School of Mechanical and Design Engineering

Design and Digital Twin Optimisation of a Hybrid Flow Manufacturing System for a Hydraulic Disc Brake Caliper

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List of Abbreviations

Abbreviation	**Definition**
CNC	Computer Numerical Control
ED	Enterprise Dynamics
EoL	End of Line
FLT	Forklift Truck
HR	Human Resources
KPI	Key Performance Indicator
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
S&OP	Sales and Operations Planning
WIP	Work in Progress
RFID	Radio Frequency Identification
COBOT	Collaborative Robot
OPC UA	Open Platforms Communications Unified Architecture

1.0 Introduction

Hydraulic disc brake calipers are safety critical components that rely on precision machining, manual assembly, and controlled hydraulic testing. They typically consist of an aluminium housing with seals, piston assembly, torque controlled fastening, and final leak verification before release.

This report develops a hybrid flow manufacturing system for the hydraulic disc brake caliper assembly, comprising parallel CNC machining followed by manual assembly arranged in a flow line, before in line pressure decay testing. This production structure reflects the varying operational requirements of the component, with machining activities organised around batch fixture processing, and downstream assembly configured as a controlled flow system with defined manning levels and work in process limits.

The aim of the report is to design and evaluate a sustainable manufacturing system for the product and to define a digital twin framework for later implementation in Enterprise Dynamics. A preliminary design target of 1000 units per day is adopted as the basis for manufacturability analysis, design capacity assessment, takt time determination, and line balancing. The study also considers reliability, defect generation, rework, lean WIP control, and sustainability-oriented improvement opportunities.

Accordingly, the report progresses from the product manufacturability and design capacity into manufacturing system design, before establishing the modelling framework required to evaluate operational performance and identify improvement opportunities through digital and Industry 4.0 based optimisation.

2.0 Manufacturability Analysis and Design Capacity

2.1 Product manufacturability characteristics

Manufacturability of the hydraulic disc brake caliper assembly depends on three consecutive requirements: accurate machining of the aluminium housing, consistent sealing and fastening during assembly, and final confirmation of hydraulic integrity. Critical hydraulic interfaces must meet controlled dimensional and surface requirements to enable smooth assembly without excessive adjustment or leak risk. Hydraulic leak performance is also influenced by assembly quality and torque control, which means manufacturability must be considered across the full machining and assembly route rather than at component level alone (Awad & Alkelani, 2012). The principal product implications are summarised in Table 1**.**

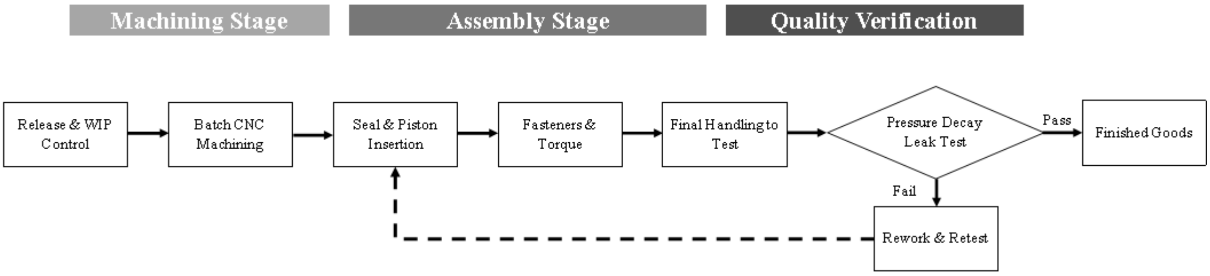
Table 1: Product manufacturability characteristics

Product feature	**Manufacturing implication**	**System consequence**
Aluminium housing	Requires repeatable CNC machining of bores, ports, and sealing faces	Upstream batch machining cell required
Functional bores and ports	Dimensional and surface control needed for fit and hydraulic performance	Machining quality directly affects downstream assembly
Sealing interfaces	Sensitive to variation in geometry, cleanliness, and handling	Controlled manual seal and piston assembly required
Fastened joints	Torque consistency influences leak risk and assembly quality	Dedicated fastening and torque station required
Hydraulic integrity requirement	Machined conformity alone does not guarantee leak free assembly	Final pressure decay test required as end of line quality gate

2.2 Proposed process route and manufacturing rationale

The proposed route comprises batch CNC machining of the aluminium housing, followed by manual assembly in a flow sequence and in line pressure decay testing. Batch machining is selected because fixture-based processing supports repeatability and capacity growth through parallel machine use. Rusu et al. (2025) show that in a hydraulic component production case study, fixture redesign reduced machining time from 16 minutes for 8 parts to 8 minutes for 16 parts increasing output from 240 to 480 parts). CNC capacity planning must also account for loading, clamping, and unloading time rather than cutting time alone (Aggarwal et al., 2020). Manual assembly is retained for seal fitting, piston insertion and torque-controlled fastening, while pressure decay testing provides the final hydraulic quality gate (Li et al., 2024). The conceptual route is shown in Figure 1.

Figure 1: Proposed value stream mapping before any modelling



2.3 Design capacity basis and takt time

A design capacity of 1,000 units per day (~ 250,000 units per year) was selected to reflect a high-volume automotive production context as defined by Groover (2016), which is broadly consistent with Tier 1 brake component supply volumes. Net available production time and takt time were derived from the defined shift pattern and break allowances, as shown in Equations 1-2 and Table 2.

Equation 1: Net available production time

$$T_{net} = N_s \times (T_s - T_b)$$

Where:

$T_{net} = net\ available\ production\ time\ per\ day$
$N_s = number\ of\ shifts\ per\ day$
$T_s = shift\ length$
$T_b = break\ allowance\ per\ shift$

$$\Rightarrow T_{net} = 2 \times (480 - 45) = 870\ min/day$$

Equation 2: Takt time

$$T_{takt} = \frac{T_{net}}{D}$$

Where:

$T_{takt} = takt\ time$
$T_{net} = net\ available\ production\ time\ per\ day$
$D = daily\ demand$

$$\Rightarrow T_{takt} = \frac{52{,}00}{1000} = 52.2\ s/unit$$

Table 2: Design capacity basis

Parameter	Value
Shift length	8 h/shift
Break allowance	45 min/shift
Shifts per day	2
Net available time per shift	435 min
Net available time per day	870 min ⇒ 52,200s
Preliminary design target	1000 units/day
Takt time	52.2 s/unit

The resulting takt time provides the main benchmark for the initial capacity assessment. Any stage operating above this value cannot meet the required output on a single resource and therefore requires either parallel capacity, task redistribution, or process improvement.

This basis is simplified and should be treated as a starting point rather than a forecast of actual output. It excludes production losses, so its main purpose is to set a clear benchmark for the initial capacity assessment.

2.4 Preliminary capacity analysis and expected constraints

Table 3 compares effective station times against takt to assess whether the proposed route can sustain the target output. Under the current assumptions, several operations exceed takt, so parallel resources are required at more than one stage of the system

Table 3: Preliminary station timing and required resources

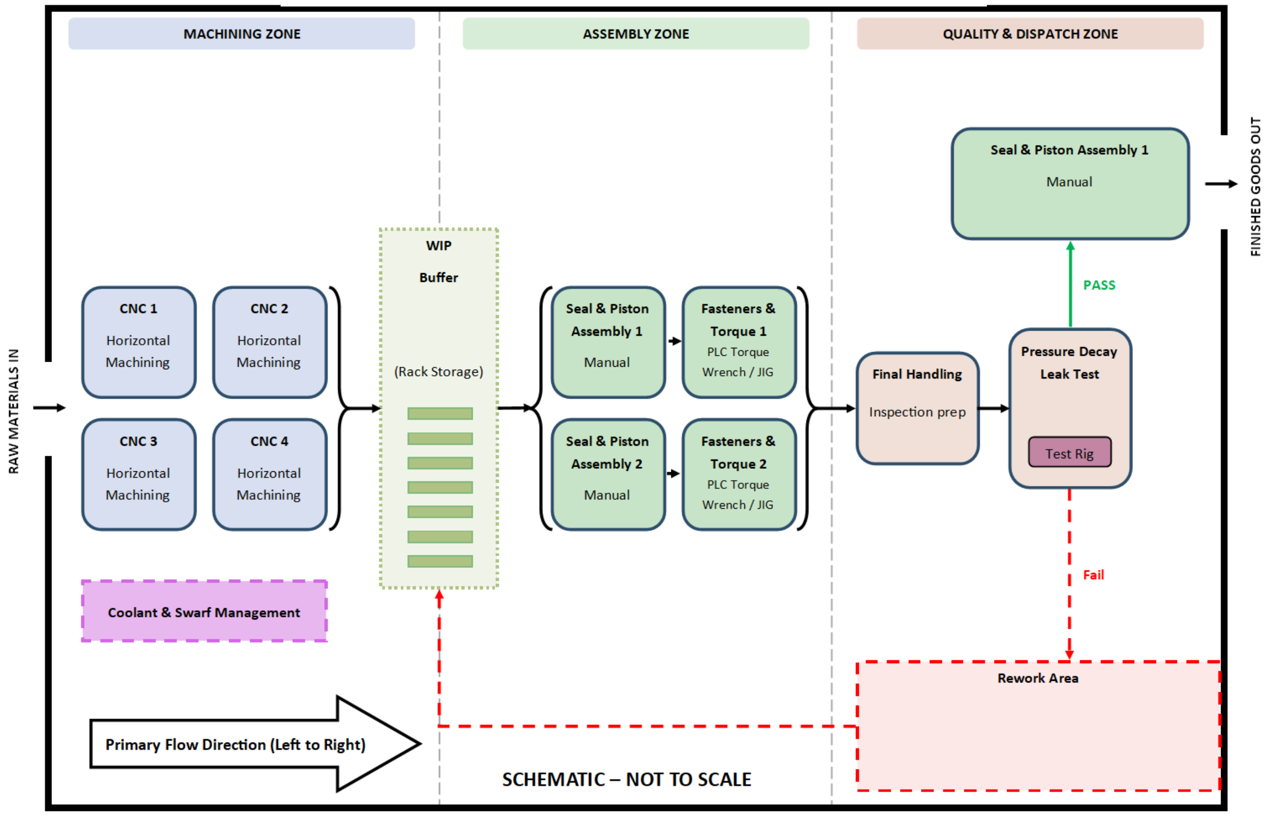
Station	Effective time (min/unit)	Takt comparison	Minimum parallel resources	Capacity judgement
CNC machining, baseline	3.15	Above takt	4	Dominant baseline constraint
CNC machining, optimised	1.07	Above takt	2	Constraint severity reduced
Seal and piston insertion	1.5	Above takt	2	Likely downstream constraint after machining improvement
Fasteners and torque	1.0	Above takt	2	Secondary assembly constraint
Final handling to test	0.5	Below takt	1	Lower constraint risk
Leak test	0.3	Below takt	1	Unlikely nominal constraint

CNC machining remains the main expected baseline constraint due to its range above takt. Even with improved machining, upstream processing will likely govern throughput, while manual assembly becomes more influential as machining capacity improves. Final handling and leak testing appear adequate under nominal conditions. These results define the initial resource basis and bottleneck hypothesis for Chapter 4.

3.0 Sustainable Manufacturing System Design

The system uses a hybrid flow structure to match the different demands of machining, assembly and final testing at the required output. CNC machining is used upstream because it provides repeatability and practical capacity scaling through parallel machines, which is necessary given the loading identified in Section 2. Manual assembly is retained downstream because, at the proposed volume, it offers a more flexible and proportionate solution than dedicated automation. Leak testing is positioned before packout as the final quality gate, as internal leakage cannot be reliably identified through visual inspection and must be verified through acceptance testing to ensure component reliability (Li et al., 2024).

Figure 2: Proposed facility layout of the manufacturing system



The system design acknowledges the broader sustainability context of aluminium component manufacturing. Although primary aluminium production is highly energy intensive, recycled aluminium requires approximately 5% of that energy input, making closed loop material sourcing a meaningful sustainability driver for automotives supply chains (Luo et al., 2025). CNC machining energy consumption can be further reduced through minimum quantity lubrication and alternative cooling strategies, which also minimise cutting fluid waste and associated environmental hazards (Gupta et al., 2023). Socially, retaining manual assembly preserved skilled employment and maintains workforce flexibility, while keeping CAPEX proportionate to the target volume, avoiding overcommitting to fixed automation at a scale where manual operations remain economically viable.

Downstream of machining, the line follows a sequential flow arrangement with buffers used to separate batch production from assembly. Parallel stations are applied at machining and assembly where capacity demands, helping flow without overcomplicating the layout. Labour is assigned to defined assembly stages rather than shared across the line, which supports consistent task execution and reduces avoidable movement. The layout is appropriate as it balances flow control with operational simplicity, although it remains sensitive to resource allocation and stable upstream supply.

The system retains failed units within the line through rework rather than treating nonconformance as immediate loss. Capacity is increased through parallel resources instead of full automation, keeping the design proportionate to the target volume. Manual assembly also preserves flexibility as manual workstations can be reconfigured easier than dedicated automates stations (Huettemann et al., 2016). It is limited by higher volumes likely requiring further automation.

The design maintains control of work in process and contains defects within the line rather than allowing failures to propagate downstream. This improves flow control but introduces additional recirculation and associated resource demand. System performance therefore depends on maintaining stable internal flow rather than on the level of automation alone. This configuration prioritises flexibility and scalability over strict automation efficiency but introduces dependence on labour stability and upstream consistency, increasing sensitivity to resource allocation and flow variability.

4.0 Digital Twin Modelling and System Performance

4.1 Digital Twin Model Development

The baseline model represented the proposed manufacturing operations system at a system level. It was used to establish the initial flow structure, resource loading and reliability logic before later refinement. Source release was controlled using the takt time derived in Section 2.3.

Figure 3: Enterprise Dynamics baseline digital twin of the proposed hydraulic disc brake caliper manufacturing system after a 24 h simulation run

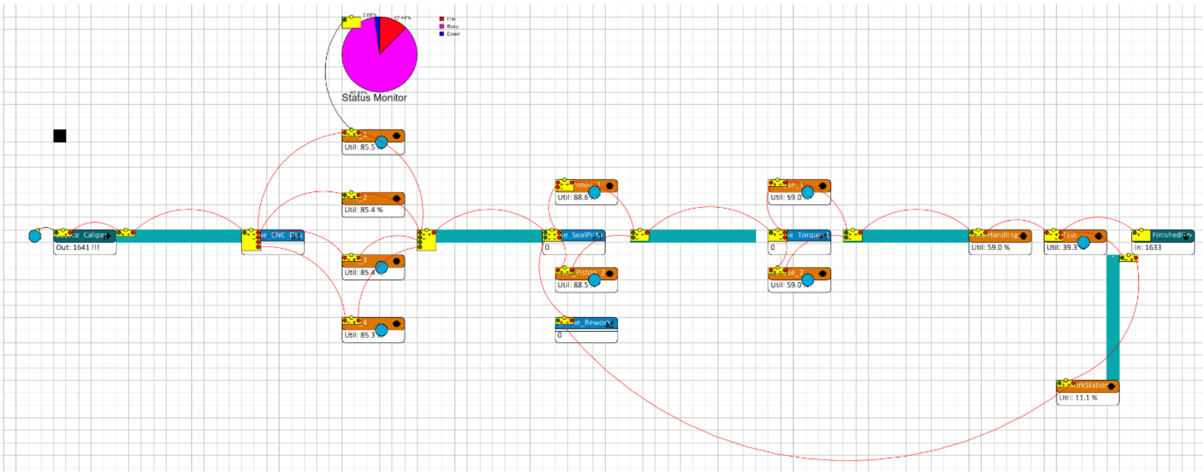
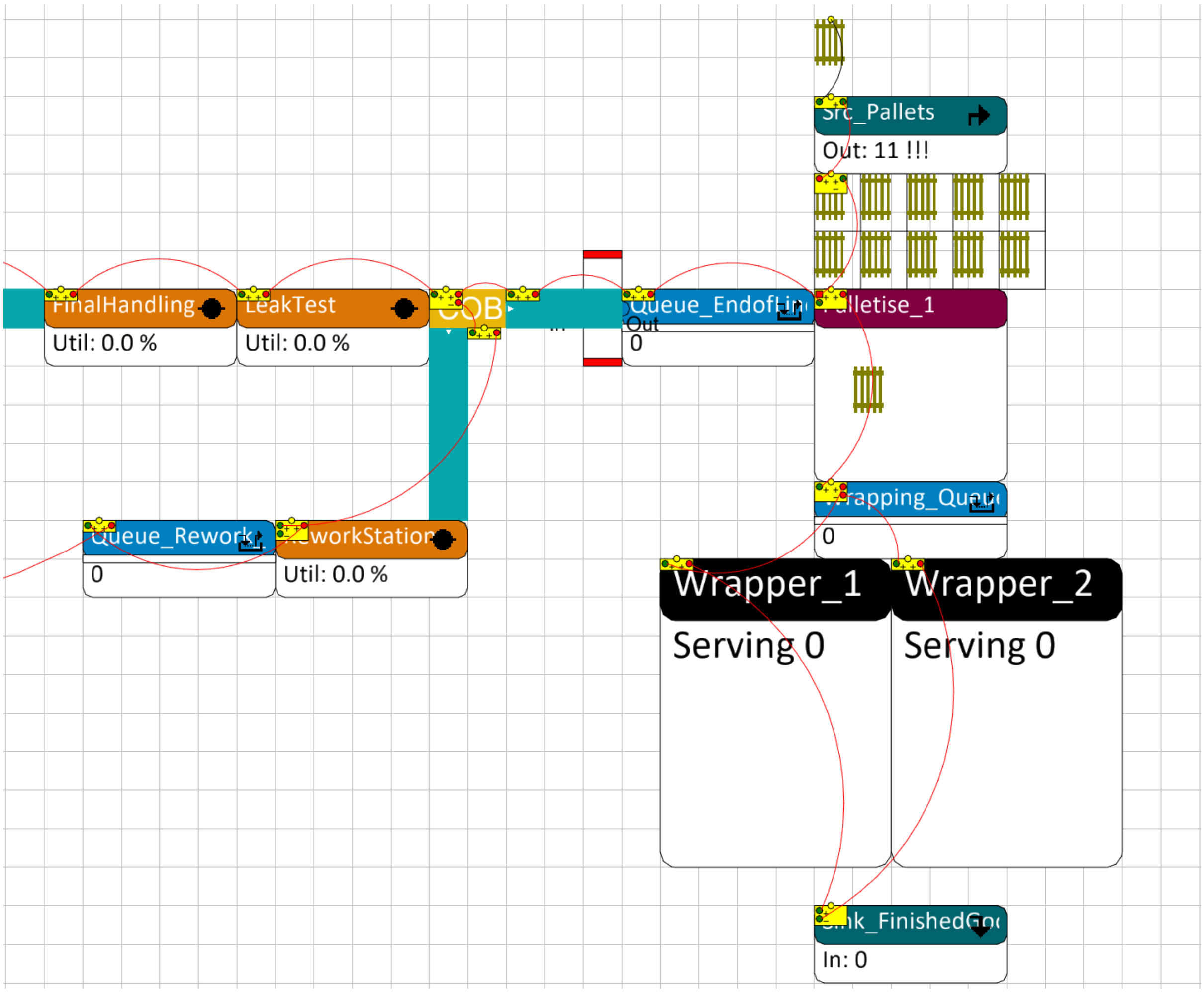


Table 4: Baseline digital twin structure and simulation inputs

Stage	Resources	ED input basis	Control / reliability basis
Source release	1 source	Release interval set to takt time from Section 2.3	Controlled flow input
CNC machining	4 parallel stations	180 s per station	MTTF 15h, MTTR 0.5h
Seal and piston assembly	2 parallel stations	90 s per station	Nominally available in baseline
Final handling	1 station	30 s	Nominally available in baseline
Leak testing	1 station	20 s	97% pass, 3% rework, MTTF 30h, MTTR 0.17 h
Rework	1 station	150 s	Returns failed units to assembly stage
Simulation horizon	Whole model	24 h	Baseline performance assessment

The final model revision extended the baseline structure by adding internal logistics, digital control, and palletised dispatch. Internal transfer within the rework area was represented explicitly through an FLT. An RFID gate was added at EoL for identification and routing control. Palletising was remodelled as an Assembler, supported by a finite pallet store positioned beside the station, so that pallets entered through the first channel and finished calipers through the second to produce one palletised outbound load rather than allowing pallets to pass as standalone finished goods. Unlimited pallets were used to represent pallet replenishment through supply chain arrangements. A COBOT station was used to integrate a Human centred design, working alongside operators, reducing repetitive motions and safety concerns.

Figure 4:RFID gate, COBOT station, and Palletising routing.



The final digital twin was also linked to a live Excel dashboard using the 'ExcelActiveX' atom. This was applied as a real time monitoring layer rather than as additional routing logic, therefore leaving production outputs untouched. Product labels were used to record leak test attempt number and product level test records, while ExcelActiveX exported selected simulation outputs for external KPI analysis using excel formulas to reduce strain on the Enterprise Dynamic model, allowing compartmentalising of the digital twin. The dashboard structure is summarised in Table 5

Figure 5: Quality and Production Digital Twin Dashboards after a 10 hour simulation

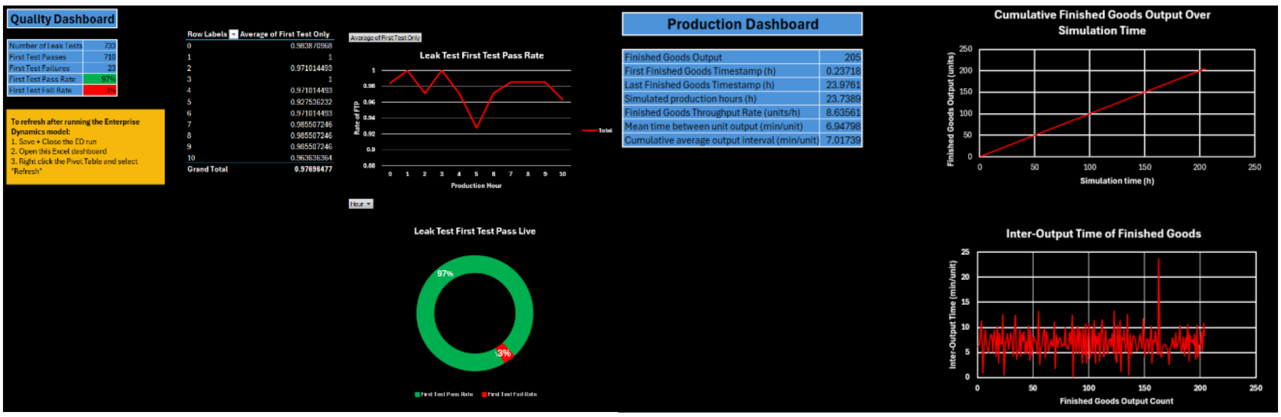


Table 5: Digital twin dashboard structure

Dashboard view	Exported / Calculated Measure	Purpose
Quality Dashboard	Leak test timestamp	Records when each unit reached the leak test decision point
Quality Dashboard	Leak test result	Separates FTP from units routed to rework
Quality Dashboard	Leak test attempt number	Excludes retested units from FTP calculations
Production Dashboard	Finished goods timestamp	Records completed output at the final sink after palletising, wrapping and packout
Production Dashboard	Inter-output time	Shows the time interval between finished goods units
Production Dashboard	Finished goods throughput rate	Measures completed output per simulated production hour.

4.2 Model Verification and Baseline Diagnosis

During a simulated 24 hours run, verification confirmed the baseline digital twin model followed the intended routing, including correct rework return without disassembly, and remained free from deadlock or unintended flow disruption. The difference between source output and finished goods indicates work-in-progress accumulation rather than loss of flow.

Table 6: Baseline loading and flow checks (24 h)

Metric	Result	Use	Metric	Result	Use
Run length	24 h	Time horizon	Seal utilisation	87.9-88%	Spare capacity
Source Out	1641	Release level	Torque utilisation	58.5-58.6%	Spare Capacity
Sink In	1633	Completed output	Final handling utilisation	58.8%	Spare capacity
CNC Utilisation	85.3-85.5%	Governing load	Leak test utilisation	39%	Non-constraint
Rework utilisation	9.0%	Recirculation			

Table 6 shows that the baseline exceeded the required daily output but did so through uneven resource loading rather than balanced capacity. CNC stations remained the governing constraint, while torque, handling, and leak testing retained substantial spare capacity. This creates an operational trade-off. If the same release logic is maintained, output above the S&OP requirement would require either additional finished goods storage or a revised release target for subsequent shifts. The 24-hour analysis alone could not rule out later blockage. A subsequent 30-day continuous run recorded no sustained blockage. This supports the line's operability over a longer planning period with loading imbalance retained.

4.3 Targeted Improvements and Scenario Testing

The scenarios (Table 6) were used to test if the baseline constraint was more sensitive to processing or availability. Cycle time reductions were applied in systematic changes; without defined engineering literature, they should be treated as sensitivity tests rather than implementable improvements. Their limited effect on output shows that local time reductions do not improve system performance unless they act on the governing constraint. Changes to machine availability had a stronger effect, indicating that the constraint was more sensitive to downtime than nominal cycle time.

Labour and supporting system scenarios were utilised to evaluate operational feasibility rather than throughput improvement. Labour changes had little effect on throughput but showed that staffing can constrain how the system operates in practice. FLT based rework return and EOL packout completed the production representation without changing capacity. Their value therefore lies in improving digital twin completeness, not output.

4.4 Impact Assessment and System Level Findings

The results in Table 5 and Table 6 show that only scenarios affecting the upstream resource produced measurable throughput improvement. Cycle time reductions applied away from this stage produced negligible improvement, confirming they acted as sensitivity tests rather than optimisation. In contrast, availability changes at the governing stage produced quantifiable gains, indicating performance was constrained by downtime rather than nominal processing time.

Table 7: Comparative results of baseline and optimisation scenarios

Scenario	Change introduced	Finished goods (units/24 h)	Change vs baseline (units/24 h)
S0 (Baseline)	No change	1633	0
S1	Seal and piston reduced to 75 s	1634	+1
S2	CNC cycle reduced to 165 s	1634	+1
S3	Combined cycle time changes	1634	+1
S4	CNC MTTR reduced to 900 s	1648	+15
S5	Combined cycle time changes with CNC MTTR reduced to 900 s	1648	+15
S6	Human resource logic validated	1648	+15
S7	Dedicated seal and torque teams	1648	+15
S8	Reduced manning	Not viable; Complete line blockage at 17 h	N/A

Achieving greater output did not resolve the imbalance in resource loading or release control. Manufacturing performance depends on the interaction of multiple flows, including availability, maintenance, and quality control, rather than output alone (Gejo-García et al., 2022). Labour, FLT, and packout scenarios did not increase throughput but defined operational feasibility and system completeness. The system is therefore stable and capable, but effective operation depends on controlling the governing resource and aligning release with demand. The spare capacity at torque and final handling stations suggests consolidation potential, however, as CNC availability governs throughput, reallocation would not improve finished output under current conditions.

The scenario set indicates that availability improvement had the strongest effect on output under the current assumptions. Human resource modelling was useful for testing manning feasibility, but it did not improve throughput beyond the best availability-based case. Reduced manning was not viable, which indicates that labour can constrain feasibility even when it does not increase maximum output. The excel dashboards extended this comparison by separating throughput from quality and output rhythm.

5.0 Industry 4.0 Optimisation and Critical Evaluation

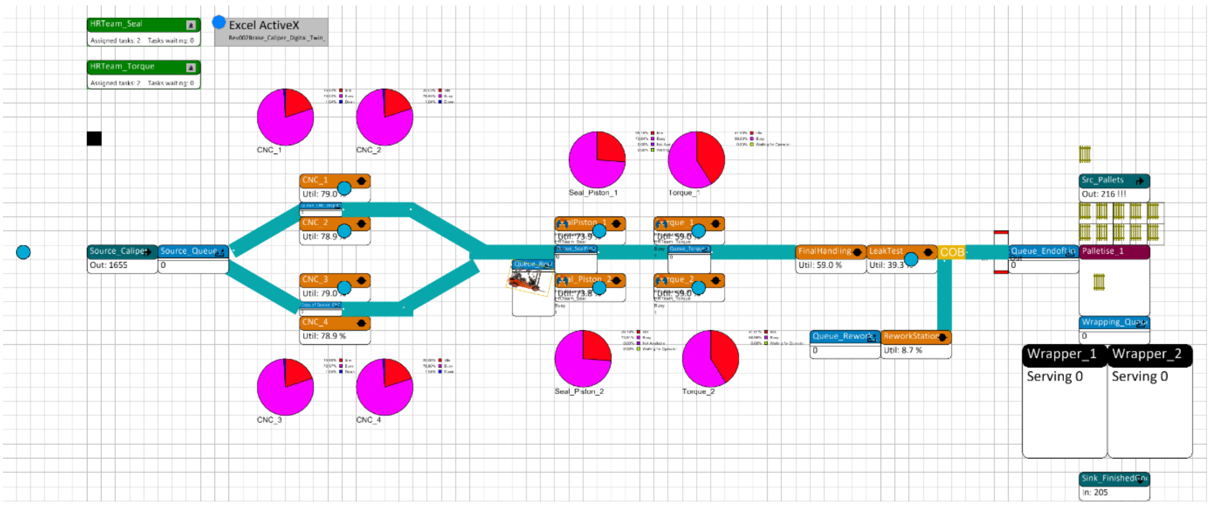
The scenario results in Table 7 show that CNC availability had a stronger effect on finished output than further nominal cycle time reduction. The scenarios based on availability produced the clearest system level improvement, while cycle time reductions produced only marginal gains. This indicates that the main optimisation level is recovery of the CNC machining constraint rather than further compression of downstream task times.

The interpretation is limited by the model scope and input assumptions. Because processing times, defect routing and reliability values were treated as defined scenario inputs, relative system sensitivity is reflected in the results, as opposed to a guaranteed production forecast. The cycle time scenarios reduced local loading but did not materially improve finished output because they did not act on CNC outputs. Industry 4.0 value is therefore only justified where digital monitoring improves CNC fault detection, maintenance response, and availability recovery, rather than being applied uniformly across the line.

Human Resource and COBOT modelling added human centred Industry 4.0 check rather than a pure cycle time optimisation. The reduced manning scenario was not viable, while validated and dedicated HR scenarios did not increase output beyond the best availability-based case. This indicates that labour should be retained as an operationally robust constraint, with the COBOT used to augment handling and quality routing rather than replace the assembly workforce.

The preferred optimisation direction is availability centred Industry 4.0 deployment, supported by workforce design that protects model feasibility. In industrial use, equivalent dashboard inputs could be captured through OPC UA tags linked to machine status, and quality or production metrics, since OPC UA provides a standardised interface for CNC monitoring and data exchange with higher level management systems (Martins et al., 2023). However, the dashboard developed here remains simulation based, so live use would require validated facility level data before operational benefit could be claimed.

Figure 6: Final manufacturing system layout



6.0 Conclusion

This study developed a hybrid flow manufacturing system for a hydraulic disc brake caliper and implemented it as a digital twin within Enterprise Dynamics. Manufacturing analysis and capacity assessment were used to define the system structure, resource allocation, and control logic, with CNC machining identified as the governing constraint. The model integrated flow behaviour, reliability effects, defect recirculation, and takt based release, providing a system level representation of the proposed production line.

Simulation was used to verify model behaviour and test targeted changes to processing time, availability, and system configuration. The results showed that system performance was governed by upstream availability, with cycle time reductions acting primarily as sensitivity tests and downtime reduction providing measurable improvement. Additional elements, including labour configuration, FLT based rework, and packout, extended the model to reflect operational feasibility without altering throughput.

The digital twin therefore provides a realistic and functional representation of the manufacturing system, suitable for evaluating performance and supporting targeted optimisation. Its accuracy remains dependent on input assumptions and model scope, but it demonstrates effective application of manufacturing systems design, modelling, and analysis within the constraints of the coursework.

Appendices

Appendix A. Literature and Engineering basis for preliminary timing and reliability inputs

Appendix 1: Literature and engineering basis for preliminary timing inputs

Parameter	**Value used**	**Basis**	**Source / rationale**
Batch machining time baseline	16 mins per 8 parts	Literature derived	(Rusu et al., 2025)
Batch machining time, optimised	8 mins per 16 parts	Literature derived	(Rusu et al., 2025)
CNC handling time	550 s per batch	Literature derived	Derived from summed load, clamp, unclamp, and unload elements (Aggarwal et al., 2020)
Seal and piston insertion	1.5 min/unit	Engineering estimate	Based on task decomposition and sensitivity analysis
Fasteners and Torque	1.0 min/unit	Engineering estimate	Based on task decomposition and sensitivity analysis
Final handling to test	0.5 min/unit	Engineering estimate	Based on task decomposition and sensitivity analysis
Leak test cycle time	20 s/unit	Hybrid basis	Pressure decay method (Li et al., 2024); baseline cycle time adopted as planning input
Leak defect rate	3% baseline	Hybrid basis	Controlled production subset based on in-plant hydraulic leak range (Awad & Alkelani, 2012)
Rework time	2.5 min/unit	Engineering estimate	Based on task decomposition and sensitivity analysis
CNC MTTF	15 h	Literature derived proxy	Proxy reliability input derived from (Barletta et al., 2014)
CNC MTTR	0.5 h	Literature derived proxy	Proxy reliability input derived from (Barletta et al., 2014)
Leak tester MTTF	30 h	Engineering judgement	Tested by sensitivity analysis
Leak tester MTTR	0.17 h	Hybrid basis	Informed by (Barletta et al., 2014)

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