documented. This transparency upheld the principles of scientific rigour and accountability by allowing other researchers or industrial partners to replicate and validate the findings independently.

Beyond methodological ethics, the study acknowledged social and gender-related dimensions associated with manufacturing reconfiguration. Structural changes to production layouts could influence how workers interacted with equipment and processes. To mitigate these effects, the use of simulation served as both a technical and collaborative tool. By visualising proposed reconfigurations in a digital environment, engineers and operators regardless of technical background or experience were able to engage meaningfully in evaluation and decision-making prior to any physical modification. This participatory approach reduced uncertainty, encouraged inclusivity, and promoted equitable involvement in industrial transitions.

From a gender perspective, the reliance on digital simulation reduced dependence on physically demanding or traditionally male-dominated reconfiguration tasks. By shifting focus from physical prototyping to digital analysis and system evaluation, the research provided an accessible and balanced platform for both men and women to contribute to process innovation. While this did not eliminate deeper structural inequities within industry, it demonstrated a practical pathway for promoting diversity and inclusivity in manufacturing development.

At a broader ethical level, the study recognised the limitations inherent in simulation-driven research. Digital experiments provided valuable insights into flow dynamics, performance trade-offs, and system bottlenecks; however, they could not fully capture complex real-world conditions such as operator fatigue, random breakdowns, or energy fluctuations. It was therefore the researcher's responsibility to communicate these boundaries clearly to industrial stakeholders, ensuring that simulation outcomes were interpreted as informative guidance rather than absolute predictions.

All assumptions, simplifications, and omissions including the absence of direct energy measurements were explicitly documented. This transparency prevented overstatement of results and ensured that conclusions remained proportionate to available evidence. By embedding ethical reflection and openness throughout the study, the research upheld responsible engineering practice and reinforced the integrity of its scientific and societal contribution.

11.1 Ethical Risks and Mitigation Strategies

This research considered and addressed several ethical risks. A primary concern involves the potential misapplication or overgeneralisation of simulation results to real world scenarios. Although the models are grounded in realistic production data, they remain conceptual and cannot substitute physical validation. To mitigate this, all assumptions and limitations are clearly documented, and no prescriptive recommendations are made without further empirical testing.

Another ethical dimension relates to equitable access. Reconfigurable strategies are often assumed to be feasible only for well-resourced manufacturers. This study counters that assumption by indicating how flexibility can be explored

digitally without costly physical trials, thus making process optimisation more accessible to resource constrained facilities and promoting broader adoption of digital transformation tools.

While no human participants were directly involved, the study remains sensitive to the downstream workforce implications of its findings. Reconfigurable systems may shift job roles or require new skill sets, making it ethically imperative to acknowledge the need for inclusive upskilling. The project underscores the importance of preparing the workforce for change, advocating for training strategies that prevent marginalisation and support smooth transitions. Simulation previews were not only sufficient for validating technical feasibility but also for ensuring that transitions can be understood, practiced, and socially accepted before implementation.

Taken together, this research has carefully identified and addressed ethical concerns like data integrity, transparency, risk of overgeneralisation, social concerns like workforce disruption, inclusivity, accessibility, and gender related concerns like equal participation, reduced barriers to involvement in technical change. Each of these issues was not only acknowledged but addressed through concrete actions: transparent modelling, participatory simulation, inclusive design logic, and explicit recognition of limitations. These measures are sufficient because they both anticipate potential risks and provide practical safeguards against them, ensuring that the research contributes responsibly to both industrial practice and wider society.

12 Conclusion

This thesis investigated the impact of production-flow reconfiguration on the trade-off between TH and LT in the CB and CH production systems at Aurobay Technologies. Using a DSM, DES models were developed in FACTS Analyzer to represent both the existing dedicated layout and a reconfigured shared-flow alternative. SMO using NSGA-II was applied to evaluate system behaviour across a realistic industrial operating envelope without introducing new production resources.

The results demonstrate that the dedicated baseline layout remains the dominant configuration across most industrially relevant operating conditions. Although the reconfigured layout produces feasible solutions in limited low-to-medium TH regimes, it exhibits reduced maximum TH capability and does not outperform the baseline when TH is prioritised. The optimisation analysis confirms that many reconfigured solutions are strictly dominated and that any LT improvements achieved through reconfiguration are obtained at the expense of output capacity.

The research question is therefore answered with a qualified outcome: production-flow reconfiguration can influence LT behaviour under specific operating conditions, but it does not provide general performance

improvements over a dedicated layout in a tightly constrained, high-volume engine manufacturing system.

From a methodological perspective, the study confirms the necessity of SMO for evaluating reconfiguration strategies. The combined use of DES and Pareto-based analysis enables transparent identification of trade-offs that cannot be inferred from deterministic reasoning or isolated simulation runs. The developed simulation artefact provides a specific, decision-support basis for assessing when reconfiguration is feasible and when dedicated configurations should be retained.

The results provide evidence-based guidance for reconfiguration decisions under the REFUSE project. Rather than assuming flexibility to be inherently beneficial, the study demonstrates the importance of evaluating structural changes against realistic operating constraints. Reconfiguration should therefore be applied selectively and conditionally, supported by walkthrough validation, rather than as a general strategy for performance improvement.

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Appendix 1: Nomenclature

AGV – Automated Guided Vehicle

CB – Cylinder Block

CH – Cylinder Head

CI – Confidence Interval

DES – Discrete Event Simulation

DSM – Design Science Methodology

EPT – Effective Processing Time

FACTS Analyzer – Factory Conceptual Design Simulation Tool

JIT – Just-In-Time

KPI – Key Performance Indicator

LT – Lead Time

MAPE – Mean Absolute Percentage Error

MES – Manufacturing Execution System

MTTR – Mean Time to Repair

MOO – Multi-Objective Optimisation

NSGA-II – Non-Dominated Sorting Genetic Algorithm II

OP – Operation Code

RMS – Reconfigurable Manufacturing System

SMO – Simulation-Based Multi-Objective Optimisation

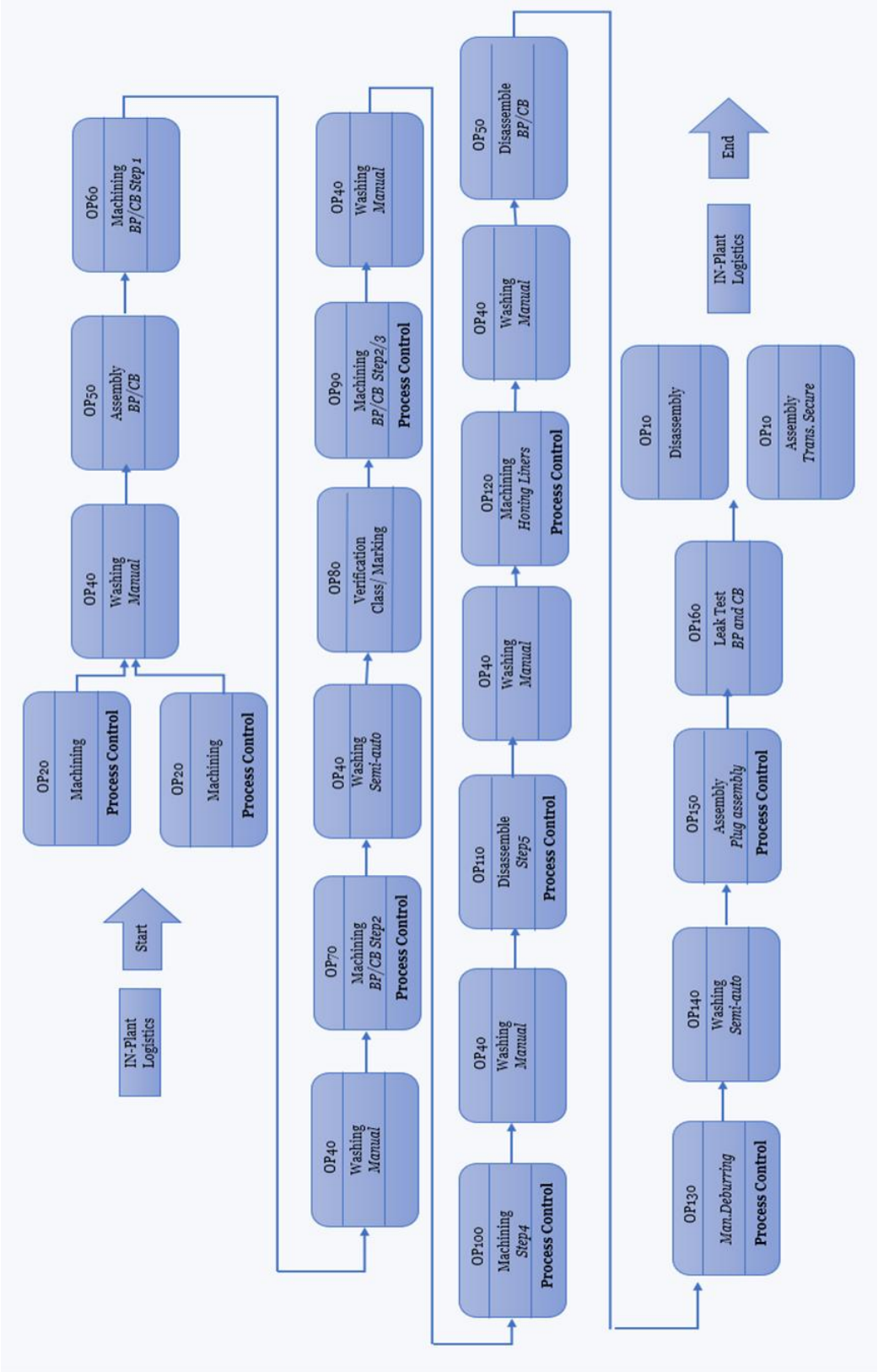
SDG – Sustainable Development Goal

TH – Throughput

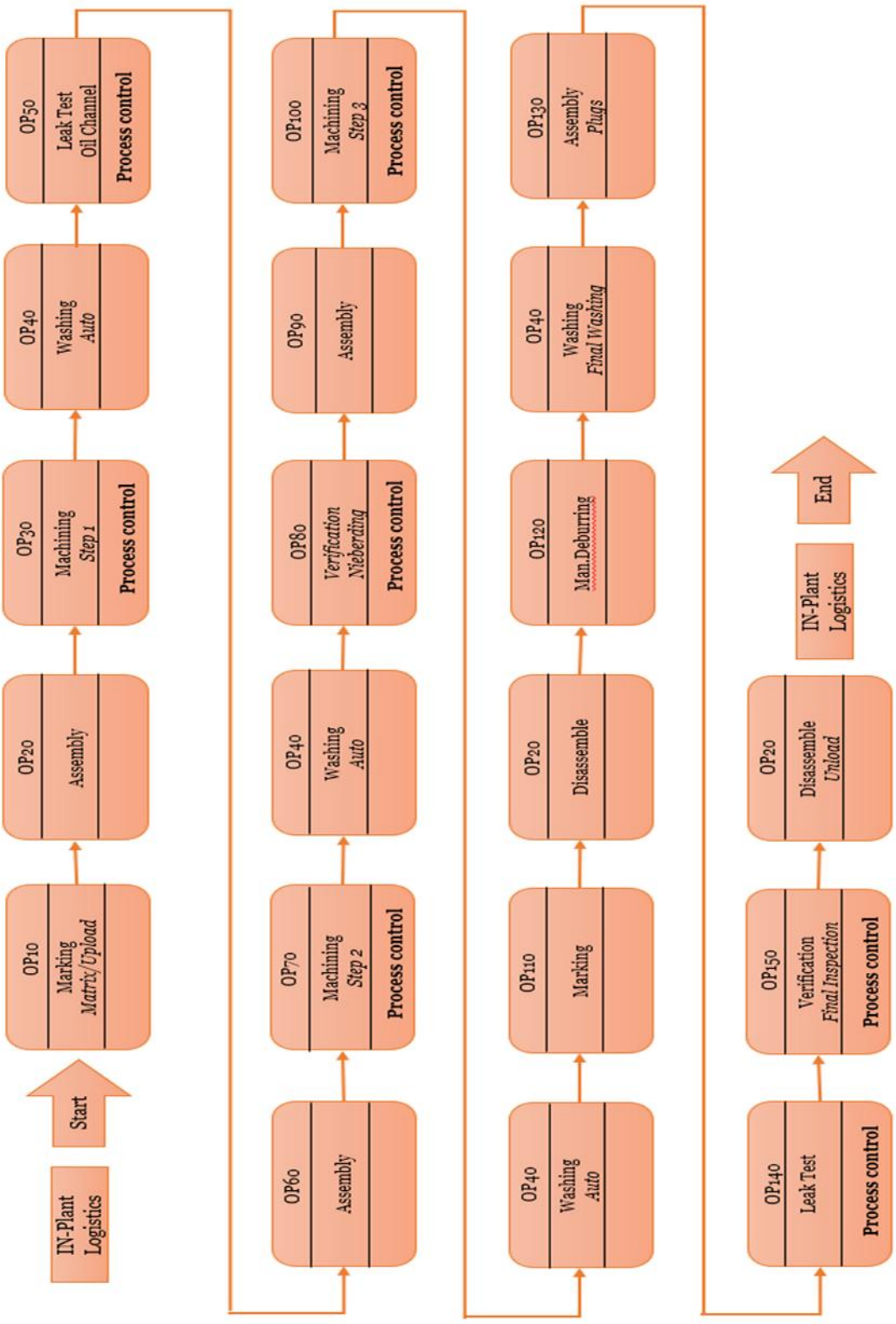
TNB – Total Number of Buffers

WIP – Work in Progress

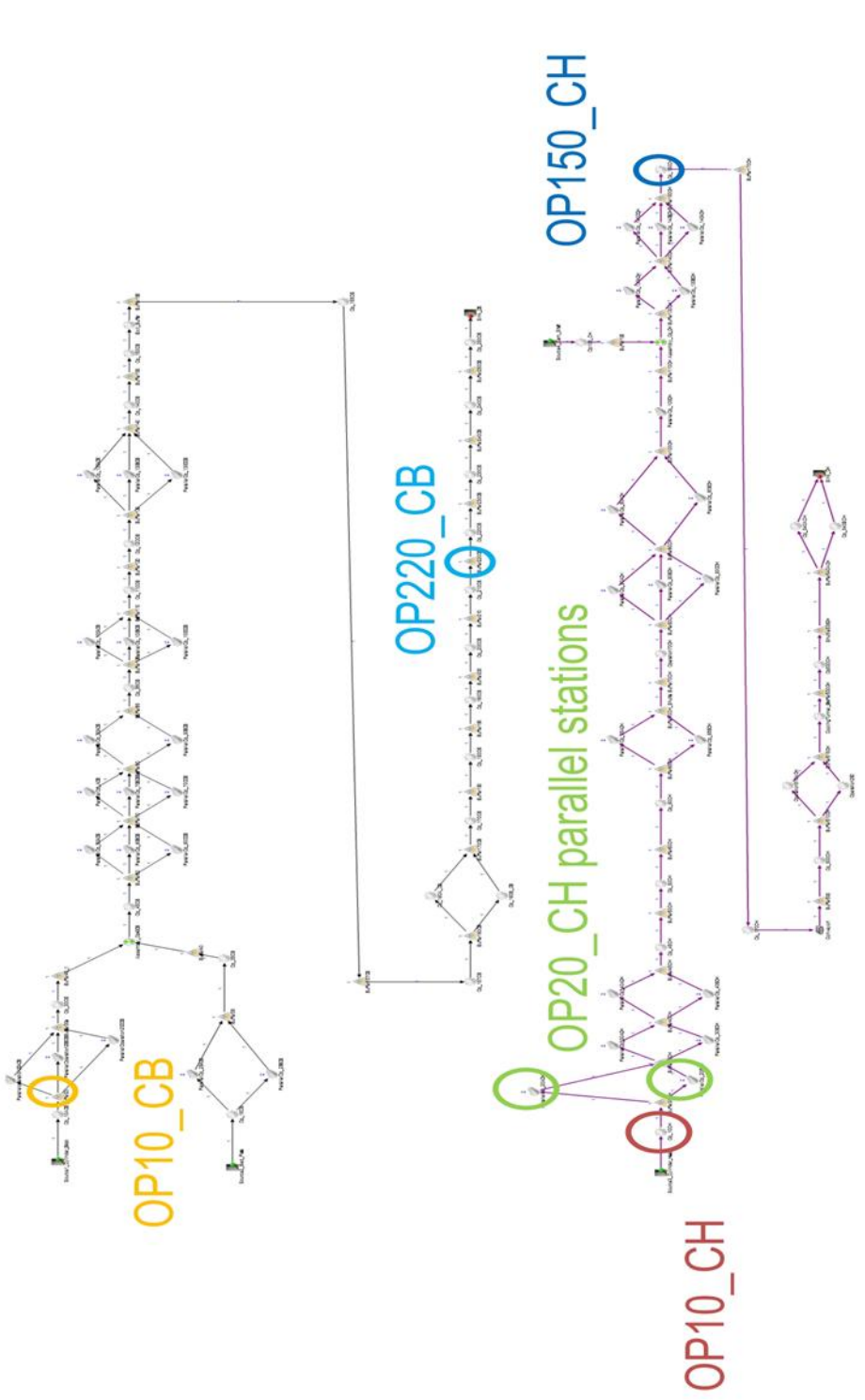
Appendix 2: Process Flow Diagram Low Flow Line Cylinder Head



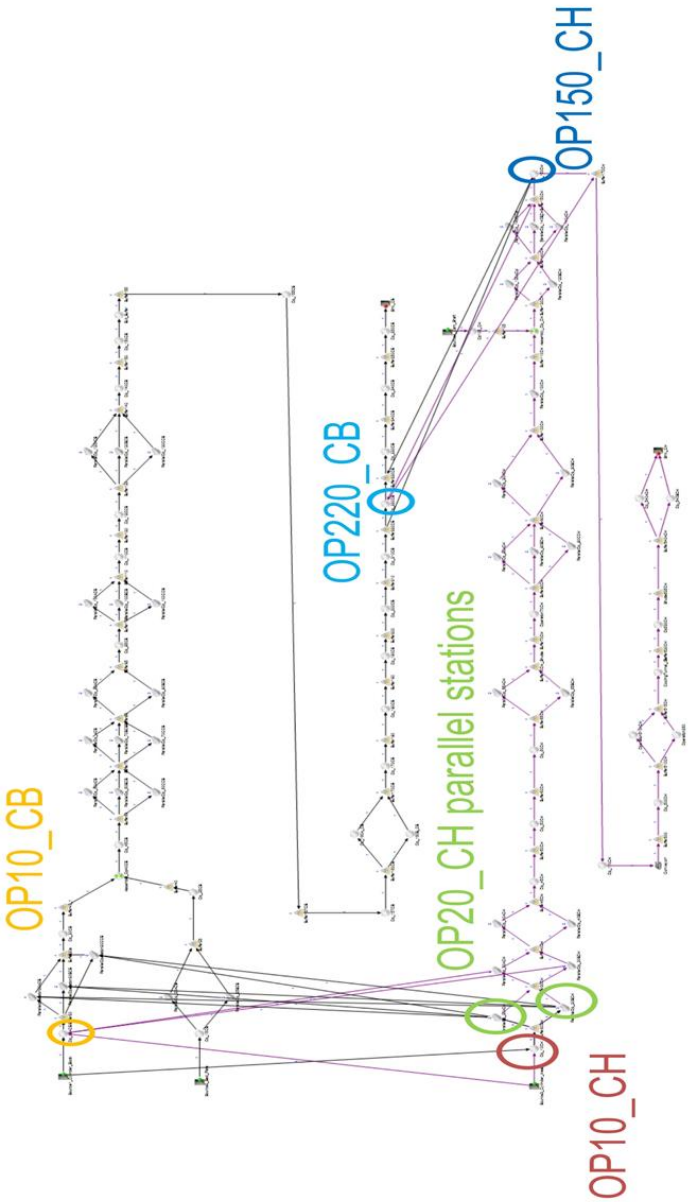
Appendix 3: Process Flow Diagram Low Flow Line Cylinder Block



Appendix 4: FACTS Model of Current production Lines



Appendix 5: FACTS Model of Reconfigured Scenario



Appendix 6: Simulation Results of Baseline

Output	Mean	Std. Dev.	Replicati on 1	Replicati on 2	Replicati on 3	Replicati on 4	Replicati on 5	Replicati on 6	Replicati on 7	Replicati on 8	Replicati on 9	Replicati on 10	Replicati on 11	Replicati on 12	Replicati on 13	Replicati on 14	Replicati on 15	Replicati on 16	Replicati on 17	Replicati on 18	Replicati on 19	Replicati on 20
Plant: throughput	114.99875	0.85068401132751 3	115.575	115.8333333333333	115.2666666666667	115.85	116.3166666666667	114.2833333333333	115.2583333333333	115.2583333333333	115.925	113.6	114.35	116	115.15	114.775	114.5	113.275	115.5583333333333	115.0333333333333	114.1833333333333	113.9833333333333
Plant: leadTime	3484.526 60903867	35.89709 9572687	3453.564 45517084	3483.757 74351687	3519.848 66039167	3448.171 48316018	3433.705 64177017	3540.500 62512686	3547.583 2988623	3421.072 52410462	3506.686 36977409	3509.973 04842009	3438.330 92614671	3496.393 91174261	3514.075 18944476	3482.592 59403539	3448.322 27496595	3516.802 31143626	3501.454 43214849	3481.875 69573688	3469.025 53441034	3476.795 46040829
Plant: wip	120.3715 20039998	1.265864 73408615	119.7829 30298618	121.2336 47188088	121.6885 49398977	120.2118 109104	120.0738 91960526	121.4743 4779423	122.5016 81873495	118.3770 47654414	122.0062 59551499	119.8303 10951868	118.2630 06794968	121.6575 07944977	121.6416 79931254	120.0681 35969605	118.9105 73959799	119.3729 2967834	121.5266 21690942	120.3002 28876911	119.1137 00002671	119.3955 38368386
Plant: produced Parts	13799.85	102.08215219629 6	13869	13900	13832	13902	13958	13714	13831	13831	13911	13632	13722	13920	13818	13773	13740	13593	13867	13804	13702	13678
Cylinder_Block: throughput	54.36166 66666667	0.75002144218861 1	55.31666 66666667	54.98333 33333333	54.5	55	55.19166 66666667	53.71666 66666667	54.28333 33333333	54.4	55.23333 33333333	53.06666 66666667	54.10833 33333333	55.25833 33333333	54.80833 33333333	53.875	53.75833 33333333	53.1	54.91666 66666667	54.76666 66666667	53.24166 66666667	53.70833 33333333
Cylinder_Block: leadTime	3838.203 64298562	79.50937 71681888	3761.429 45699365	3817.175 50188747	3936.027 62066558	3815.317 0439307	3717.205 62782304	3972.986 51553967	4003.646 70323008	3710.346 94389572	3889.613 15302895	3886.543 40298097	3725.069 39743365	3848.755 78057716	3875.653 11870996	3802.787 48559576	3776.609 69100807	3883.991 23305289	3840.144 56181522	3821.458 16540344	3824.962 96908349	3854.348 4870569
Cylinder_Block: wip	57.95137 30808854	1.303442 36306376	57.74047 00429205	58.34088 48485515	59.56886 39243202	58.48652 42975587	57.03199 78995932	59.32171 12248112	60.34421 57763704	55.93651 34017474	59.75467 28201495	57.25246 2087438	56.04833 01984047	59.00445 88757778	59.09053 93461903	56.96012 53780014	56.47179 4825334	56.89119 42004893	58.59658 16000398	58.08714 20736005	56.52645 26031634	57.57252 61932463
Cylinder_Block: produced Parts	6523.4	90.00257 30626338	6638	6598	6540	6600	6623	6446	6514	6528	6628	6368	6493	6631	6577	6465	6451	6372	6590	6572	6389	6445
Cylinder_Head: throughput	60.63708 33333333	0.28837712627575 7	60.25833 33333333	60.85	60.76666 66666667	60.85	61.125	60.56666 66666667	60.975	60.85833 33333333	60.69166 66666667	60.53333 33333333	60.24166 66666667	60.74166 66666667	60.34166 66666667	60.9	60.74166 66666667	60.175	60.64166 66666667	60.26666 66666667	60.94166 66666667	60.275
Cylinder_Head: leadTime	3167.587 42264051	20.98700 30397702	3170.946 85288902	3182.485 43870596	3146.588 86881305	3116.322 57860179	3177.724 67276837	3156.928 24626047	3141.570 31320537	3162.496 12914415	3158.198 28527412	3179.851 9005892	3180.785 91382604	3175.840 81087254	3185.653 97127362	3199.333 15589393	3157.777 32766348	3192.785 16581361	3194.739 03370082	3173.283 88287063	3158.060 91385425	3140.374 99078984
Cylinder_Head: wip	53.36127 78650436	0.381847 48732995 4	53.06073 80636957	53.86929 33173206	53.09713 21983666	52.66735 91112106	53.96358 55482506	53.08355 86741798	53.15923 29067689	53.45562 78121968	53.20700 27288957	53.46938 2587986	53.23382 81130909	53.60961 44035193	53.40477 1570159	54.08139 43550347	53.27804 36086027	53.42722 4221715	53.83003 00711199	53.15623 88493168	53.48716 98109025	52.68432 93485404
Cylinder_Head: produced Parts	7276.45	34.60525 51530909	7231	7302	7292	7302	7335	7268	7317	7303	7283	7264	7229	7289	7241	7308	7289	7221	7277	7232	7313	7233

Appendix 7: Simulation Results of Reconfigured Line

Output	Mean	Std. Dev.	Replicati on 1	Replicati on 2	Replicati on 3	Replicati on 4	Replicati on 5	Replicati on 6	Replicati on 7	Replicati on 8	Replicati on 9	Replicati on 10	Replicati on 11	Replicati on 12	Replicati on 13	Replicati on 14	Replicati on 15	Replicati on 16	Replicati on 17	Replicati on 18	Replicati on 19	Replicati on 20
Plant: throughput	102.625	1.004420 05611338	103.8	103.4583 33333333	102.775	103.6583 33333333	103.5333 33333333	102.175	103.1166 66666667	102.7333 33333333	104	100.7083 33333333	101.5166 66666667	103.45	103.45	102.2083 33333333	101.975	100.9583 33333333	103.275	102.7583 33333333	101.2416 66666667	101.7083 33333333
Plant: leadTime	3210.288 05614881	34.56912 31237536	3156.163 00238984	3202.946 82706865	3230.248 77758611	3181.705 11433626	3159.078 57489211	3265.614 10610438	3244.854 83739111	3205.921 51673087	3196.947 57302926	3245.515 35089578	3166.766 25412183	3194.664 53354636	3204.032 51182487	3201.365 66679963	3223.477 09371959	3282.710 3205964	3185.980 42308622	3186.274 60262579	3230.714 80121696	3240.779 23501424
Plant: wip	100.9101 89920366	0.834033 45472801	100.4079 3845268	101.4828 38370369	101.6679 51260397	101.2677 30872252	100.3003 86804693	102.1388 62911014	102.3467 13310647	100.6258 35473891	101.7206 040008	100.1404 04769181	98.70335 97631662	101.1051 0991775	101.5519 96946782	100.2826 26125992	100.7899 57506007	101.1605 15656354	100.8755 79958828	100.2960 84075764	100.2371 56444307	101.1021 45786444
Plant: produced Parts	12315	120.5304 06733606	12456	12415	12333	12439	12424	12261	12374	12328	12480	12085	12182	12414	12414	12265	12237	12115	12393	12331	12149	12205
Cylinder_Block: throughput	51.33458 33333333	0.484868 06398616 4	51.925	51.74166 66666667	51.4	51.74166 66666667	51.79166 66666667	51.08333 33333333	51.54166 66666667	51.46666 66666667	52.00833 33333333	50.4	50.75833 33333333	51.8	51.69166 66666667	51.13333 33333333	50.95	50.64166 66666667	51.65	51.44166 66666667	50.68333 33333333	50.84166 66666667
Cylinder_Block: leadTime	3628.874 88453889	69.14718 52925374	3515.453 73720411	3614.812 37944748	3674.835 08772798	3593.408 97062001	3531.531 4115447	3746.109 73743712	3705.269 8763131	3631.714 89715347	3604.437 32890332	3697.035 15704014	3535.202 8953768	3601.970 47296897	3613.866 47273465	3605.773 7722707	3663.399 1807566	3748.778 44302127	3557.571 47103955	3570.737 09142499	3683.554 16090981	3682.035 14692671
Cylinder_Block: wip	51.70030 28177846	0.802346 06741917 6	50.68467 55094486	51.92854 94511778	52.47453 44636801	51.83408 2190455	50.77815 13464508	53.18177 14650607	53.08082 32356267	51.70343 42165138	52.03841 01102539	51.61596 30103515	49.85485 66861664	51.68196 86201045	51.94744 35303202	51.18296 43149906	51.88649 36372829	52.40386 15750289	51.02014 88110072	50.92140 03349109	51.73521 59010458	52.05130 79458165
Cylinder_Block: produced Parts	6160.15	58.18416 76783389	6231	6209	6168	6209	6215	6130	6185	6176	6241	6048	6091	6216	6203	6136	6114	6077	6198	6173	6082	6101
Cylinder_Head: throughput	51.29041 66666667	0.524566 62006736 3	51.875	51.71666 66666667	51.375	51.91666 66666667	51.74166 66666667	51.09166 66666667	51.575	51.26666 66666667	51.99166 66666667	50.30833 33333333	50.75833 33333333	51.65	51.75833 33333333	51.075	51.025	50.31666 66666667	51.625	51.31666 66666667	50.55833 33333333	50.86666 66666667
Cylinder_Head: leadTime	2791.327 61847808	10.99937 47861836	2796.525 96325286	2790.882 17758104	2785.446 123741	2771.389 02386021	2786.265 82246887	2785.196 8462659	2784.737 36837632	2778.467 04379687	2789.327 19053047	2793.172 83183647	2798.329 61286686	2786.175 71143423	2794.726 43236529	2796.495 68231557	2784.201 63395408	2813.631 82109723	2814.209 42789417	2800.875 61864439	2776.755 84528291	2799.740 19199689
Cylinder_Head: wip	39.78082 81438136	0.391732 30220801 5	40.32592 75858967	40.09788 06907796	39.77784 1490386	39.95646 37775329	40.06038 15741606	39.54269 49934882	39.89816 51305892	39.57795 84886177	40.26510 59945606	39.03730 68940367	39.46457 96143194	39.98569 51756662	40.17242 6528808	39.68829 32611864	39.43514 55915766	39.36976 82793417	40.35822 55382239	39.95669 91767702	39.06406 55306406	39.58193 75596906
Cylinder_Head: produced Parts	6154.85	62.94799 44080826	6225	6206	6165	6230	6209	6131	6189	6152	6239	6037	6091	6198	6211	6129	6123	6038	6195	6158	6067	6104