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PROCESS SIMULATION FOR CONTINUOUS IMPROVEMENT

Manufacturing Systems & Simulation– ACMA6002

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Glossary of Terms

Abbreviation	Definition
5S	Sort-Set in order-Shine-Standardise-Sustain the cycle
CI	Continuous Improvement
CI	Confidence Interval
CV	Coefficient of Variation
DES	Discrete Event Simulation
DMAIC	Define–Measure–Analyse–Improve–Control
FMEA	Failure Mode & Effects Analysis
JIT	Just-in-Time
KPI	Key Performance Indicator
MSA	Measurement Systems Analysis
OEE	Overall Equipment Effectiveness
PPH	Parts Per Hour
SIMAN	General-purpose simulation language
SPC	Statistical Process Control
Takt	Production rate required to meet demand
TPM	Total Productive Maintenance
TPS	Toyota Production System
VSM	Value Stream Map
WIP	Work-in-Progress

1. Introduction & Process Selection

Tenneco Highpoint is a tier-1 automotive supplier of emissions (exhaust) systems, based in Merthyr Tydfil, South Wales. Their business is centred on welding sub-assemblies, including mufflers and resonators, which are assembled into a final unit before shipment to their just-in-time (JIT) sequencing plant. The L461 P6 MHEV Cold End is the highest-volume product in the range (Figure 1).

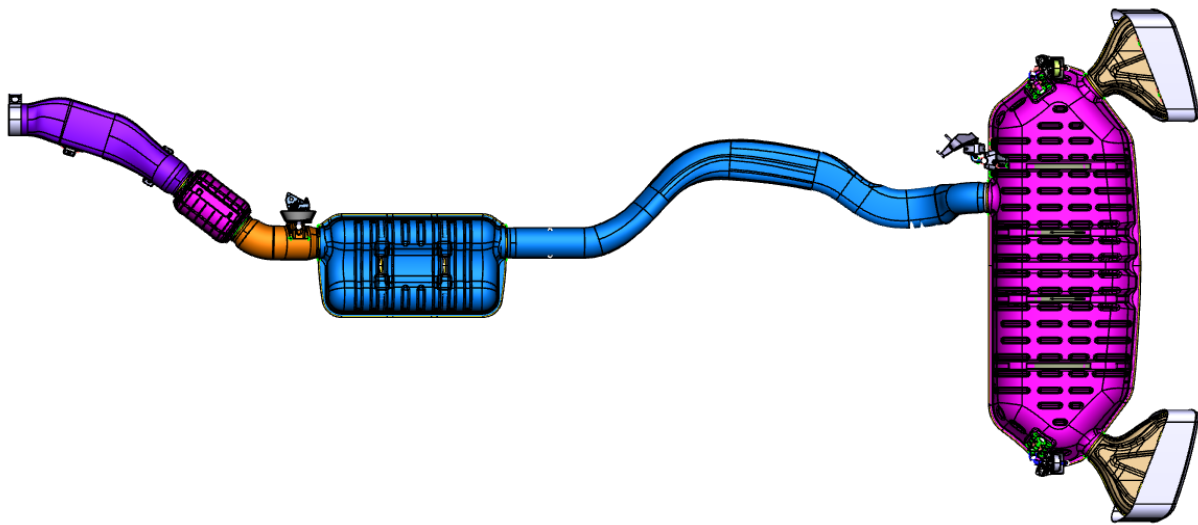


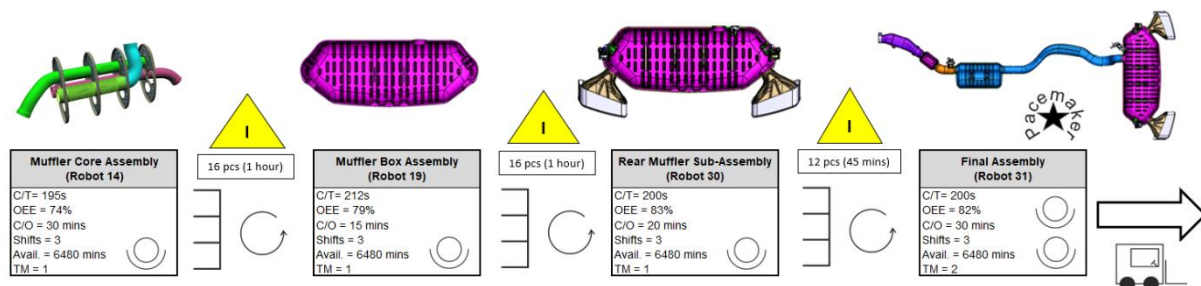
Figure 1: L461 P6 MHEV Cold End CAD Model.

At the start of 2023, a Continuous Improvement (CI) team was assembled to reduce warehouse space utilisation by 1,000 m² and avoid off-site storage. The P6 MHEV Cold End line was converted from several batch processes to single-piece flow, reducing reliance on large sub-assemblies held as WIP (work in progress) that had been stored in the warehouse for approximately two days before returning to downstream processes. The project concluded in January 2024, achieving a 1050 m² space reduction. Since then, the operations team has raised concerns about line balancing, as upstream processes intermittently stop when kanban buffers reach capacity. These imbalances are evident in the Q2 2025 Overall Equipment Effectiveness (OEE) results (Table 1).

Table 1: Q2 2025 OEE results.

Process Description	Cell No.	OEE
Muffler Core Assembly	Robot 14	74%
Muffler Box Assembly	Robot 19	79%
Rear Muffler Sub-Assembly	Robot 30	83%
Final Assembly	Robot 31	82%

The current-state value stream map (VSM) in Appendix 1 summarises the high-level material and information flow, aiding in the identification of waste (Nash and Poling, 2008). Key metrics - including cycle times, changeovers and OEE - were supplied by the process engineer. The single-piece-flow section (Figures 2–3) was the focus of this study. Breakdowns in flow were most evident between Robots 14 and 19 due to cycle-time mismatch. The final assembly cell acted as the pacemaker, pulling material from upstream; this pull-control made problems visible, aligning with one of the key benefits highlighted by Bicheno and Holweg (2016).

*Figure 2: P6 MHEV single-piece flow value stream map section.*

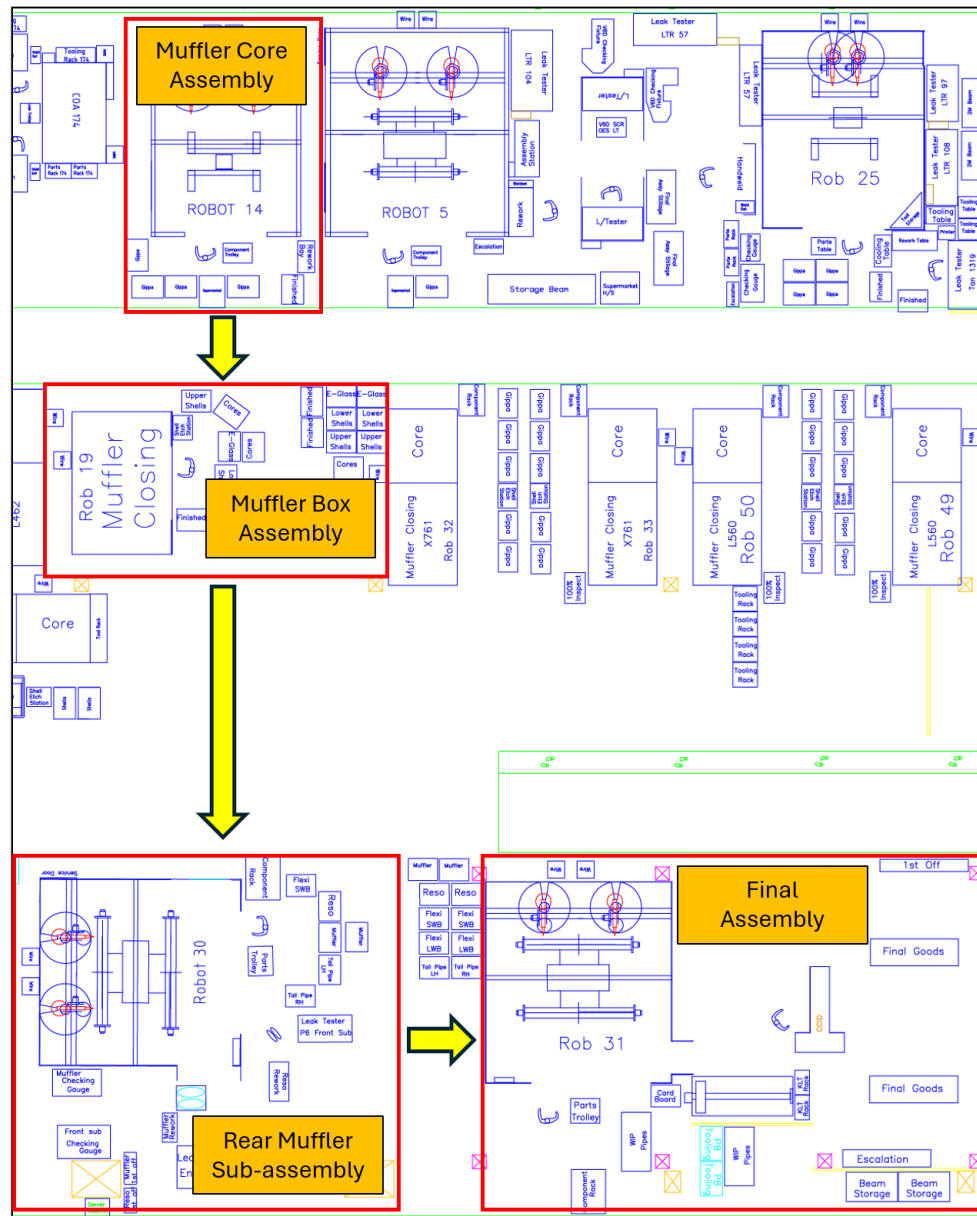


Figure 3: Plan view of P6 MHEV single-piece flow value stream.

However, a VSM only provides a static snapshot; it cannot capture variability, queues or blocking. To quantify these dynamics and test improvements, the processes were modelled using Rockwell Arena, a discrete-event simulation (DES) tool. DES models the system's event-driven behaviour and supports "what-if" experiments with statistical confidence (Pedrielli *et al.*, 2012). The aim was to use this model to analyse the system and recommend improvements - addressing line-balancing issues and reducing space and WIP without compromising throughput.

2. Data Collection

The cycle time and OEE data contained in the VSM provided a high-level overview of the process imbalances; however, creating a DES model to conduct in-depth analysis required further data collection. Table 2 lists each of the individual process elements, including material movement, inventory/WIP, and product assembly (both manual and automated). Automated operations, such as those completed by a robot, were recorded and assigned fixed cycle times due to their inherent repeatability. Human-based operations were evaluated by timing 10 cycles per operation to obtain the minimum, mode, and maximum cycle time values, with process abnormalities excluded from the assessment. The leak test failure rate was calculated by assessing 100 parts across five separate shifts.

Table 2: Current-State Process Breakdown: P6 MHEV Cold End

Cell No.	Process Element	Resource No.	Part Qty Per Cycle	Cycle Time			Process Activity Type	Comments
				Min (s)	Average (s)	Max (s)		
R14	Incoming material		6		1200		Transfer	6x assemblies = 1 batch
	Material supermarket (R14)	N/A	N/A				Non-Value Added	Stores maximum of 12x assemblies (2 batches)
	Load components (R14)	OP1	1	40	45	50	Value Added	
	Muffler core assy welding (R14)	R14	1		140		Value Added	
	Unload muffler core assy (R14)	OP1	1	13	15	17	Value Added	
	Muffler core assy to box assy	OP1	Every 8 cycles	14	16	18	Transfer	8 assemblies = 1 batch (gippa)
R19	Muffler core assy WIP (R19)	N/A	N/A				Non-Value Added	Stores maximum of 16 assemblies = 2 batches (gippas)
	Load components (R19)	OP2	1	21	25	29	Value Added	
	Muffler box assembly welding (R19)	R19	1		170		Value Added	
	Unload muffler box assy (R19)	OP2	1	10	12	14	Value Added	
	Muffler box assy to rear sub-assy	OP2	Every 8 cycles	13	15	17	Transfer	8 assemblies = 1 batch (gippa)
R30	Muffler box assy WIP (R30)	N/A	N/A				Non-Value Added	Stores maximum of 16 assemblies = 2 batches (gippas)
	Load components (R30)	OP3	1	31	35	39	Value Added	
	L460 rear sub-assembly welding (R30)	R30	1		150		Value Added	L460 Variant (45% of demand)
	L461 rear sub-assembly welding (R30)	R30	1		155		Value Added	L461 Variant (55% of demand)
	Unload rear sub-assy (R30)	OP3	1	16	18	20	Value Added	
	Rear sub-assy to final assy	OP3	Every 6 cycles	17	20	23	Transfer	6 assemblies = 1 batch (gippa)
R31	Rear sub-assy WIP (R31)	N/A	N/A				Non-Value Added	Stores maximum of 12
	Load components (R31)	OP4	1	42	46	50	Value Added	
	Final assembly welding (R31)	R31	1		165		Value Added	
	Unload final assy (R31)	OP4	1	22	25	28	Value Added	
	Final assembly to leak test	OP4	1	10	12	14	Transfer	
	Load final assembly into leak test	OP5	1	22	25	28	Necessary Non-Value Added	
	Leak test final assembly	LTR	1		150		Necessary Non-Value Added	
	Unload final assy from leak test	OP5	1	15	18	21	Necessary Non-Value Added	
	If fails leak test, transfer to QC inspection	OP5	Every 20 cycles	12	14	16	Non-Value Added	5% of product
	If pass leak test, load into finished goods stillage	OP5	1	17	20	23	Necessary Non-Value Added	
	Finished goods stillage inventory	N/A	N/A				Non-Value Added	Stores maximum of 10 assemblies = 2 batches (stillages)
	Finished goods stillage collection	TUG	5	900	1000	1100	Necessary Non-Value Added	5 assemblies per stillage

Legend
Material Movement
WIP/Inventory
Assembly Process

3. Current-state DES model

Arena is a discrete-event simulation (DES) environment that combines the GUI (graphical user interface) ease of high-level simulators with the flexibility of simulation languages, using interchangeable module templates grouped into panels; its hierarchical design lets you work from drag-and-drop blocks down to SIMAN-level constructs in the same interface. Models are assembled from familiar modules - *Create, Process, Decide, Assign, Record, Batch, Separate, Dispose* - with additional *Advanced Process/Transfer* options when more detailed information is required (Kelton, Sadowski and Zupick, 2015).

3.1 DES Model Setup

Programming began with the *Create* module, which generates entities representing raw materials or assemblies; *Entities per Arrival* (quantity per release) and *Time Between Arrivals* set the arrival pattern. The set values equated to a total of 150 entities entering the model during one simulation cycle. Upon entity creation, the model reads the next record from `Part_Configuration_P6MHEV.csv` (Figure 4) using a *Read/Write* module, and assigns order attributes (e.g., variant L460 or L461) to the entity. This serves as a file-based import of the daily production plan, reflecting the required order mix and sequence.

	A
1	Variant
2	L460
3	L461
4	L461
5	L460
6	L461
7	L461
8	L461
9	L461

Figure 4: Part configuration file.

Process modules placed in sequence represent operations performed by resources. Each process employs *Seize-Delay-Release* logic: it seizes the required resource units, delays for the operation time, then releases the resources for the next entity. Machine operations utilise a constant delay (reflecting repeatable cycle times), while human operations use a triangular delay $TRIA(\text{min, most-likely, max})$ to account for human variability. Variable displays (Figure 5) illustrated average utilisation of resources, alongside indicators that highlighted whether a resource was idle or busy.

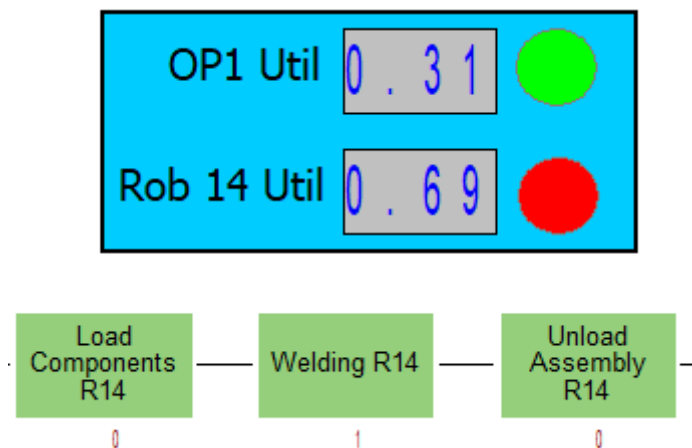


Figure 5: Robot 14 status indicators.

To prevent entities from entering a process unless downstream space is available, *Hold (Scan for Condition)* modules were placed immediately before the relevant processes. For example, the *Material Supermarket R14* hold (Figure 6) contains the following expression:

```
ResUtil(R14) == 0 && ResUtil(OP1) == 0 && (NQ(Material
Supermarket R19.Queue) + NQ(R14 Parts Output.Queue)) <= 15
```

This gate opens only when Robot 14 and Operator 1 are idle and the combined WIP in *Material Supermarket R19* and *R14 Parts Output* queues is ≤ 15 , implementing a pull control that enforces a 16-piece cap on the supermarket. On-screen variable displays showed the number of entities currently held, which were used to verify that supermarket limits were not exceeded.

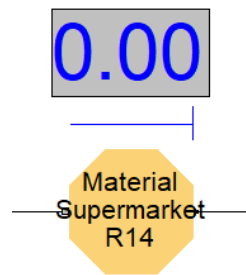


Figure 6: Material Supermarket R14 Hold module.

After each part left the process, a *Record (Time Between)* module (Figure 7) logged the interval to the next departure. The inverse of the mean inter-departure time is the assembly cell's throughput rate; idle time and blocking (e.g., a full kanban) are captured naturally as longer gaps. This metric is a fundamental KPI (key performance indicator) for measuring balancing loss in the value stream (SLACK, 2024).

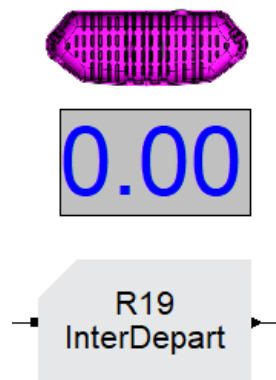


Figure 7: Robot 19 Record module.

Batch (Temporary) modules (Figure 8) were placed immediately before material-transfer operations to form loads of N units, and *Separate* modules were placed after to restore single-piece flow - i.e., WIP is aggregated into transfer lots, moved, then split at the next operation. The material transfer module simulated the time required to transfer the WIP to the downstream supermarket location.

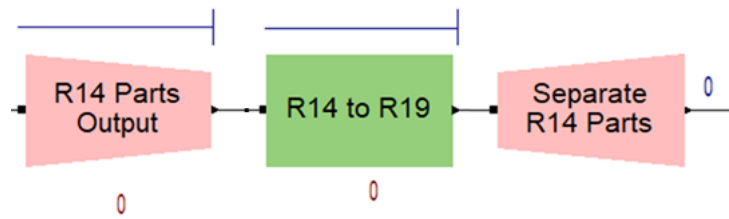


Figure 8: Robot 14 to Robot 19 batch and separate modules.

Decide modules route entities based on chance or conditions. Because the weld cycle time at Robot 30 varies by variant, an *N-way by Condition Decide* directs parts to variant-specific process modules (Figure 9): entities with L460 follow the L460 branch; L461 follow the L461 branch (per the part-configuration file).

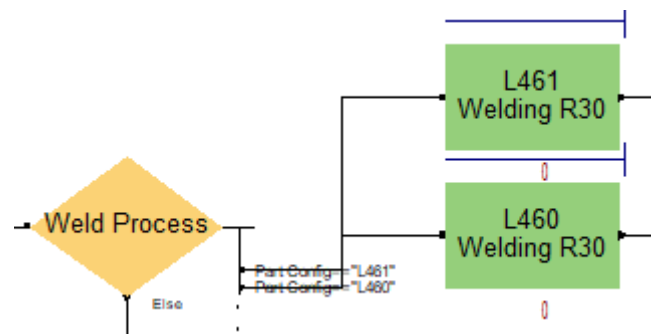


Figure 9: Robot 30 weld process decision module.

A *2-way by Chance Decide* modelled the leak-test outcome at Robot 31 (95% pass, 5% fail), routing failures to quality inspection. An *Assign* on each branch updated counters ($LTPass = LTPass + 1$ on the pass branch; $LTFail = LTFail + 1$ on the fail branch). These counters drove a live leak-test yield (%) display using: $100 * LTPass / MAX(1, LTPass + LTFail)$.

The final *Dispose* module displayed in Figure 10 terminates conforming parts; its *Number Out* statistic provides the throughput of good units.

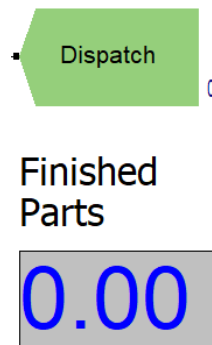


Figure 10: Dispose module.

The complete Arena DES model is presented in Appendix 2.

3.2 DES Model Parameters

Before operating the simulation, the run parameters were configured, and the required statistics were enabled. For this study, reporting focused on queues, resources, entities, and processes (e.g., record entity statistics, relevant tallies and time-persistent measures).

The simulation length for this study was set to 8 hours, corresponding to a single production shift. A warm-up period of 1.5 hours was introduced; this ensured that the final report excluded data collected during the first 1.5 hours, a period when buffers and lines are being filled.

In Arena, performance results are reported with confidence intervals as mean $\pm$ half-width; the half-width represents the margin of error at the chosen confidence level (e.g., 95%) and shrinks as more data is collected or variability is reduced (Cumming, 2012). Arena won't provide half-widths until that single replication has at least 320 observations (post-warm-up), or multiple replications are performed (Kelton, Sadowski and Zupick, 2015). A total of 5 replications were performed for this project.

3.3 DES Model Verification

Verification was iterative: after each module was added, the model was run to confirm it executed as intended. The process data in Table 2 was used as a reference when verifying logic and routing. Stress tests (e.g., temporarily inflating upstream cycle times) were conducted to confirm pull controls - such as supermarket caps - never exceeded their thresholds during the run. Figure 11 shows a stress-test screenshot of the model where Robot 19's weld cycle time was inflated to 1,000 seconds, which drove the R14 and R19 supermarkets to their caps. As expected, downstream stations starved - note the low utilisation at Robot 30.

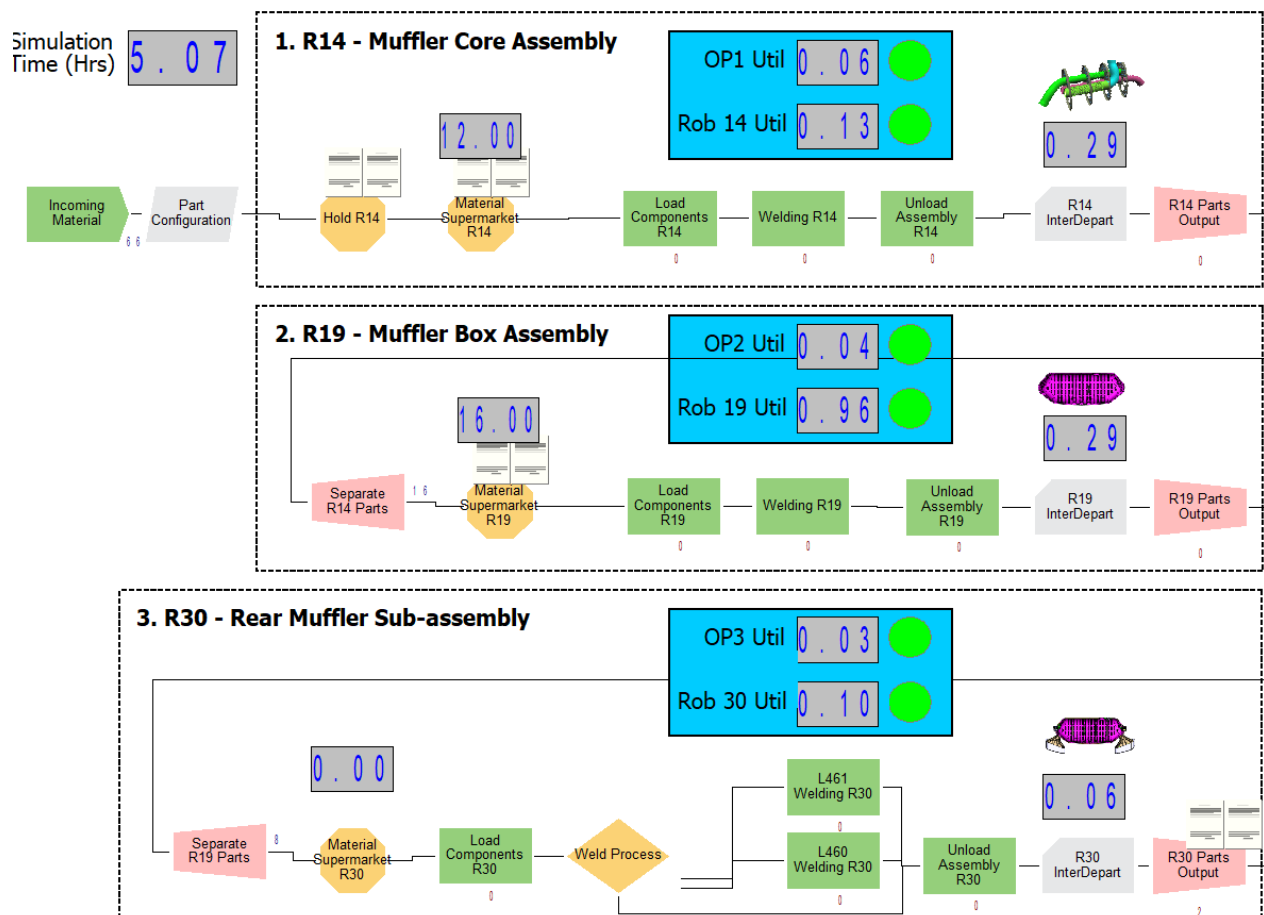


Figure 11: Material Supermarket stress-test.

4. Baseline DES Results

Key performance indicators (KPIs) translate the model into actionable decisions, linking performance to business goals (meeting takt, cutting WIP/space, improving OEE). Arena's power lies in its ability to produce these KPIs with statistical confidence, while capturing dynamic effects (blocking, starvation, variability) that static tools omit, and enabling what-if scenarios to see how buffer sizes, staffing, or cycle times change the outputs.

4.1 Flow / Rate

Throughput rate measures the number of work items completed per time period within a process. In the simulation, throughput metrics were reported in parts per hour and as inter-departure mean $\pm$ half-width (Table 3). The pacemaker cell, Robot 31, set the pace for the entire value stream (Lean Enterprise Institute, 2025) at a rate of 13.9 parts per hour (PPH); this value was only 0.2 PPH lower than the customer's takt time, indicating a narrow margin for stoppages, such as machine breakdowns.

To assess flow consistency, the coefficient of variation (CV) of Robot 31's inter-departure times was calculated. A lower CV indicates smoother flow, while a higher CV suggests uneven departures, which can increase queues and WIP, even at the same average throughput rate (Abdi, 2010). The value of 24% indicates moderate variability in throughput. While the process was not highly erratic, it does show noticeable fluctuations around the average rate. This level of variation may be influenced by factors such as bottlenecks, inconsistent cycle times, or resource availability.

The following expression was created to calculate Robot 31's coefficient of variation:

$$\left(\text{TNUM}(\text{Interdepart_R31}) > 1 \right) * \left(\text{TSTD}(\text{Interdepart_R31}) / \text{MAX}(1.0\text{E-}9, \text{TAVG}(\text{Interdepart_R31})) \right)$$

Table 3: Throughput KPIs.

Identifier	Mean (Hrs)	Half-width (Hrs)	Parts/Hr	Parts/Hr $\pm$	CV
Robot 14 Throughput	0.0563	0.0011	17.8	0.36	-
Robot 19 Throughput	0.0602	0.0018	16.6	0.50	-
Robot 30 Throughput	0.0650	0.0020	15.4	0.46	-
Robot 31 Throughput	0.0719	0.0029	13.9	0.56	24%

4.2 Time / WIP

The mean quantity of WIP accumulated at key points within the value stream is displayed in Table 4. Excessive WIP can result in longer lead times, higher inventory costs and increased risk of product damage.

Table 4: WIP KPIs.

Identifier	Mean (Qty)	Half-width (Qty) $\pm$
Total WIP	35.14	1.15
R14 Supermarket WIP	3.28	0.11
R19 Supermarket WIP	6.62	0.22
R30 Supermarket WIP	7.24	0.26
R31 Supermarket WIP	7.67	0.28

Total lead time is measured from the start of the production stream to the point at which finished goods are completed. Hold time refers to the duration materials spend idle, without being actively processed. Both these KPIs were used to identify unbalanced workstations and bottlenecks within the production process (Table 5).

Table 5: Lead & hold time KPIs.

Identifier	Mean (Hrs)	Half-width (Hrs) $\pm$
Total Lead Time	2.514	0.082
R14 Hold Time	0.171	0.007
R19 Hold Time	0.320	0.012
R30 Hold Time	0.435	0.018
R31 Hold Time	0.507	0.019

Balancing loss is the share of a resource's planned production time that is non-productive due to starvation or blocking (i.e., cycle-time mismatch). For this value stream, the aggregate balancing loss was 12%. Figure 12 highlights the stations where this loss was concentrated.

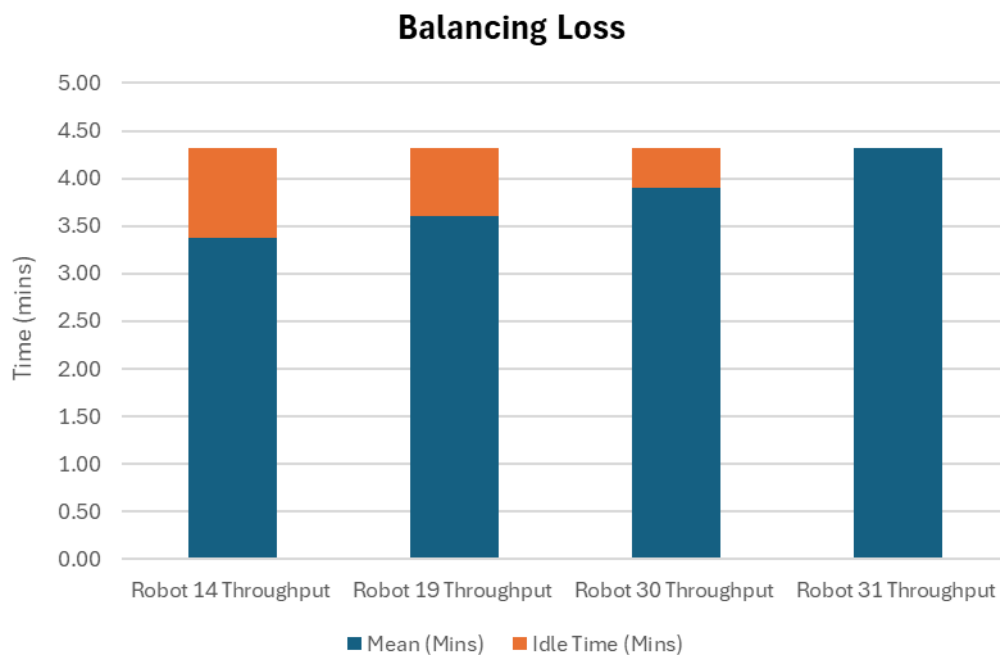


Figure 12: Balancing loss chart.

4.3 Resources

Table 6 reports resource utilisation for operators and machines. The Robot 31 welding cell was the system constraint, since it set the line throughput (13.9 parts/hr). The near-100% cell utilisation reported for Robot 14 in the 6.5-hour analysis window was a start-up artefact. During ramp-up, Robot 14 is busy filling upstream buffers and is not yet blocked by downstream limits; extending the window to 14.5 hours resulted in the time-average reducing to ~90% as normal blocking/starvation appeared.

Table 6: Resource utilisation KPIs.

Identifier	Mean %	Mean % (Cell)
R14 Utilisation	69%	99%
OP1 Utilisation	30%	
R19 Utilisation	78%	96%
OP2 Utilisation	18%	
R30 Utilisation	66%	90%
OP3 Utilisation	24%	
R31 Utilisation	67%	100%
OP4 Utilisation	33%	
LTR Utilisation	61%	86%
OP5 Utilisation	25%	

4.4 Quality

The leak-test first pass yield rate was 95.2% (CI: $\pm 2.68\%$), almost matching the initial yield obtained during the data collection phase.

4.5 Value Analysis

During model build, each time-bearing activity was assigned to one of four reporting categories in Arena:

- **Value-added:** transforms the product/service in a way that benefits the customer.
- **Non-value added:** processing that consumes time/resources without increasing customer value (e.g., inspection, rework).
- **Waiting:** resources or materials that are idle (Abdulmalek and Rajgopal, 2007).
- **Transfer time:** the movement of materials between steps.

There is also a fifth category: necessary non-value-added, which may be a regulatory inspection requirement that doesn't necessarily add value for the customer (Gellad and Day, 2016).

Figure 13 shows the percentage of total time allocated to each of the four main categories.

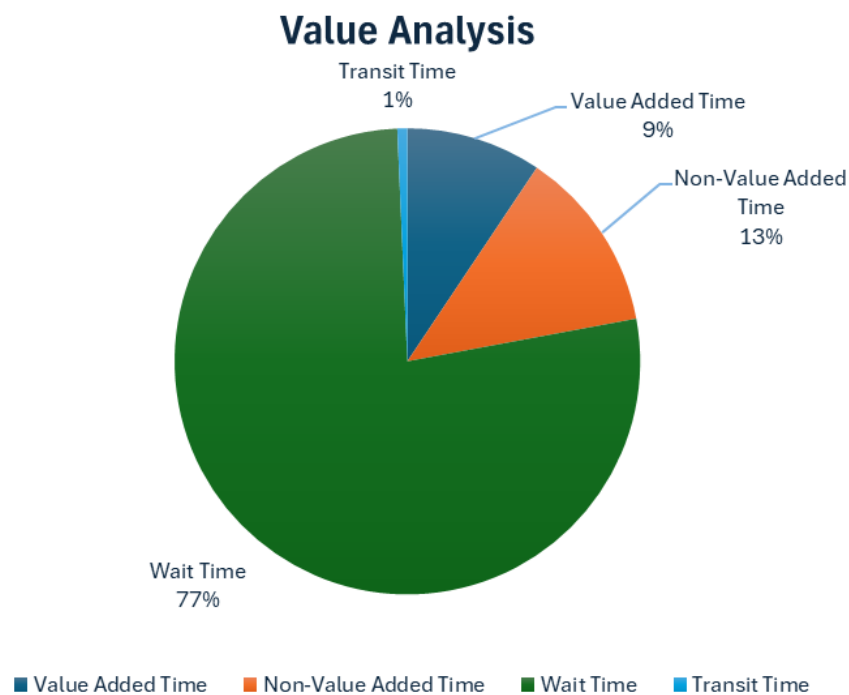


Figure 13: Value analysis pie chart.

5. Waste & Value Analysis

Waste identification in manufacturing was pioneered within the Toyota Production System (TPS) led by Taiichi Ohno. The term lean was later popularised by Womack and Jones (1996) as lean thinking, describing systematic waste elimination and continuous improvement. Lean aims for smooth, synchronised flow to deliver what customers value - perfect quality, in the right quantity, when and where needed - at the lowest possible cost (Slack, Brandon-Jones and Burgess, 2022). Toyota also highlights three root causes of waste: Mura (unevenness), Muri (overburden) and Muda (non-value-adding work), with Muda commonly grouped into the seven classic wastes (Pienkowski and Pieńkowski, 2014). The DES model was assessed against these seven wastes using the simulation results from the previous section (see Table 7).

Table 7: Seven Wastes Assessment (DES Model) (Bicheno and Holweg, 2016).

Waste Category	Observations	Evidence
1. Over-production	Technically, all processes produced more products than required, as WIP was present in the supermarkets. However, limits prevented severe overproduction. Data leads Robot 31 being a bottleneck.	Average WIP in queues: - R14: 3.28 - R19: 6.62 - R30: 7.24 - R31: 7.67
2. Waiting	Operators and machines were idle for a substantial share of on-shift time, primarily due to blocking and starvation from line imbalance.	Resource utilisation: - Machine average: 68% - Human average: 26% 77% of time-bearing activities were spent waiting.
3. Transport	Material transfers between operations were performed manually; however, at the value-stream level, they contributed only a small share of non-value-added time.	1% of time-bearing activities were spent transferring material.
4. Overprocessing	The leak-test operation does not add customer value; however, because it verifies a Critical Characteristic and is mandated, it is classified as necessary non-value-added (NNVA).	On average, 3.4 minutes per assembly was consumed by leak testing.
5. Inventory	Overall, WIP was acceptable in magnitude but poorly distributed; the supermarkets feeding R30–R31 carried disproportionate WIP as R31's constraint limited downstream pull and blocked upstream flow.	Average WIP in queues: - R14: 3.28 - R19: 6.62 - R30: 7.24 - R31: 7.67 Average total WIP: 35.15
6. Motion	The overall value-streams layout is suboptimal. There are large distances between Robots 19 and 30.	11 m gap between Robot 19 and 30.
7. Defect/rework	A high quantity of products were defective due to failing the leakage test.	4.8% defect rate.

Scholars have expanded Ohno's original seven wastes to include categories such as variation, unclear communication, and duplication (Ozgur Dogan and Simsek Yagli, 2020). Furthermore, Pawanr and Gupta (2024) show that non-cutting/standby (idle) modes can dominate machine-tool energy consumption - a form of waste that is evident in the P6 MHEV value stream, given the robots' 32% idle time.

In their assessment of how lean transformed automotive operations, Womack, Jones and Roos (2007) emphasise pacing to takt and production levelling (heijunka) to achieve smooth flow. In this value stream, the KPI set - pacemaker inter-departure CV, % time supermarkets at cap, starved/blocked time, and balancing loss - reveals pronounced unevenness (mura), which in turn drives longer lead time, higher WIP, and depressed, erratic resource utilisation. Therefore, improvements should focus on smoothing arrivals at Robot 31, aligning cycle times, and right-sizing buffers to reduce mura and its resulting wastes.

6. Opportunity Identification (Lean Evaluation)

The first opportunity for improvement is to resolve the line-balancing concerns. Creating detailed current-state standard work documents for each cell would enable a data-driven approach to developing multiple future-state value stream maps (Liker and Meier, 2005). These future states might involve:

1. Redistributing work elements or working collaboratively to reduce cycle times. For example, OP5 could support OP4 during the loading operation of Robot 31, reducing the overall throughput rate and increasing overall energy efficiency, due to reduced machine idle time (Pawanr and Gupta, 2024).
2. Repositioning machines to enable operatives to execute tasks for multiple cells. There may be an opportunity to reduce labour, while still maintaining or improving upon the existing throughput rate.
3. Deploying dual-station robotic cells to introduce parallel capacity, enabling operators to load one station while the other welds (SLACK, 2024).

A decision matrix (Figure 14, Elmansy, 2022) is an effective way to compare these proposals, based on weighted KPI criteria (throughput, WIP, utilisation, etc.), with sensitivity checks on the weights.

	Competency	Cost	Viability	Desirability	Alignment	Total
Criteria rating	3	4	5	4	2	
Idea A	1	3	3	1	1	
Weighted rating	3	12	15	4	2	36
Idea B	5	3	5	3	4	
Weighted rating	15	12	25	12	8	72
Idea C	1	2	3	1	1	
Weighted rating	3	8	15	4	2	32
Idea D	5	1	2	1	1	
Weighted rating	15	4	10	4	2	35

Figure 14: Decision matrix example (Elmansy, 2022).

Although transport accounted for only 1% of total time, an automated, paced conveyor between cells could still deliver benefits: shorter in-cell handling time, more consistent transfers, lower WIP/inventory carrying cost, and reduced damage risk from fewer interactions. Repositioning R14 and R19 closer to R30 would further cut transfer time and free floor space.

Investigations into the high leak-test failure rate should follow a systematic approach such as DMAIC. DMAIC (Define–Measure–Analyse–Improve–Control) is a structured, five-phase method for problems with unknown causes; it combines lean and statistical tools - e.g., SPC (statistical process control)/control charts, measurement system analysis (MSA), Ishikawa/5-Whys, FMEA (failure mode and effects analysis) - to quantify the problem, identify root causes, implement improvements, and hold the gains (Lal Bhaskar, 2020). Applied here, a Lean Six Sigma project using DMAIC would aim to reduce defects and cycle time, lower inventory and cost, and increase capacity and quality, ultimately enhancing customer satisfaction.

Introducing a robust Total Productive Maintenance (TPM) programme reduces unplanned downtime and quality drift by embedding autonomous maintenance, planned maintenance, and root-cause elimination, enabling reliable flow and higher OEE. As shown in Figure 15 (Roser, 2021), TPM rests on a foundation of 5S - systematic workplace organisation, standardisation, and visual control - which stabilises basic conditions and makes abnormalities obvious. Without 5S, TPM routines deteriorate, and improvements are not sustained (Bicheno and Holweg, 2016).

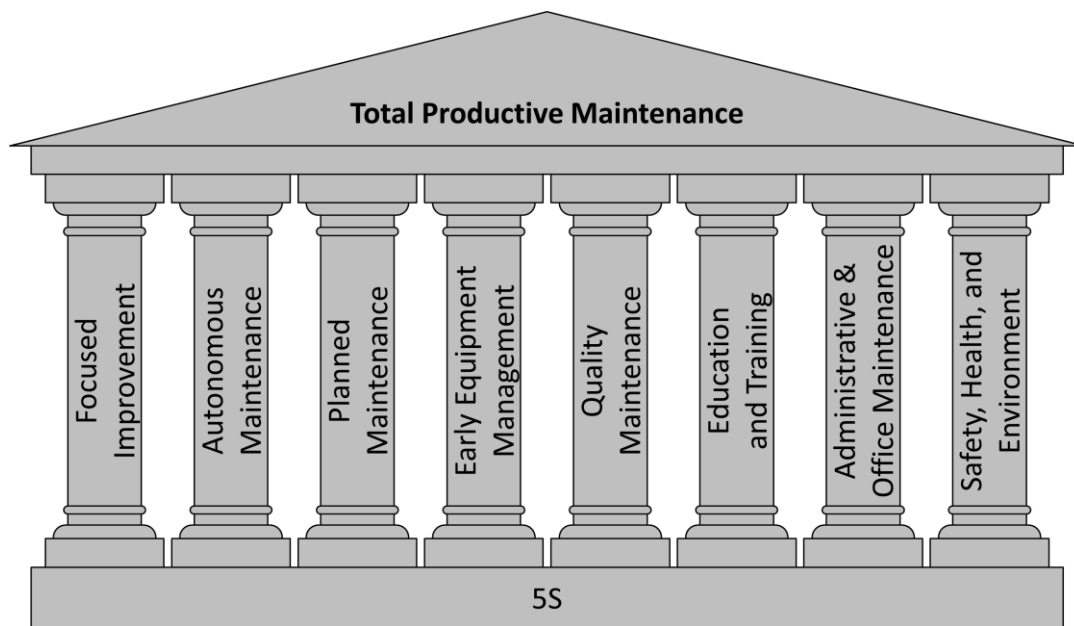


Figure 15: Eight pillars of TPM (Roser, 2021).

Before submitting any high-investment proposals to management and stakeholders, a rigorous cost-benefit analysis should be conducted to confirm economic viability (e.g., return on investment and payback within an acceptable period). The assessment must also verify that there are no adverse effects on product quality or on employee health and well-being.

7. Conclusion

This study employed discrete-event simulation (DES) to model the single-piece-flow section of an exhaust manufacturing value stream and recommend improvements to address low OEE (Overall Equipment Effectiveness) and intermittent line stoppages. The pacemaker (R31) sets throughput at 13.9 parts/hr; the inter-departure coefficient of variation (0.24) indicated moderate unevenness. Faster upstream cycles accumulated WIP (work in progress) ahead of R30–R31; after warm-up, the lead time was 2.50 ± 0.08 hours, consistent with an average WIP of 35.1 parts (Little's Law). Leak-test first-pass yield was 95.2%. Operators averaged 26% utilisation compared to 68% for machines, with a 12% balancing loss driven by starved/blocked time.

Line-balancing should be the priority, with a focus to redistribute work and (where feasible) equipment to increase utilisation, rebalance WIP, and safeguard throughput. Investigate repositioning R14/R19 closer to R30 with a synchronised conveyor to cut material transfer time and space – although this should be validated via DES and return on investment, since transport contributes only 1% of total time. Leveraging Six Sigma methodologies, such as DMAIC, could minimise leak test failures, ultimately improving the throughput rate, lowering cost and increasing capacity.

Adopting lean's discipline of systematically identifying and eliminating waste will move the line towards smooth, reliable flow and value for customers. Any high-investment proposals should undergo a rigorous cost-benefit analysis before implementation.

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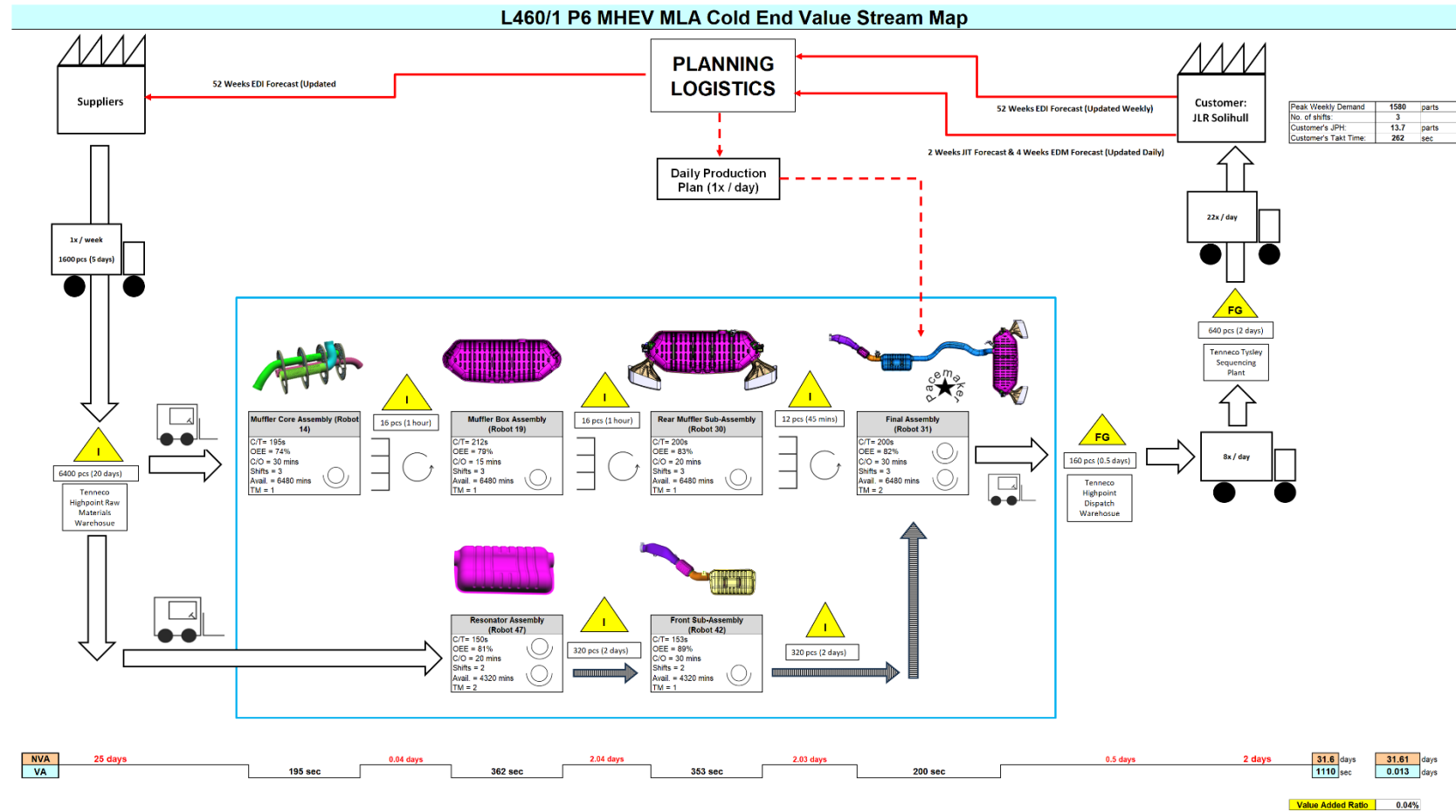
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Appendix

Appendix 1 – P6 MHEV Cold End Value Stream Map



Appendix 2 – Arena DES model for P6 MHEV Cold End product line

