Model Validation and Model Comparison Results

The following lists all obtained results from internal model analysis, sensitivity analysis, and model comparison with regard to the following publication:

"A priori performance assessment of line-less mobile assembly systems" Authors R.H. Schmitt, G. Hüttemann and S. Münker

DOI: https://doi.org/10.1016/j.cirp.2021.04.059

Cite as: Robert H. Schmitt, Guido Hüttemann, Sören Münker: A priori performance assessment of line-less mobile assembly systems. CIRP Annals, Volume 70, Issue 1, 2021,Pages 389-392

1

Results of Convergence Testing

1.1 Throughput

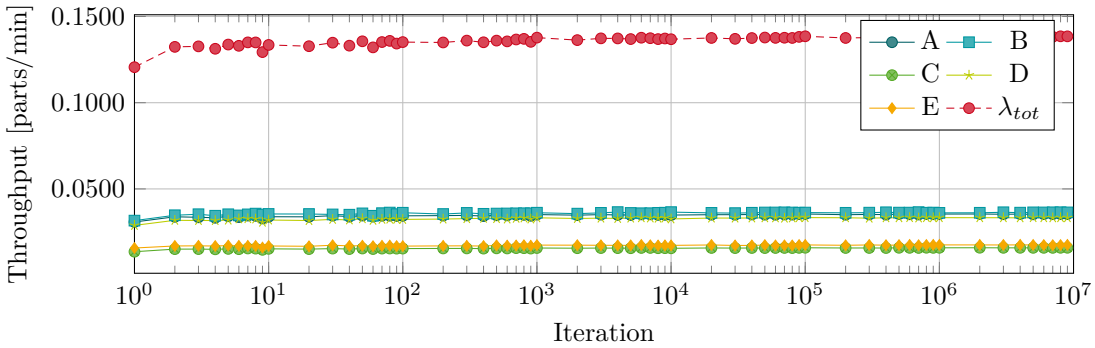

Figure 1.1: Convergence test results for throughput λ_j for products A to E and total throughput (scenario 1A)

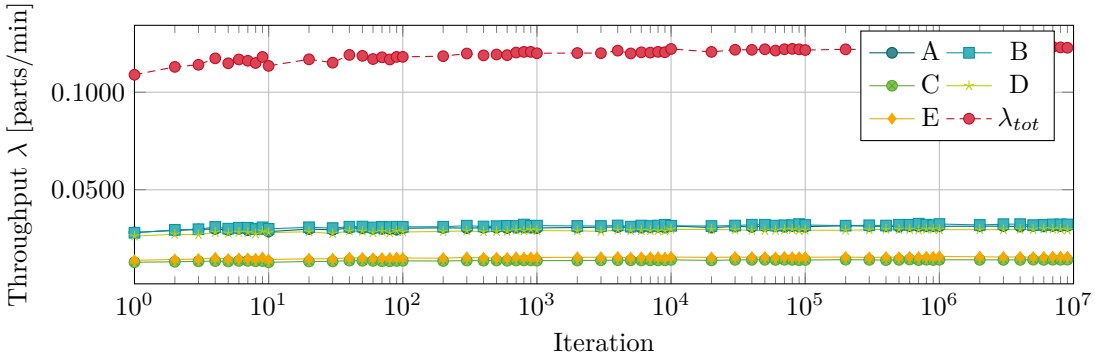

Figure 1.2: Convergence test results for throughput for products A to E and total throughput (scenario 1B)

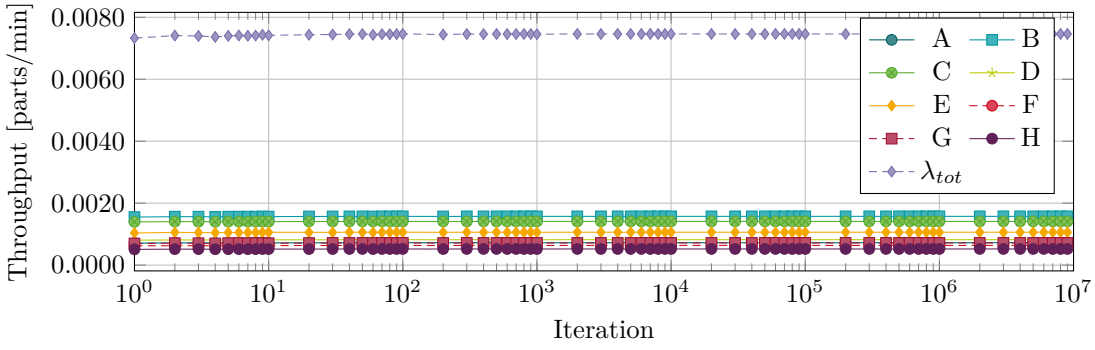

Figure 1.3: Convergence test results for throughput λ_j for products A to H and total throughput (scenario 2A)

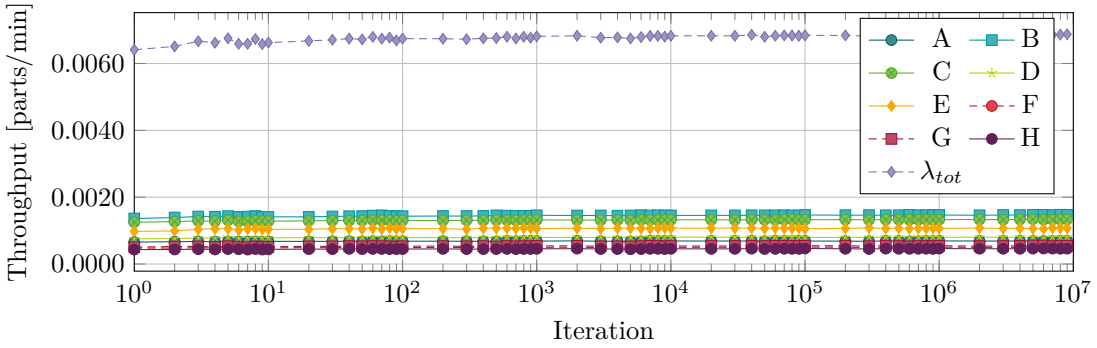

Figure 1.4: Convergence test results for throughput λ_j for products A to H and total throughput (scenario 2B)

1.2 Lead Time

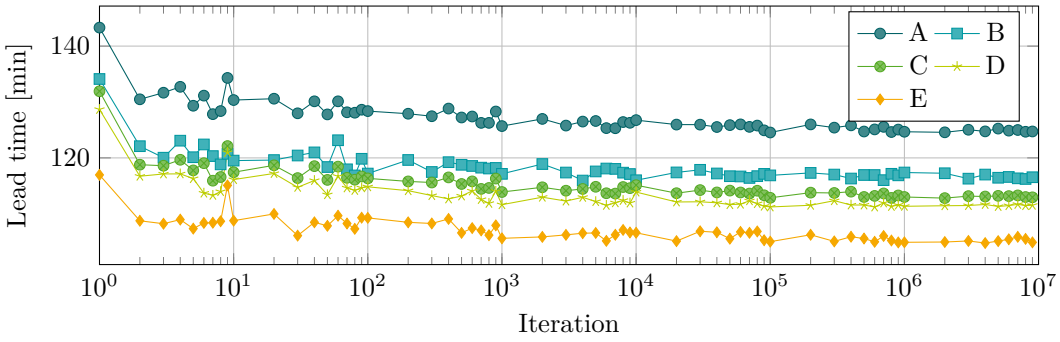

Figure 1.5: Convergence test results for lead time LT for products A to E (scenario 1A)

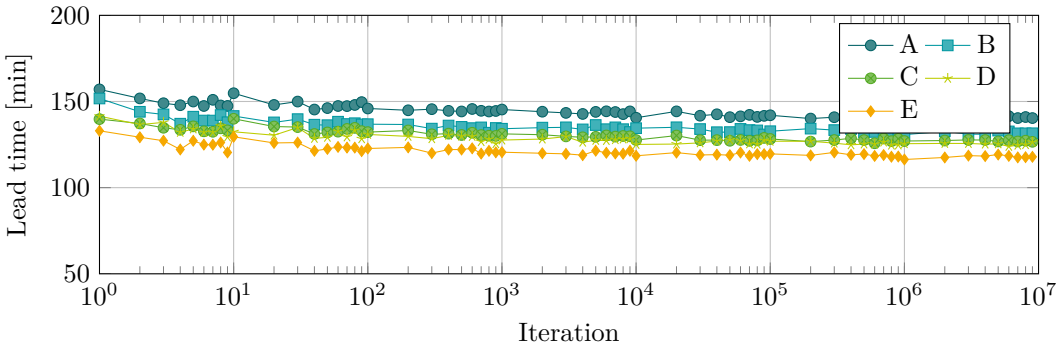

Figure 1.6: Convergence test results for lead time LT for products A to E (scenario 1B)

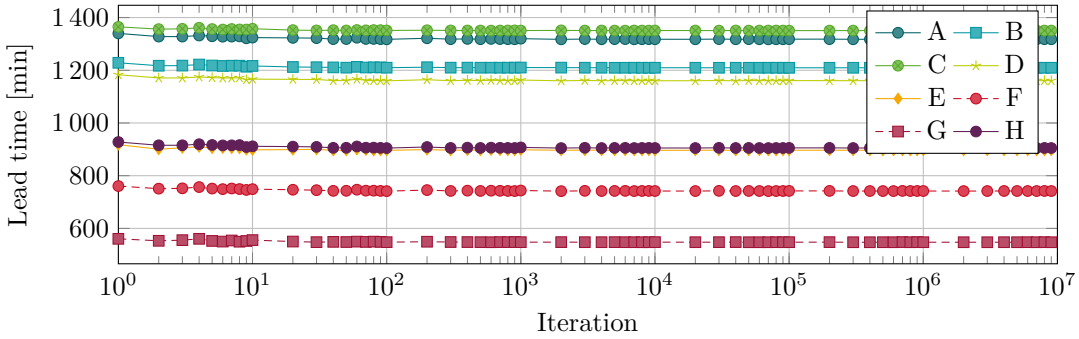

Figure 1.7: Convergence test results for lead time LT for products A to H (scenario 2A)

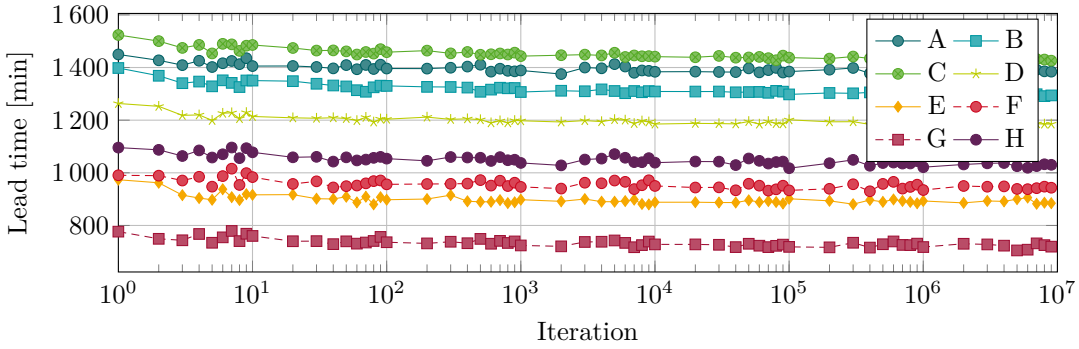

Figure 1.8: Convergence test results for lead time LT for products A to H (scenario 2B)

1.3 Station Configuration Utilisation

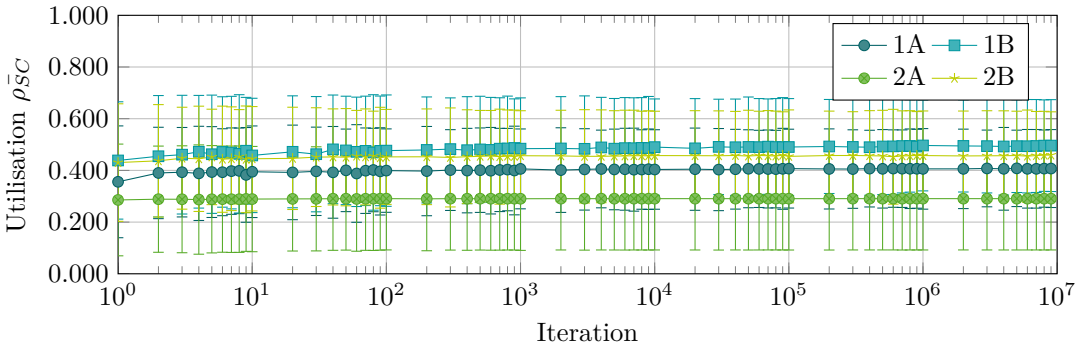

Figure 1.9: Convergence test results for mean station configuration utilisation $\bar{\rho}_{SC}$ (all scenarios)

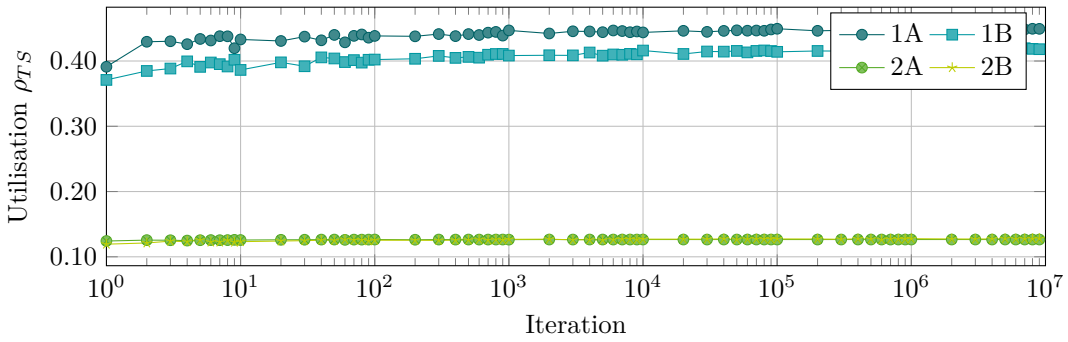

Figure 1.10: Convergence test results for transport system utilisation ρ_{TS} (all scenarios)

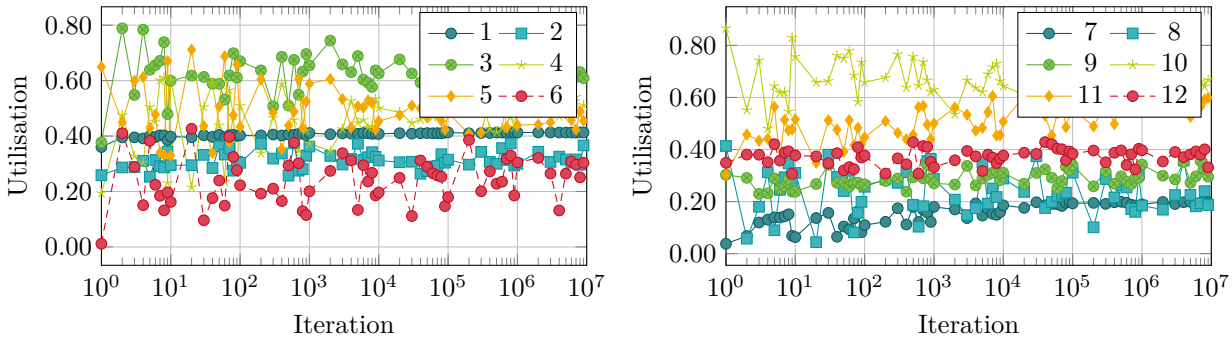

Figure 1.11: Station configuration utilisation ρ_{SC} for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 1A)

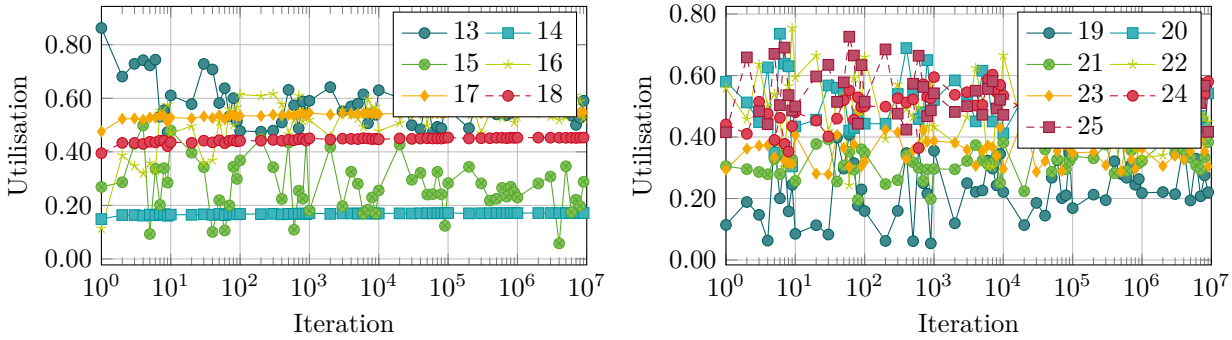

Figure 1.12: Station configuration utilisation ρ_{SC} for SC_{13} to SC_{18} (left) and SC_{19} to SC_{25} (right, scenario 1A)

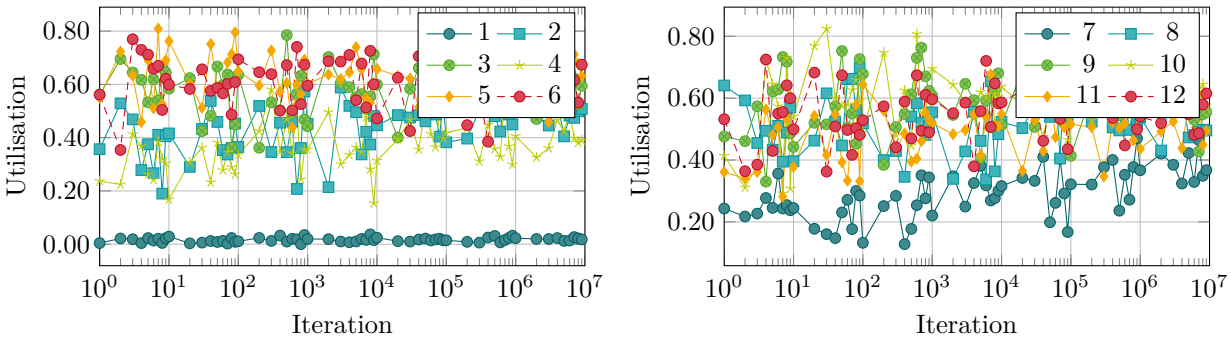

Figure 1.13: Station configuration utilisation ρ_{SC} for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 1B)

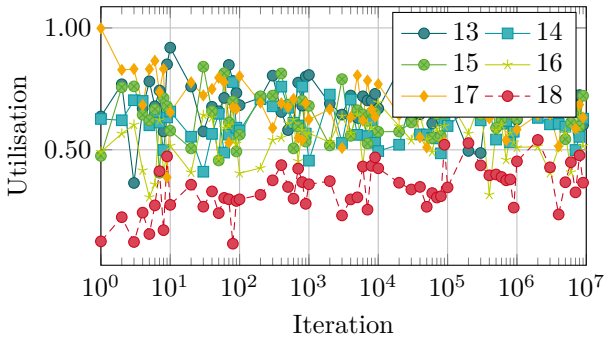

Figure 1.14: Station configuration utilisation ρ_{SC} for SC_{13} to SC_{18} (scenario 1B)

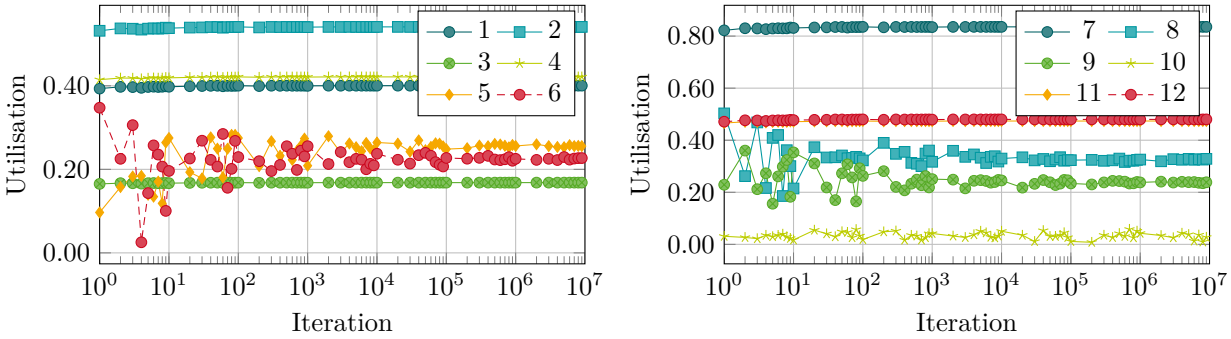

Figure 1.15: Station configuration utilisation ρ_{SC} for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 2A)

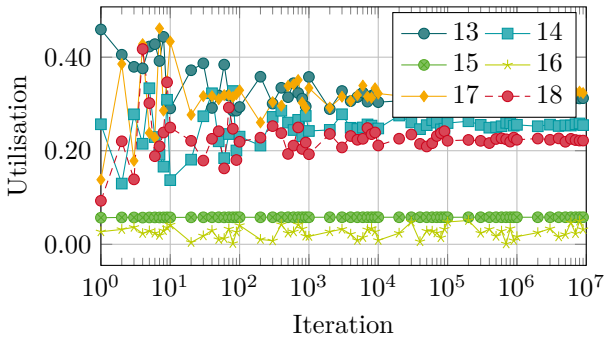

Figure 1.16: Station configuration utilisation ρ_{SC} for SC_{13} to SC_{18} (scenario 2A)

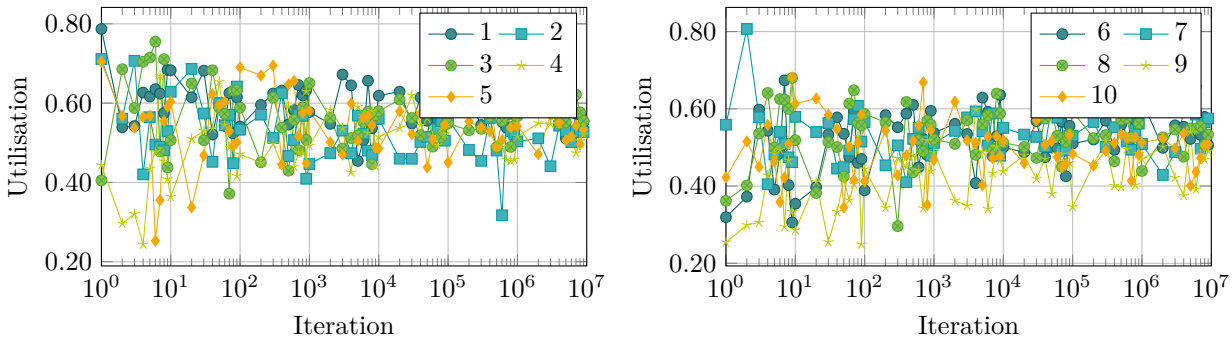

Figure 1.17: Station configuration utilisation ρ_{SC} for SC_1 to SC_5 (left) and SC_6 to SC_{10} (right, scenario 2B)

1.4 Station Configuration Utilisation for a Single Model Execution

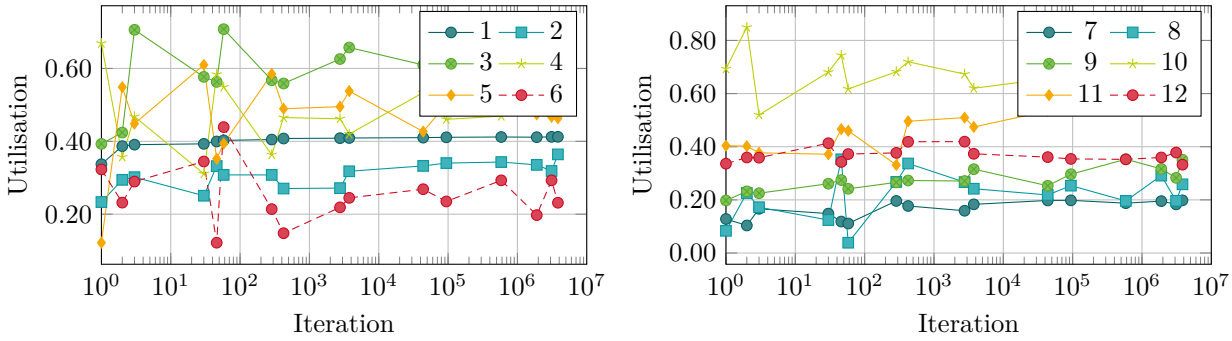

Figure 1.18: Station configuration utilisation progression ρ_{SC} for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right) for a single model execution (scenario 1A)

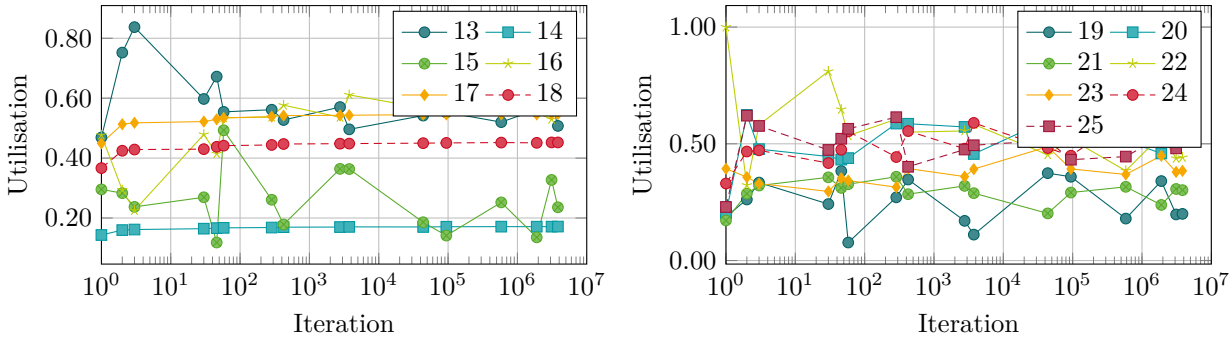

Figure 1.19: Station configuration utilisation progression ρ_{SC} for SC_{13} to SC_{18} (left) and SC_{19} to SC_{25} (right) for a single model execution (scenario 1A)

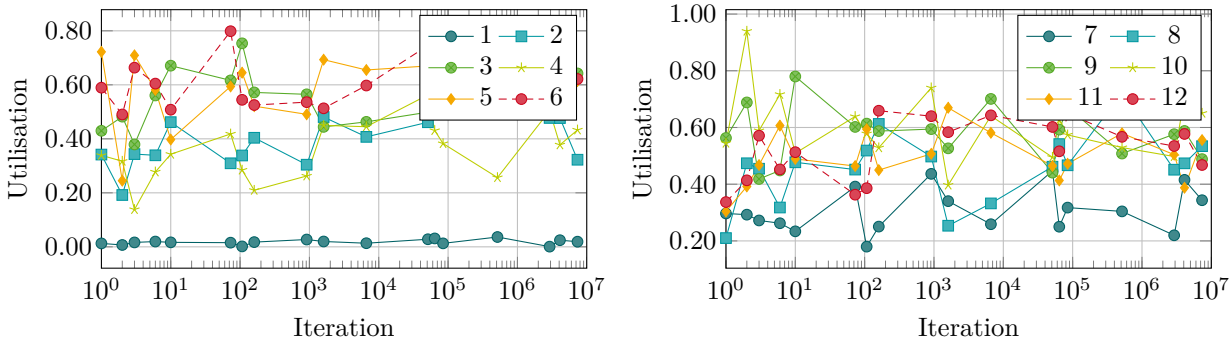

Figure 1.20: Station configuration utilisation progression ρ_{SC} for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right) for a single model execution (scenario 1B)

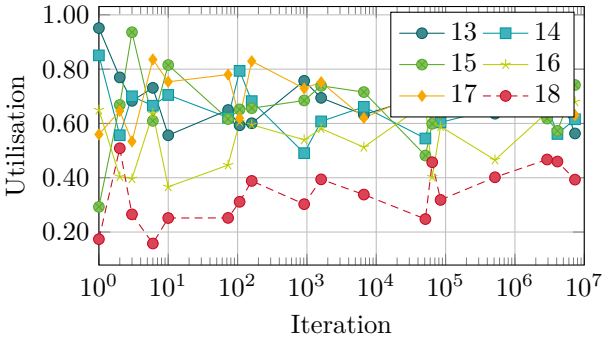

Figure 1.21: Station configuration utilisation ρ_{SC} progression for SC_{13} to SC_{18} for a single model execution (scenario 1B)

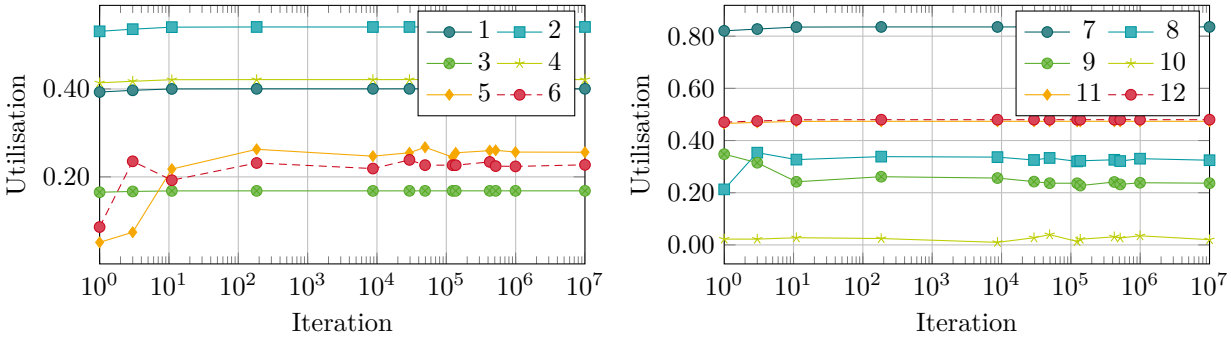

Figure 1.22: Station configuration utilisation progression ρ_{SC} for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right) for a single model execution (scenario 2A)

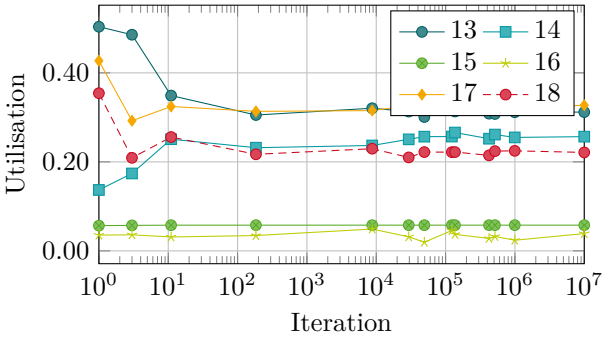

Figure 1.23: Station configuration utilisation ρ_{SC} progression for SC_{13} to SC_{18} for a single model execution (scenario 2A)

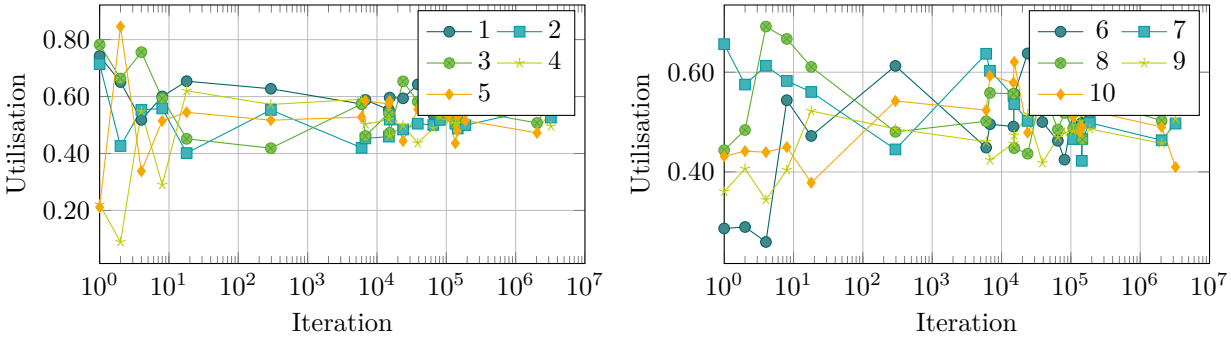

Figure 1.24: Station configuration utilisation progression ρ_{SC} for SC_1 to SC_5 (left) and SC_6 to SC_{10} (right) for a single model execution (scenario 2B)

1.5 Waiting Times at Servers

1.5.1 Waiting Time at Transport System

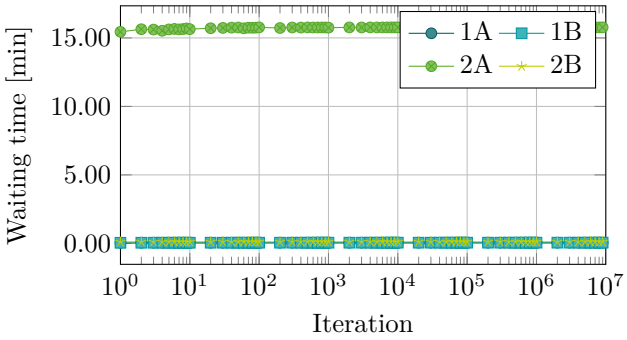

Figure 1.25: Convergence test results for waiting time at the transport system w^q_{TS} (all scenarios)

1.5.2 Waiting Times for Station Configurations

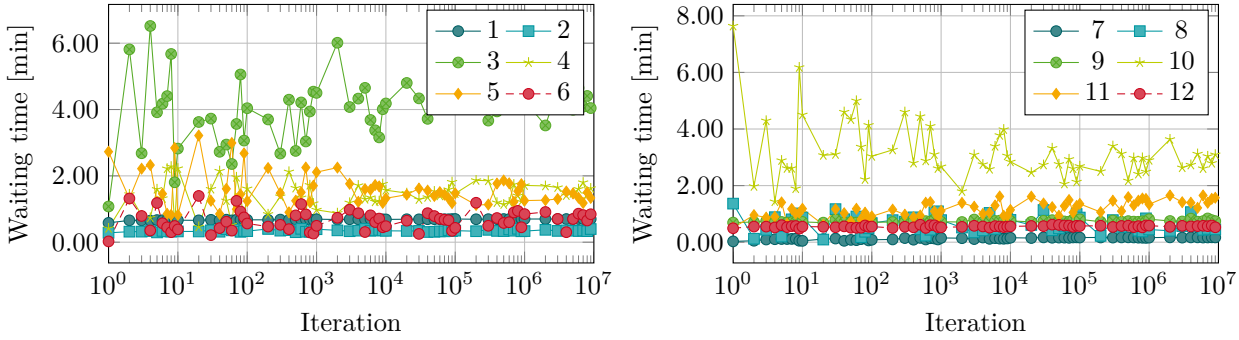

Figure 1.26: Waiting time w^q for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 1A)

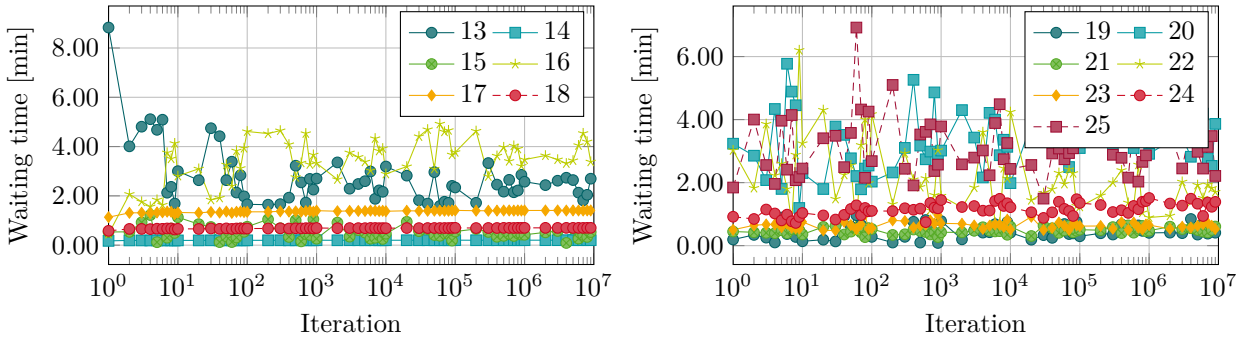

Figure 1.27: Waiting time w^q for SC_{13} to SC_{18} (left) and SC_{19} to SC_{25} (right, scenario 1A)

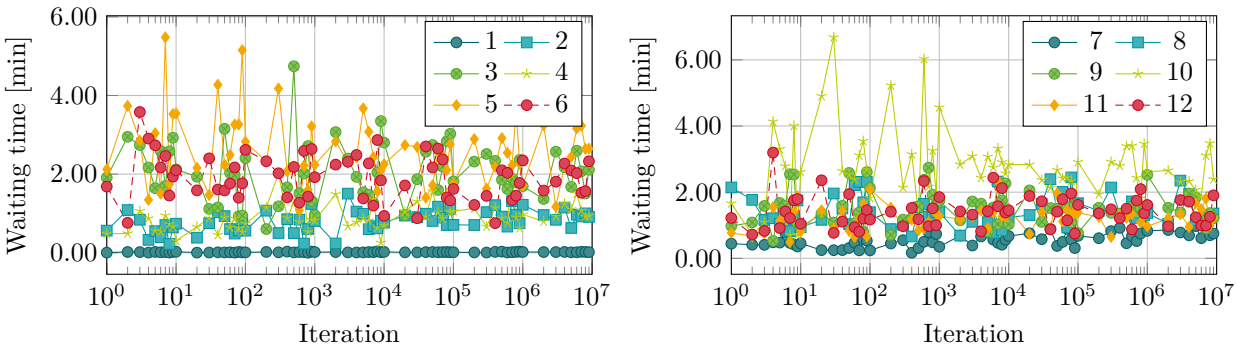

Figure 1.28: Waiting time w^q for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 1B)

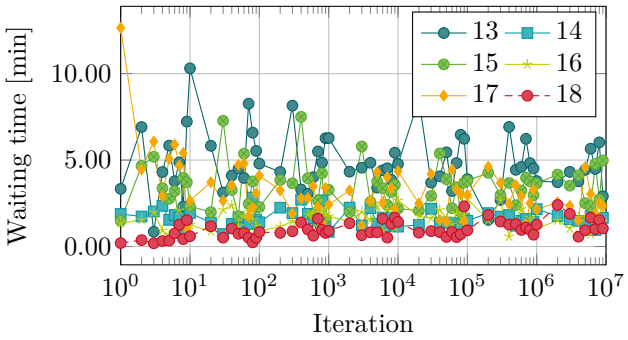

Figure 1.29: Waiting time w^q for SC_{13} to SC_{18} (scenario 1B)

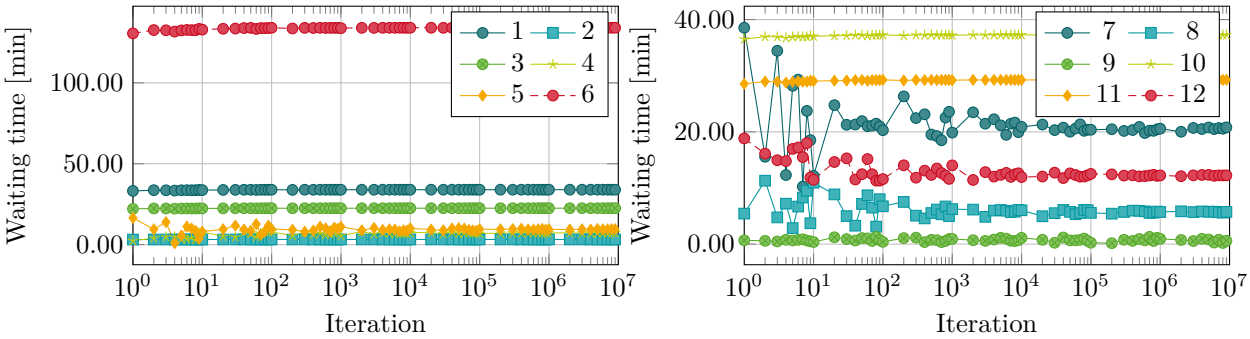

Figure 1.30: Waiting time w^q for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 2A)

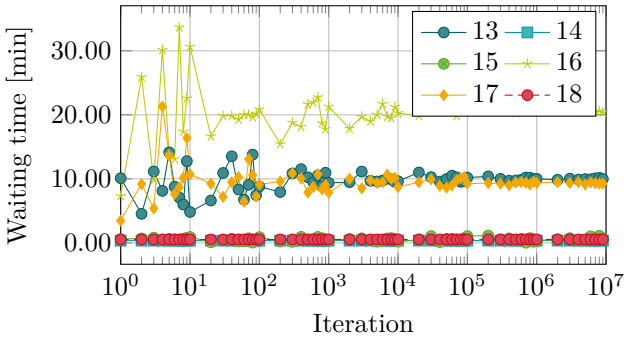

Figure 1.31: Waiting time w^q for ρ_{SC} for SC_{13} to SC_{18} (scenario 2A)

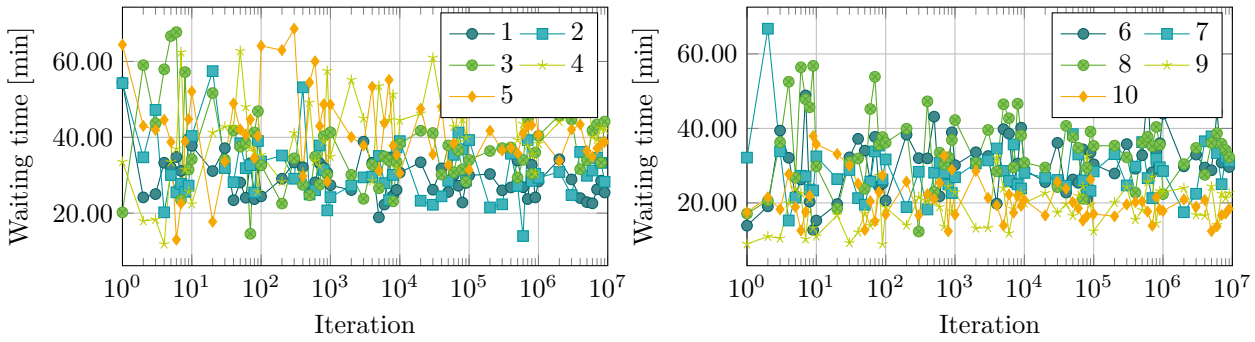

Figure 1.32: Waiting time w^q for SC_1 to SC_5 (left) and SC_6 to SC_{10} (right, scenario 2B)

1.5.3 Mean Waiting Times at Station Configurations

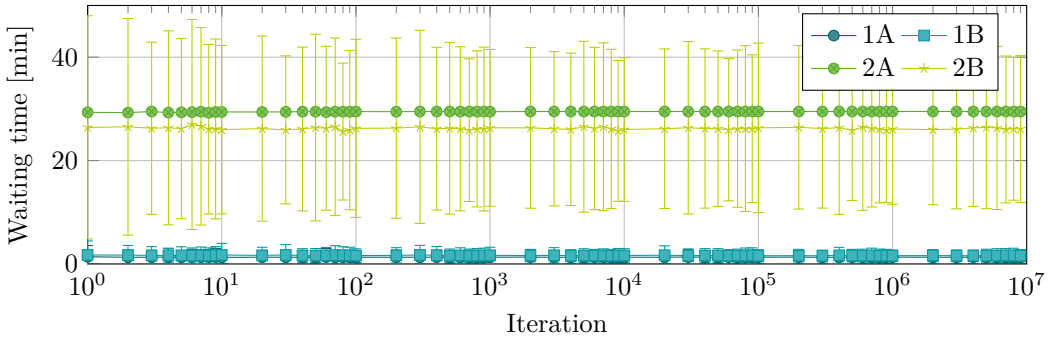

Figure 1.33: Convergence test results for mean waiting time $\bar{w}^q_{SC}$ (all scenarios)

1.6 Queue Lengths at Servers

1.6.1 Queue Lengths at Transport System

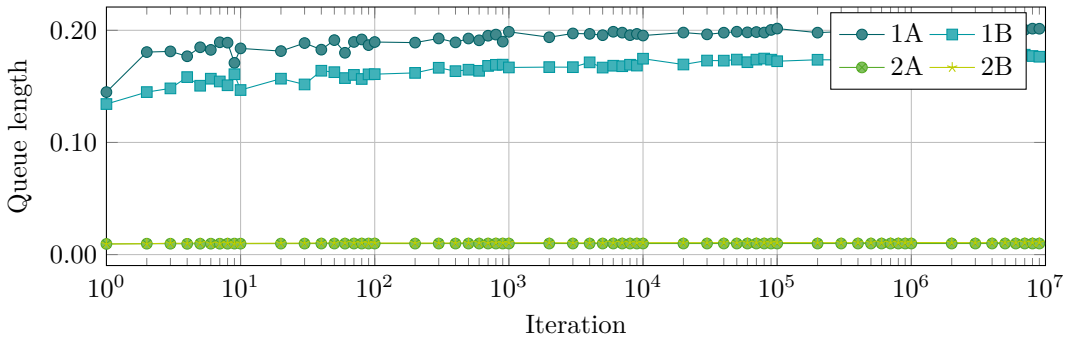

Figure 1.34: Convergence test results for queue lengths at the transport system w^q_{TS} (all scenarios)

1.6.2 Queue Lengths for Station Configurations

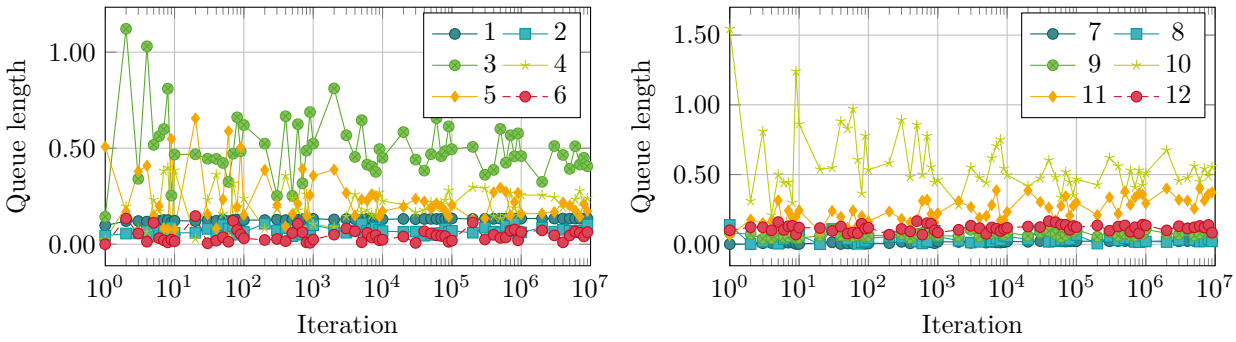

Figure 1.35: Queue lengths for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 1A)

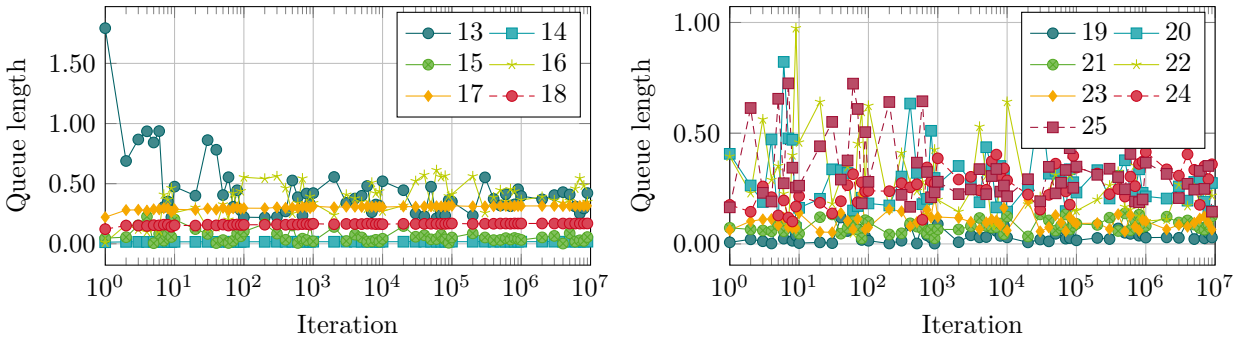

Figure 1.36: Queue lengths for SC_{13} to SC_{18} (left) and SC_{19} to SC_{25} (right, scenario 1A)

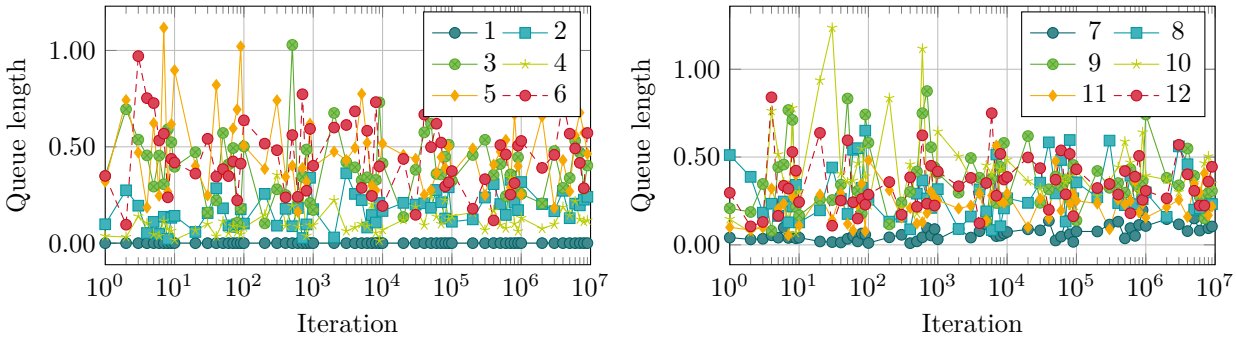

Figure 1.37: Queue lengths for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 1B)

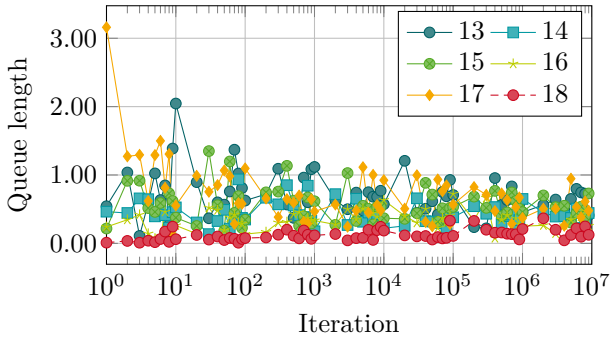

Figure 1.38: Station configuration utilisation ρ_{SC} for SC_{13} to SC_{18} (scenario 1B)

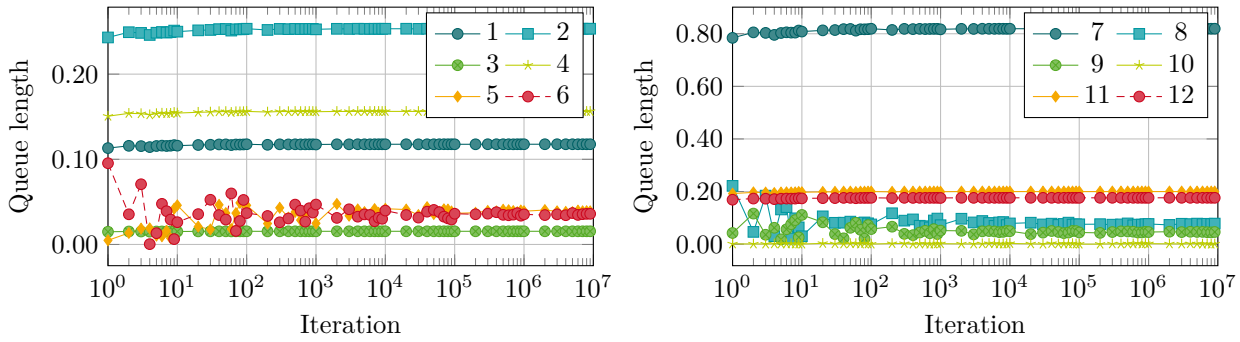

Figure 1.39: Queue lengths for SC_1 to SC_6 (left) and SC_7 to SC_{12} (right, scenario 2A)

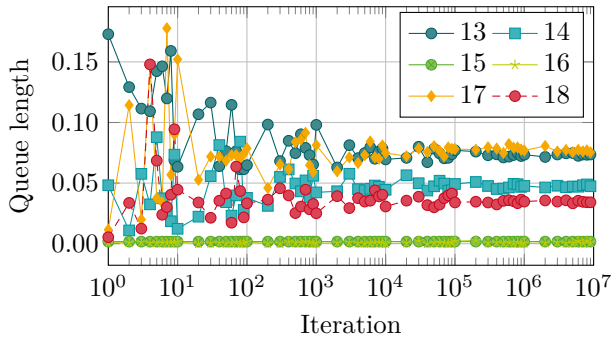

Figure 1.40: Station configuration utilisation ρ_{SC} for SC_{13} to SC_{18} (scenario 2A)

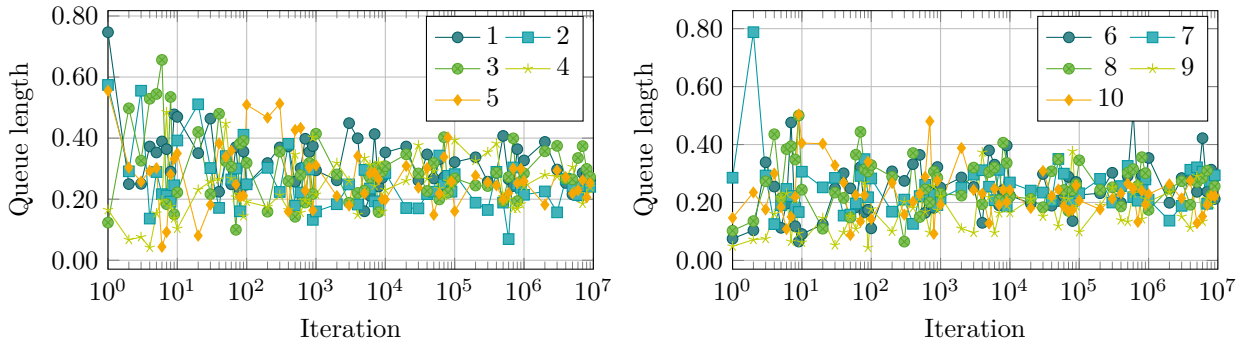

Figure 1.41: Queue lengths for SC_1 to SC_5 (left) and SC_6 to SC_{10} (right, scenario 2B)

1.6.3 Mean Queue Lengths at Station Configurations

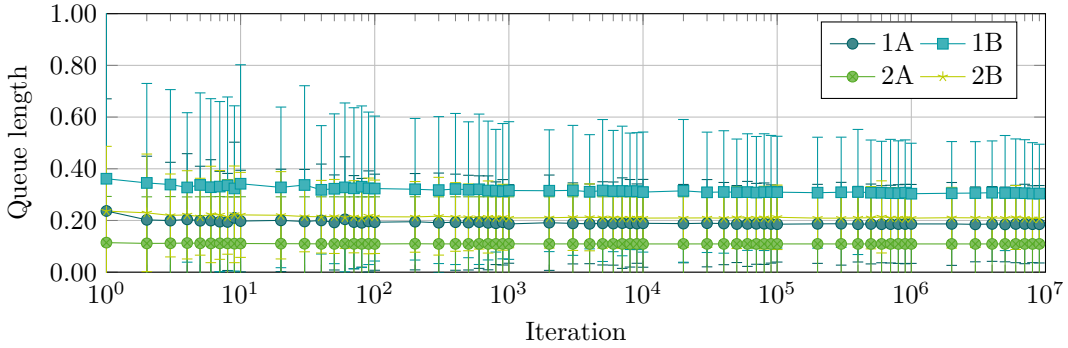

Figure 1.42: Convergence test results for mean queue length $\bar{n}^q_{SC}$ (all scenarios)

1.7 Required Resources

1.7.1 Number of Required Resources by Type

Table 1.1: Number of required resources by type for the last 5 improved iterations (scenario 1A)

Resource	Iteration n-4	Iteration n-3	Iteration n-2	Iteration n-1	Iteration n
1	6	6	6	6	6
2	2	2	2	2	2
3	3	3	3	3	3
4	1	1	2	1	1
5	2	2	2	2	2
6	2	1	2	2	2
7	2	2	2	2	2
8	3	3	3	3	3
9	4	4	4	4	4
10	2	2	2	2	2
11	5	5	5	5	5
12	6	6	6	6	6
13	2	2	2	2	2
14	3	3	3	3	3
15	1	1	2	2	2
16	1	1	1	1	1
17	2	2	2	2	2
18	7	7	7	7	7
19	5	5	6	6	6
20	6	6	6	6	6
21	4	4	4	4	4
22	2	2	3	2	2
23	2	2	2	2	2
24	2	2	2	1	1
25	4	4	4	4	4

Table 1.2: Number of required resources by type for the last 5 improved iterations (scenario 1B)

Resource	Iteration n-4	Iteration n-3	Iteration n-2	Iteration n-1	Iteration n
1	5	6	6	6	6
2	2	2	2	2	2
3	4	4	4	4	4
4	2	2	2	2	2
5	2	2	2	2	2
6	1	1	1	1	1
7	3	3	3	3	3
8	3	3	3	3	3
9	4	4	4	4	4
10	3	3	3	3	3
11	6	6	6	6	6
12	5	5	5	5	5
13	2	2	2	2	2
14	3	3	4	3	4
15	1	1	1	1	1
16	1	1	1	1	1
17	2	2	2	2	2
18	3	3	3	3	3
19	3	3	3	3	3
20	2	2	2	2	1
21	1	1	1	1	1
22	2	2	2	2	2
23	3	4	4	3	3
24	3	3	3	3	3
25	5	5	5	5	5

Table 1.3: Number of required resources by type for the last 5 improved iterations (scenario 2A)

Resource	Iteration n-4	Iteration n-3	Iteration n-2	Iteration n-1	Iteration n
1	5	5	5	5	5
2	2	2	2	2	2
3	4	4	4	4	4
4	2	2	2	2	2
5	4	4	4	4	4
6	1	1	1	1	1
7	2	2	2	2	2
8	2	2	2	2	2
9	3	3	3	3	3
10	2	2	2	2	2
11	3	3	3	3	3
12	2	2	2	2	2
13	2	2	2	2	2
14	3	3	3	3	3
15	1	1	1	1	1

Table 1.4: Number of required resources by type for the last 5 improved iterations (scenario 2B)

Resource	Iteration n-4	Iteration n-3	Iteration n-2	Iteration n-1	Iteration n
1	7	7	7	7	7
2	2	2	2	2	2
3	4	4	4	4	4
4	2	2	2	2	2
5	5	5	5	5	5
6	3	3	3	3	2
7	2	2	2	2	2
8	2	2	2	2	2
9	2	2	2	2	2
10	1	1	1	1	1
11	2	2	2	2	2
12	4	3	4	4	4
13	1	1	1	1	1
14	5	5	5	5	5
15	5	5	5	5	5

1.7.2 Resource Utilisation

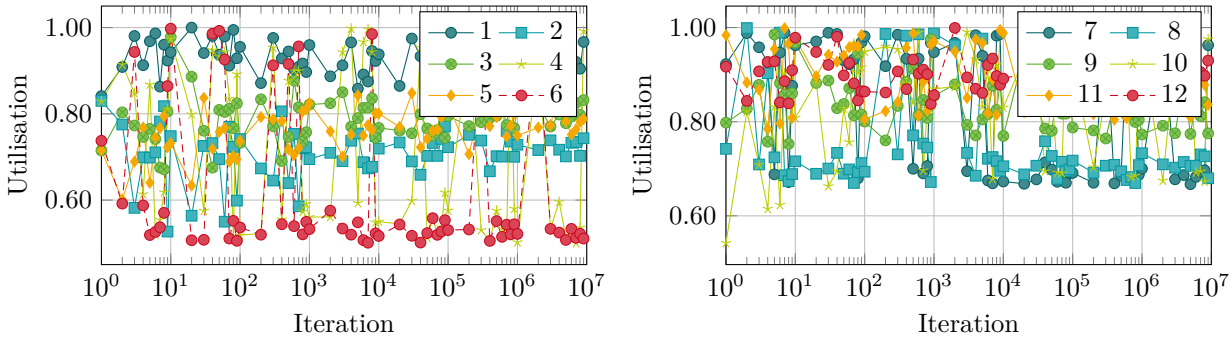

Figure 1.43: Resource utilisation ρ_R^{real} for r_1 to r_6 (left) and r_7 to r_{12} (right, scenario 1A)

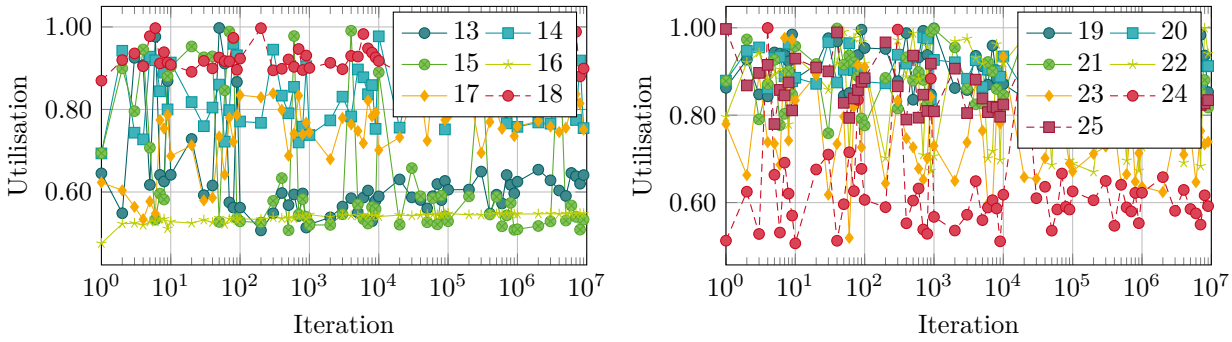

Figure 1.44: Resource utilisation ρ_R^{real} for r_{13} to r_{18} (left) and r_{19} to r_{25} (right, scenario 1A)

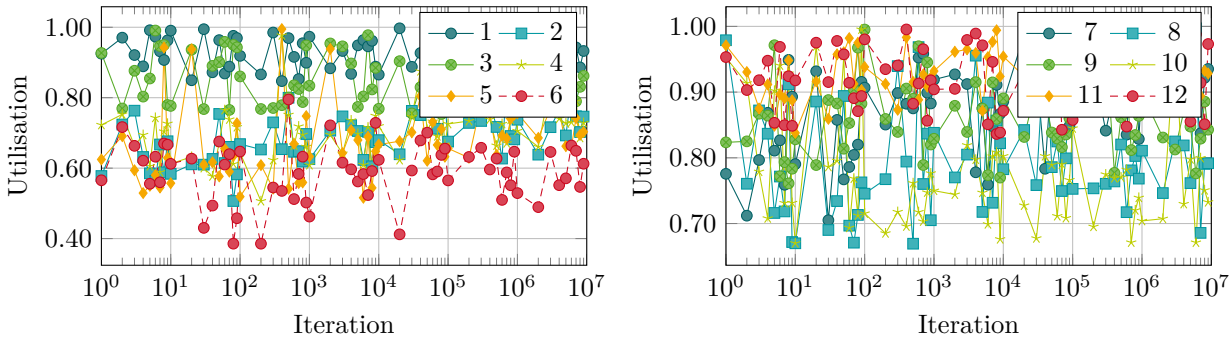

Figure 1.45: Resource utilisation ρ_R^{real} for r_1 to r_6 (left) and r_7 to r_{12} (right, scenario 1B)

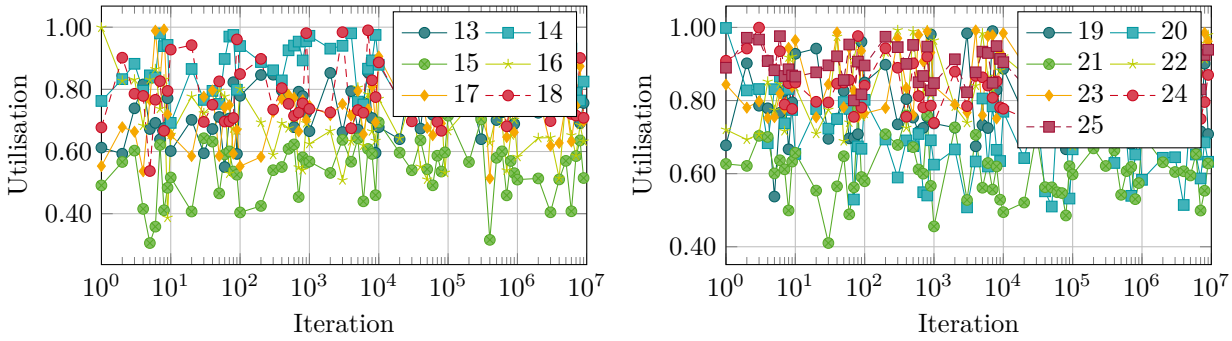

Figure 1.46: Resource utilisation ρ_R^{real} for r_{13} to r_{18} (left) and r_{19} to r_{25} (right, scenario 1B)

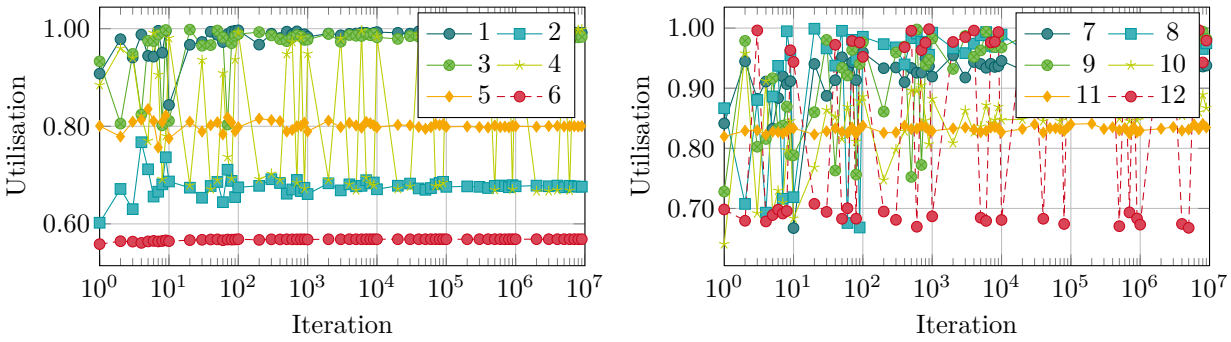

Figure 1.47: Resource utilisation ρ_R^{real} for r_1 to r_5 (left) and r_6 to r_{10} (right, scenario 2A)

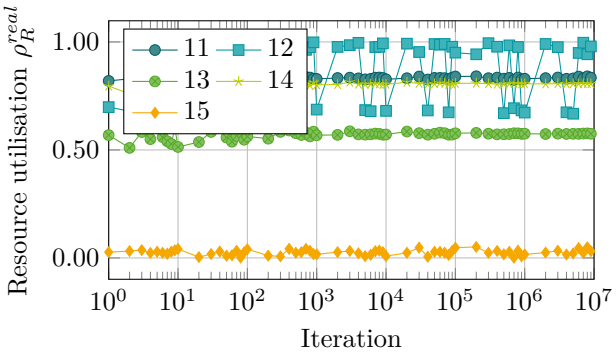

Figure 1.48: Resource utilisation for r_{11} to r_{15} (scenario 2A)

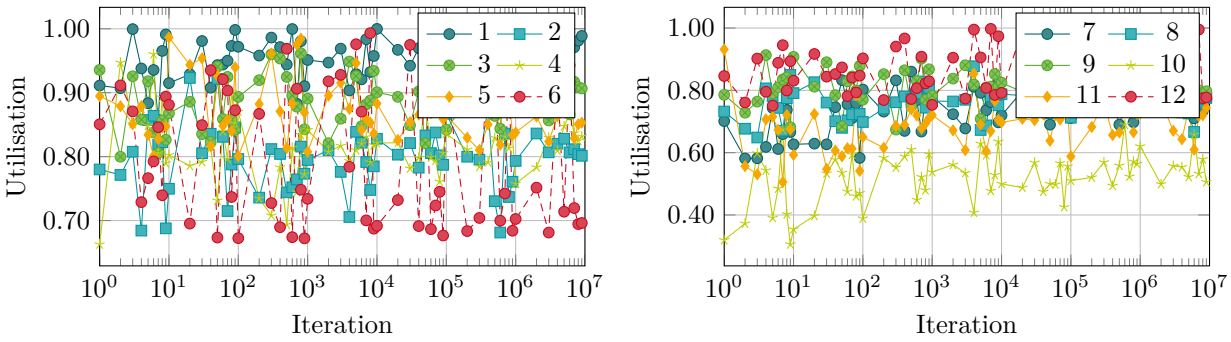

Figure 1.49: Resource utilisation ρ_R^{real} for r_1 to r_5 (left) and r_6 to r_{10} (right, scenario 2B)

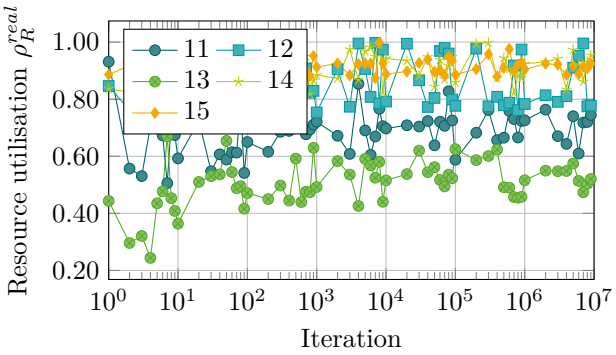

Figure 1.50: Resource utilisation for r_{11} to r_{15} (scenario 2B)

2

Results of Sensitivity Analysis

2.1 Experimental Design

As with the tests for internal validity, all four scenarios are used for the sensitivity analysis. All input variables concerning the assembly process are varied based on a single factorial design. The purpose of the single factor analysis is to perform a qualitative analysis of the input variables' impact and is deemed sufficient for this purpose. Furthermore, a quantitative model as obtained from a full factorial analysis does not meet the intended purpose as it is specific for each scenario. Table **??** gives an overview of the experimental design with the input variables, the interval, and the increments with which they are varied. Note that results cannot be directly compared between scenarios. However, as the scenarios are based on substantially different design choices, it is worth investigating whether effects can be attributed to the respective design decisions.

The meaningfulness of variations of the production program is limited as its effect on the output variables is highly dependent on the details of the production scenario and process design. Nevertheless, variations are analysed to show the direct impact of varying the relative share of one product within the production program. This aims at detecting input influence on model throughput. Based on scenario 1A, the production program as specified by the use case, is changed so that all products have an equal share (0.2). For each experiment, the share of product E (f_E) is exchanged by a value according to the experiment plan, and the production program is normalised. Furthermore, the effect of the proposed extension to include reconfiguration efforts is examined by varying the share of p_{rc} in the same range as for f_E. The reconfiguration time t_{RC} is varied as well as described in the experiment plan. The analysis assumes the equal distribution of reconfiguration efforts on stations (i.e. equally distributed $\vec{p}_{SC}^{RC}$).

Note that during computation, the sequence of the experiments has not been randomised as the fully automated MCS and EMVA process is considered to be independent of operator influence and is itself based on random experiments. The random seed is shuffled before model execution to avoid unintended recreation of seemingly random results.

Further note, that convergence is evaluated qualitatively. It is therefore unnecessary to evaluate data for each station configuration; thus, the following graphs are limited to the first six data points (sc_i, r_l).

Table 2.1: Overview on experimental design for sensitivity analysis. Increment and interval refer to single factor variation; sets in factors to full factorial analysis.

Variable	Interval	Increment	Annotation
U (WIP)	$[1; 50]$	1	-
$\mathbf{D}$	$[0.1; 2.0]$	0.1	Element-wise multiplication of all elements of matrix $\mathbf{D}$ with factor
n_{TS}	$[1; 20]$	1	-
v_{TS}	$[0.1; 2.0]$	0.1	Element-wise multiplication of original use case value with factor
$\mathbf{T}_{(P,PC)}$	$[0.1; 2.0]$	0.1	Element-wise multiplication of all elements of matrix $\mathbf{T}_{(P,PC)}$ with factor
$\vec{f_p}$	$[0.05; 1.0]$	0.05	Modification of the share of a single product (plus additional low end values 0.01 and 0.025)
t_{RC}	$[50; 1000]$	50	-

Table **??** gives an overview on the obtained results.

Table 2.2: Summary of sensitivity analysis. Summary is based on qualitative assessment of all scenarios. Arrows indicate factor variation towards increasing values.

	Factor	λ_j	LT_j	ρ_{TS}	w^Q_{TS}	$\bar{\rho}_{SC}$	ρ_{SC}	$\bar{w}^Q_{SC}$	w^Q_{SC}	n^Q_{TS}	$\bar{n}^Q_{SC}$	n^Q_{SC}	ρ_l	n^{real}_R
↑	U	+	+	+	+	+	+	+	+*	+	+	+*	+*	+*
↑	$\mathbf{D}$	0	0	0	0	+	0	0	0*	0	0	0*	0	0*
↑	n_{TS}	+	–	–	+	+	–	0	0*	–	0	0	0	0
↑	v_{TS}	0	0*	0	0	0	0	0	0*	0	0	0*	0	0
↑	$\mathbf{T}_{(P,PC)}$	–	+	–	+	+	–	+	+*	–	0	+*	+	+
(+) monotonically increasing, (-) monotonically decreasing, (0) neutral, (*) inconsistent behaviour														

2.2 Variation of WIP

2.2.1 Throughput (WIP)

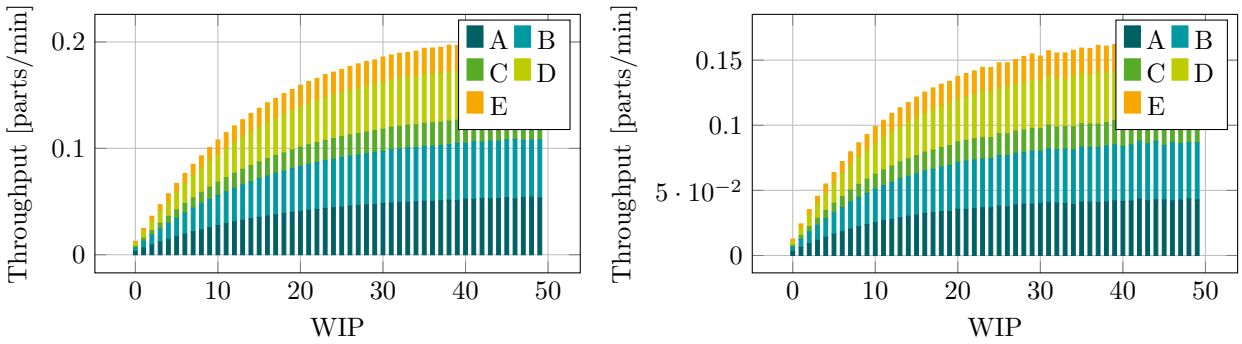

Figure 2.1: Throughput λ_j for all products for scenario 1A (left) and scenario 1B (right) over WIP variation

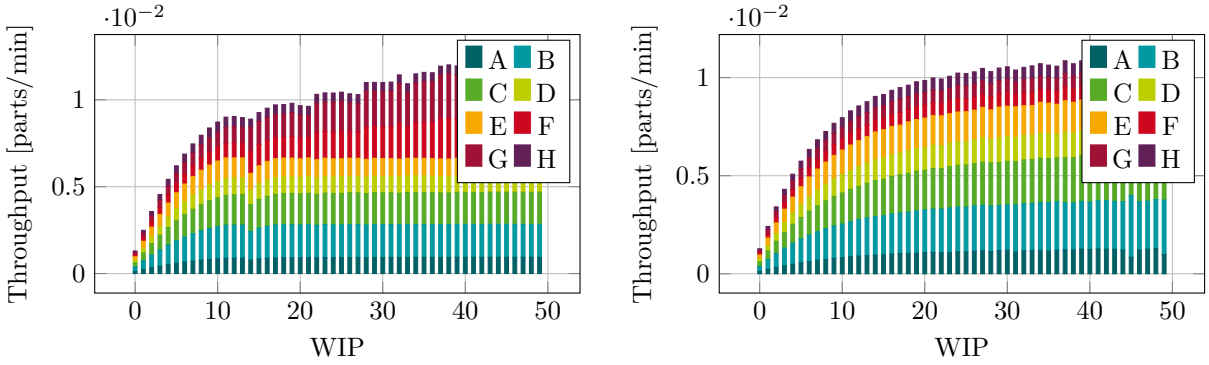

Figure 2.2: Throughput λ_j for all products for scenario 2A (left) and scenario 2B (right) over WIP variation

2.2.2 Lead Time (WIP)

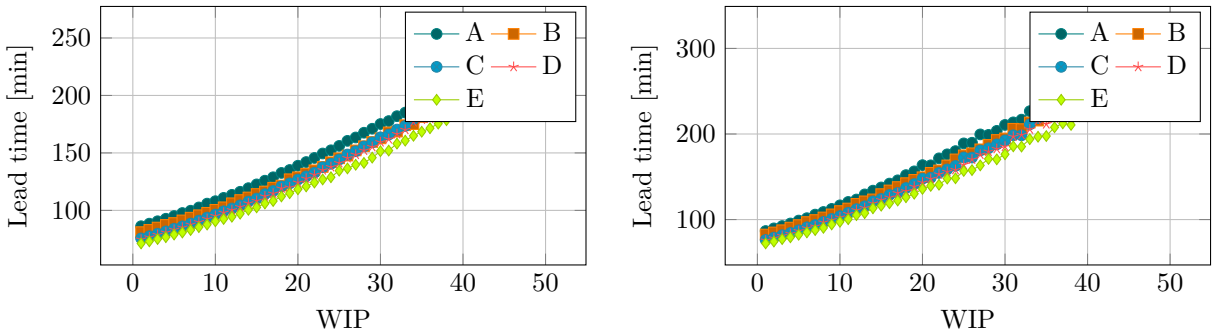

Figure 2.3: Lead time LT_j for all products for scenario 1A (left) and scenario 1B (right) over WIP variation

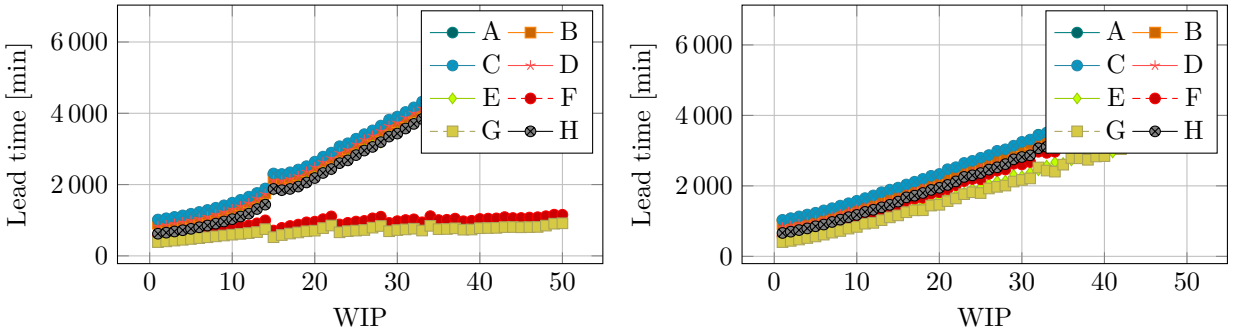

Figure 2.4: Lead time LT_j for all products for scenario 2A (left) and scenario 2B (right) over WIP variation

2.2.3 Station Configuration Utilisation (WIP)

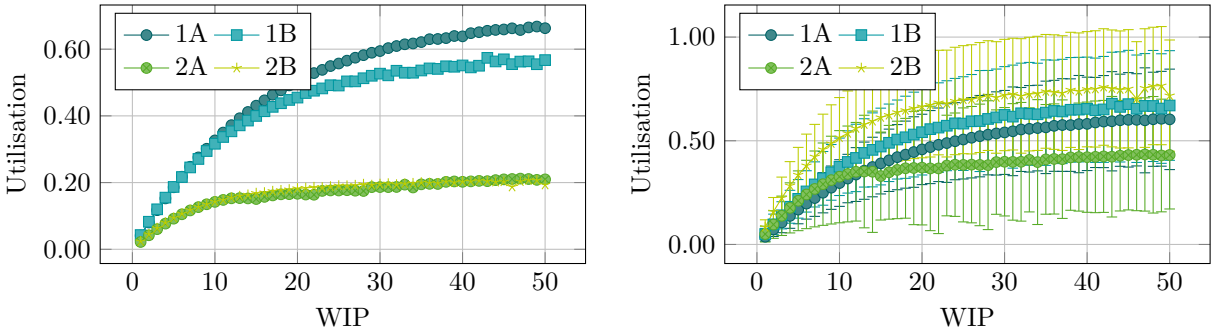

Figure 2.5: Utilisation of the transportation system ρ_{TS} (left) and mean station configuration utilisation $\bar{\rho}_{SC}$ (right) per product over WIP variation (all scenarios)

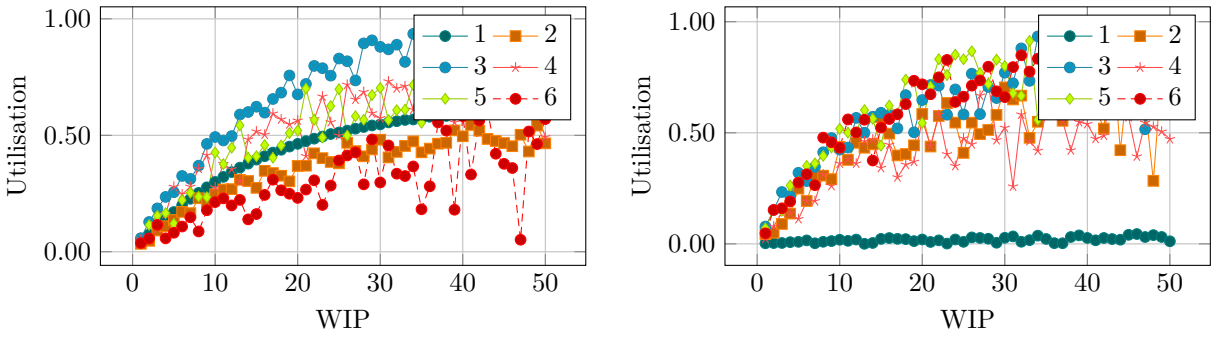

Figure 2.6: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over WIP variation

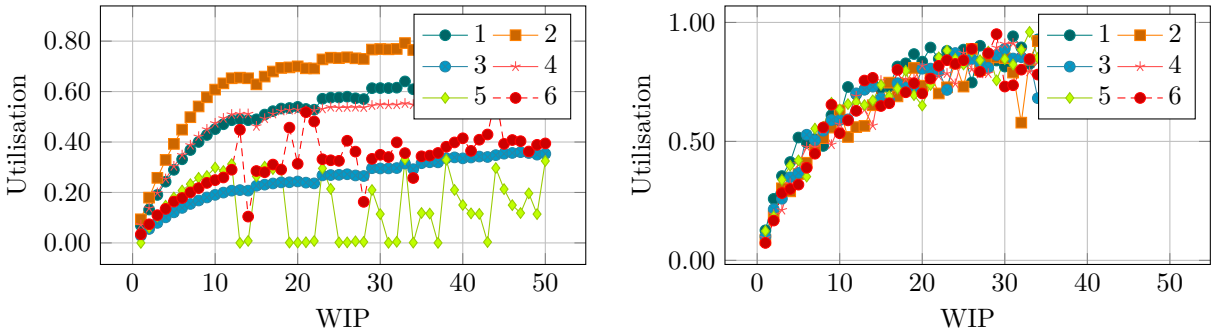

Figure 2.7: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over WIP variation

2.2.4 Waiting Times (WIP)

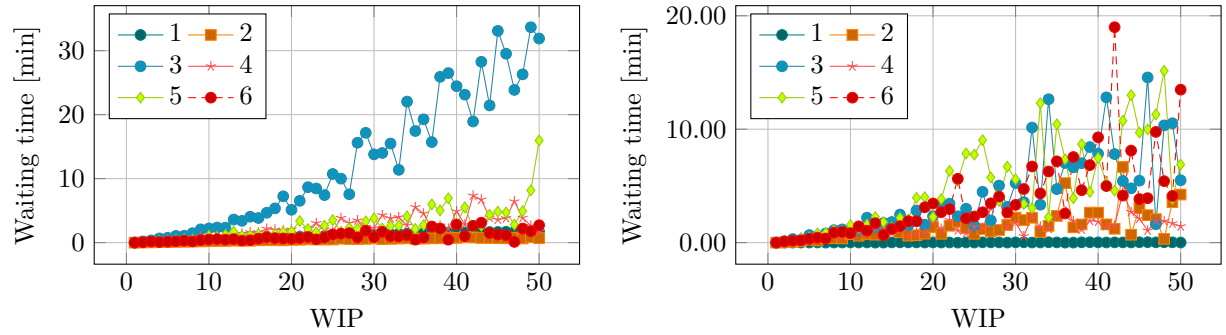

Figure 2.8: Waiting time w_{SC}^{Q} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over WIP variation

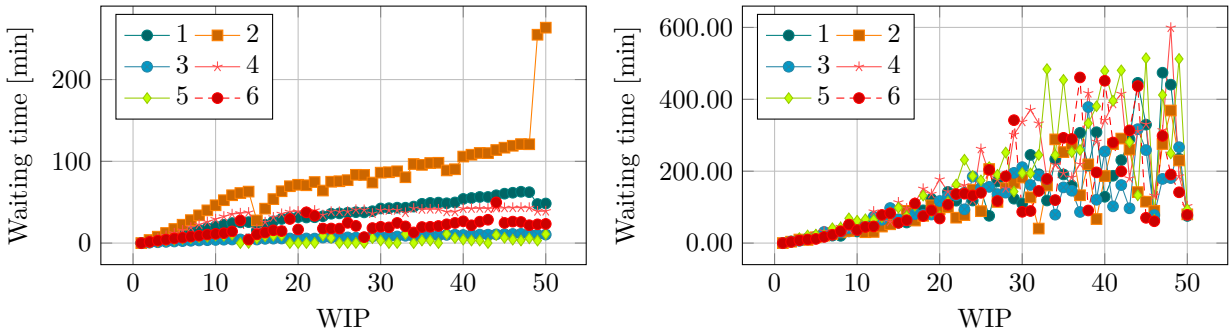

Figure 2.9: Waiting time w_{SC}^{Q} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over WIP variation

2.2.5 Queue Lengths (WIP)

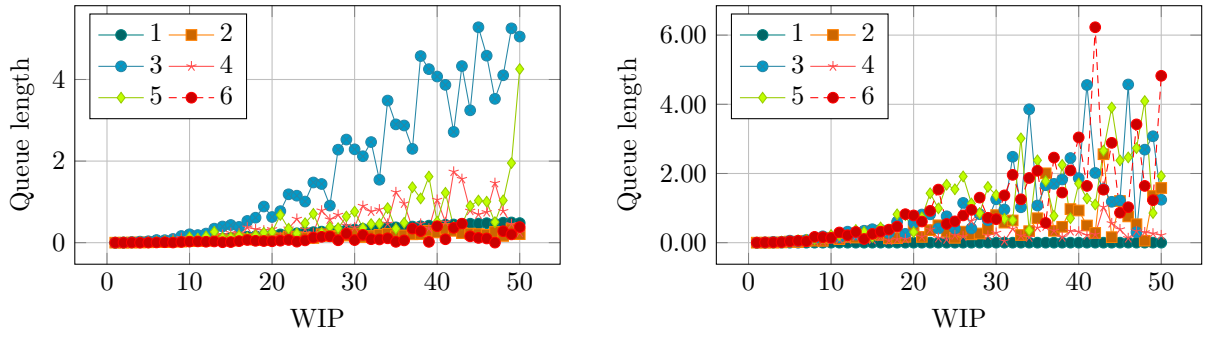

Figure 2.10: Queue lengths n_{SC}^{Q} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over WIP variation

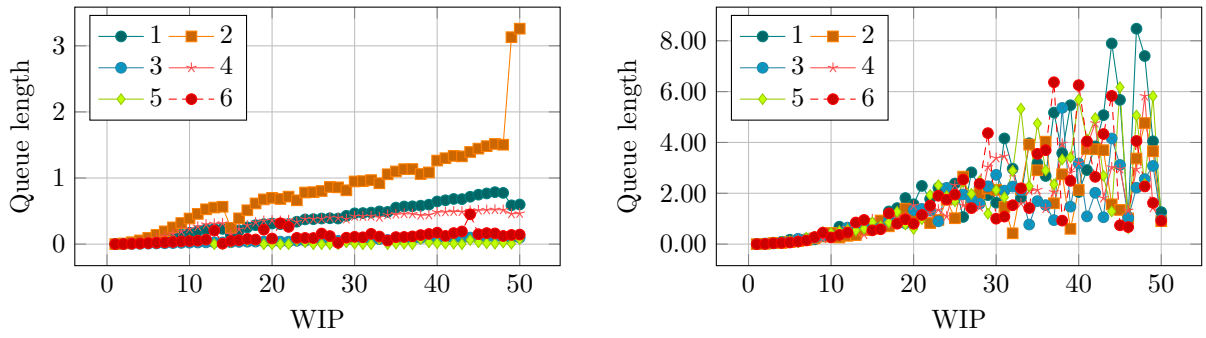

Figure 2.11: Queue lengths n_{SC}^{Q} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over WIP variation

2.2.6 Required Resources (WIP)

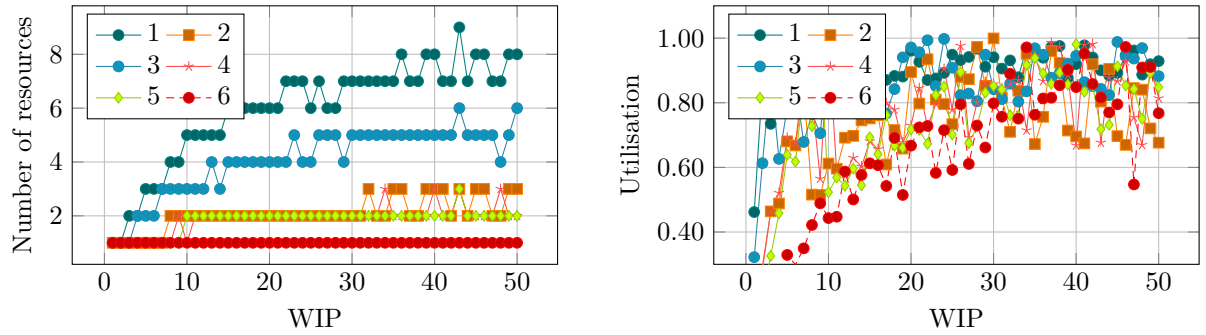

Figure 2.12: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over WIP variation (scenario 1B)

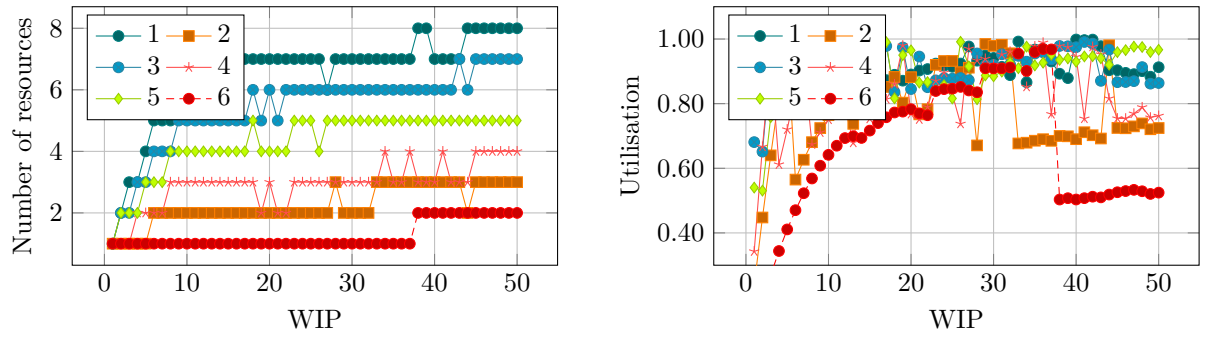

Figure 2.13: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over WIP variation (scenario 2A)

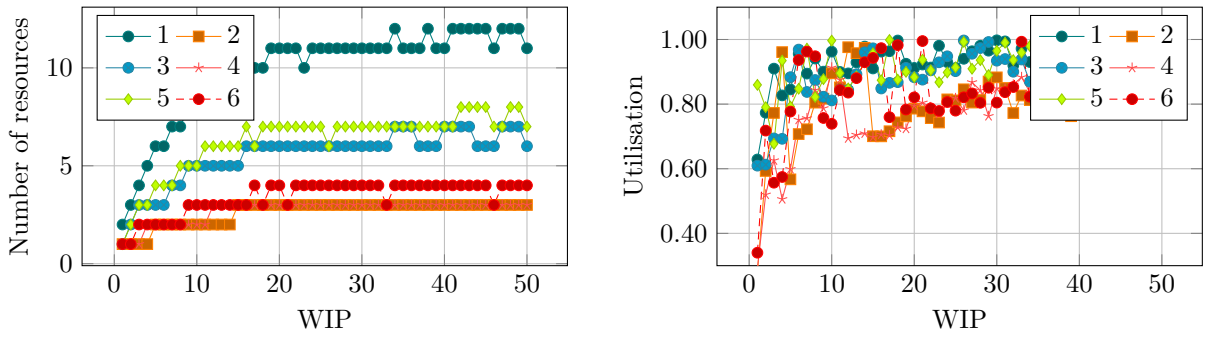

Figure 2.14: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over WIP variation (scenario 2B)

2.3 Variation of Station Distances D

2.3.1 Throughput (D)

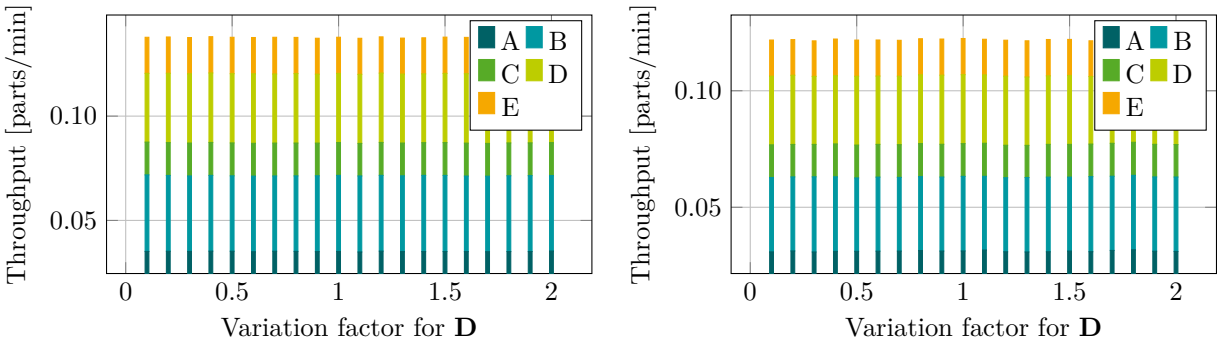

Figure 2.15: Throughput λ_j for all products for scenario 1A (left) and scenario 1B (right) over **D** variation

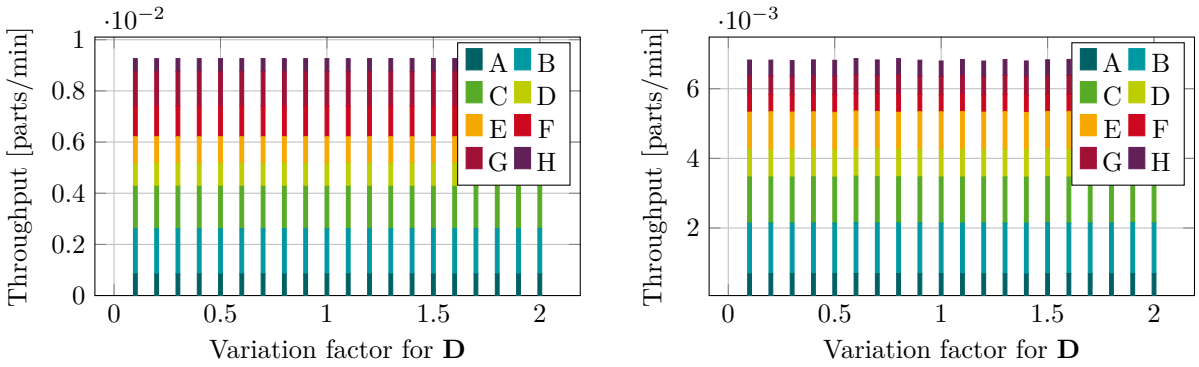

Figure 2.16: Throughput λ_j for all products for scenario 2A (left) and scenario 2B (right) over **D** variation

2.3.2 Lead time (D)

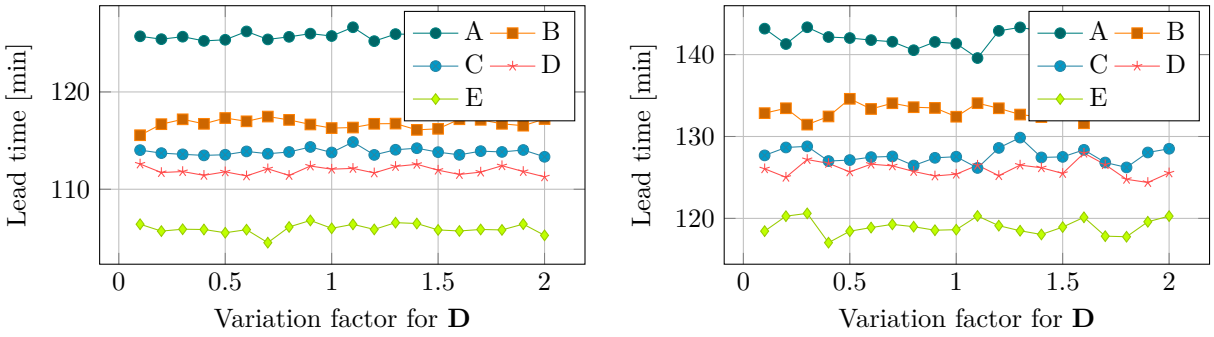

Figure 2.17: Lead time LT_j for all products for scenario 1A (left) and scenario 1B (right) over **D** variation

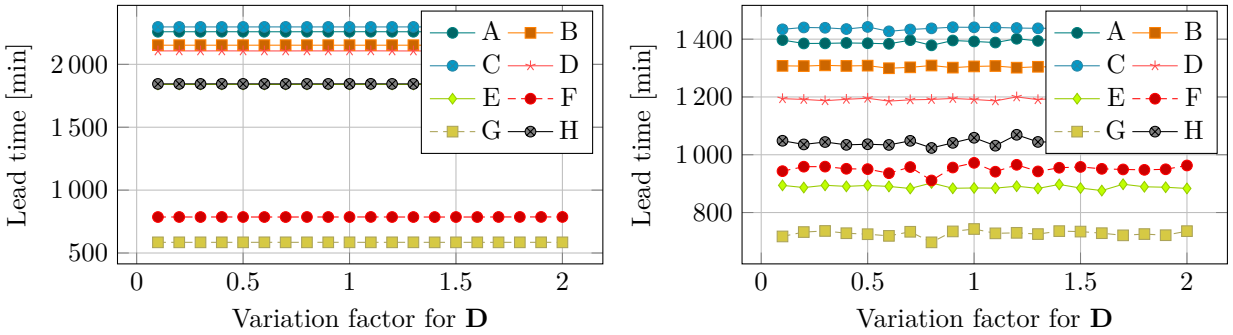

Figure 2.18: Lead time LT_j for all products for scenario 2A (left) and scenario 2B (right) over **D** variation

2.3.3 Station Configuration Utilisation (D)

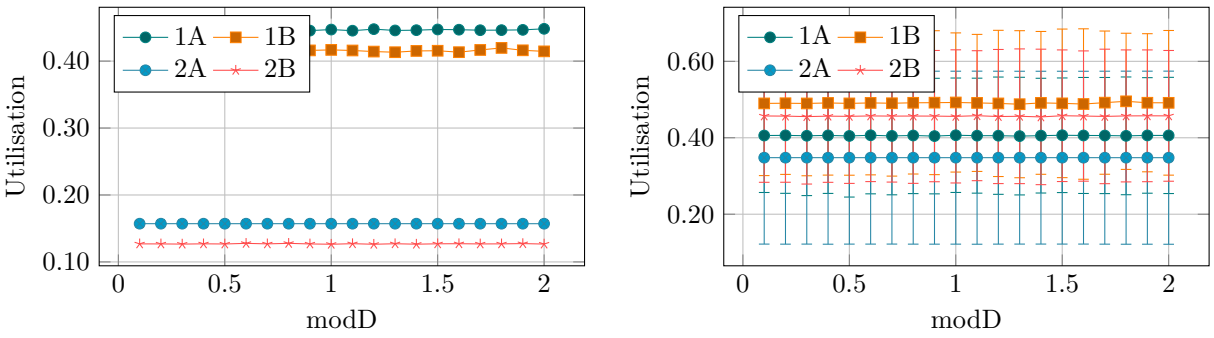

Figure 2.19: Utilisation of the transportation system ρ_{TS} (left) and mean station utilisation $\bar{\rho}_{SC}$ (right) over **D** variation (all scenarios)

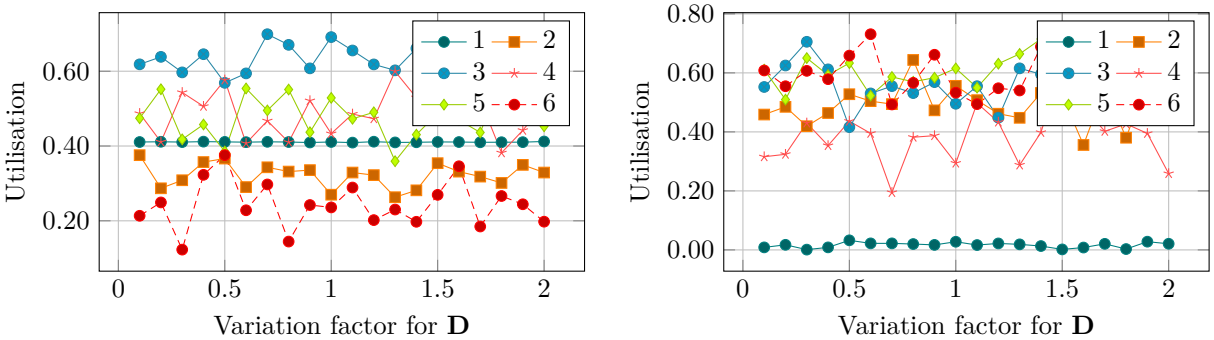

Figure 2.20: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over **D** variation

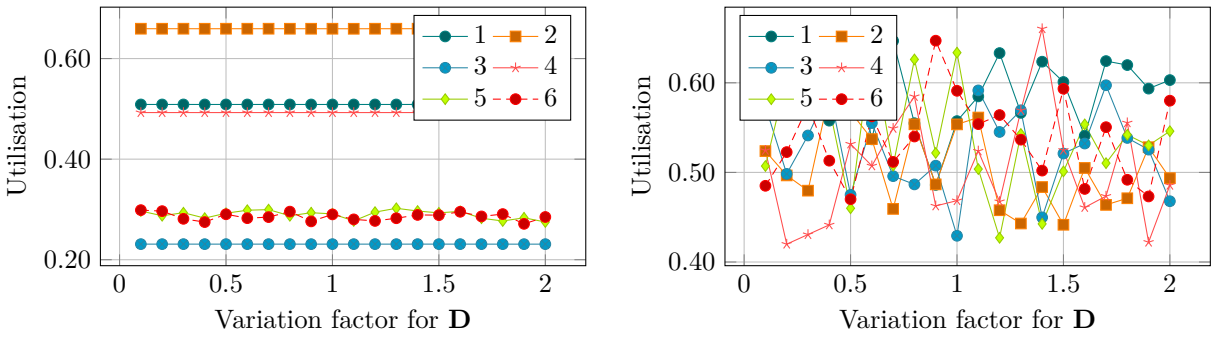

Figure 2.21: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over **D** variation

2.3.4 Waiting Times (D)

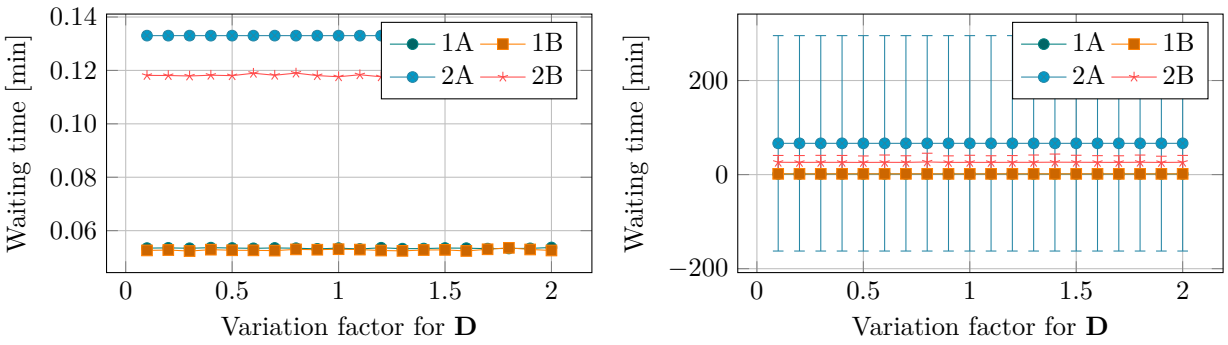

Figure 2.22: Waiting times w^Q_{TS} (left) and mean waiting time $\bar{w}^Q_{SC}$ [min] (right) over **D** variation (all scenarios)

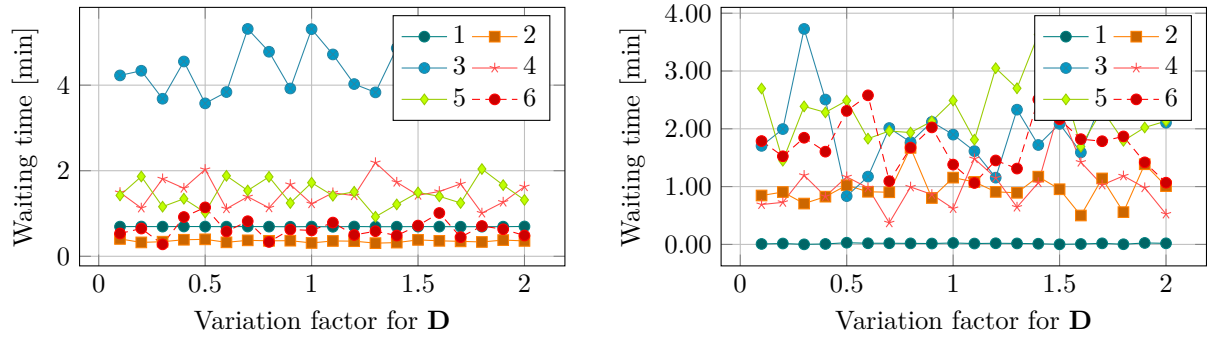

Figure 2.23: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over **D** variation

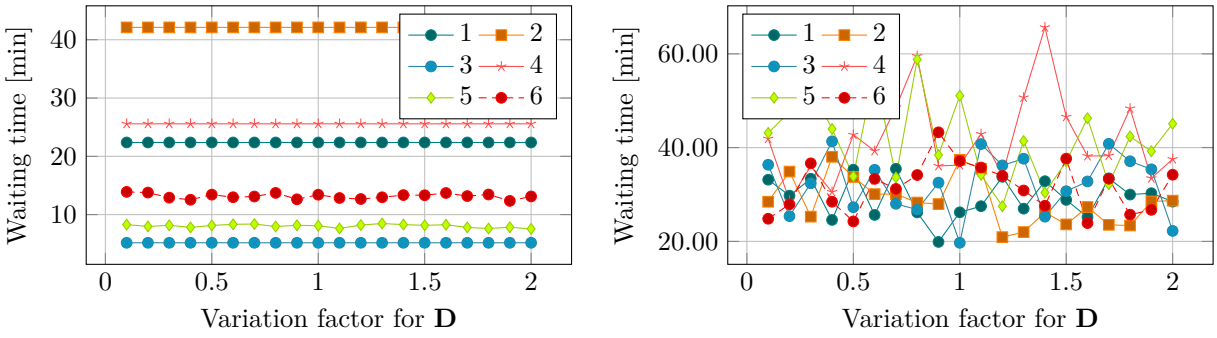

Figure 2.24: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over **D** variation

2.3.5 Queue Lengths (D)

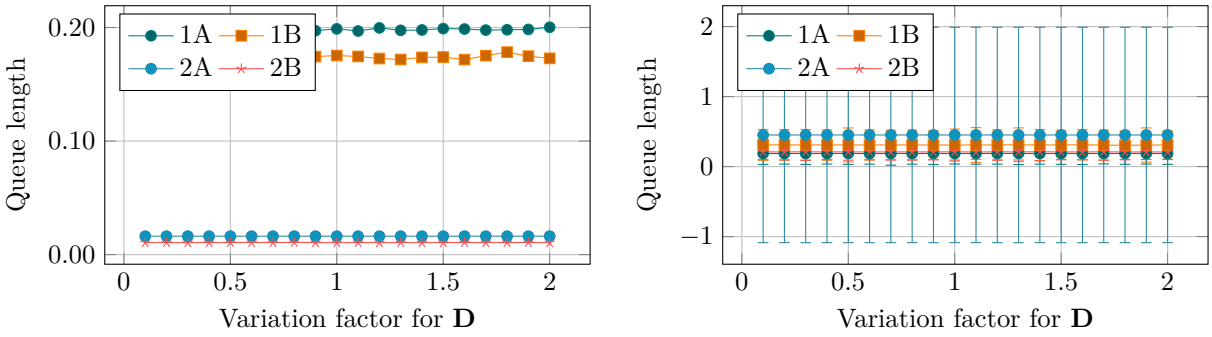

Figure 2.25: Queue length n^Q_{TS} (left) and mean queue length $\bar{n}^Q_{SC}$ (right) over **D** variation (all scenarios)

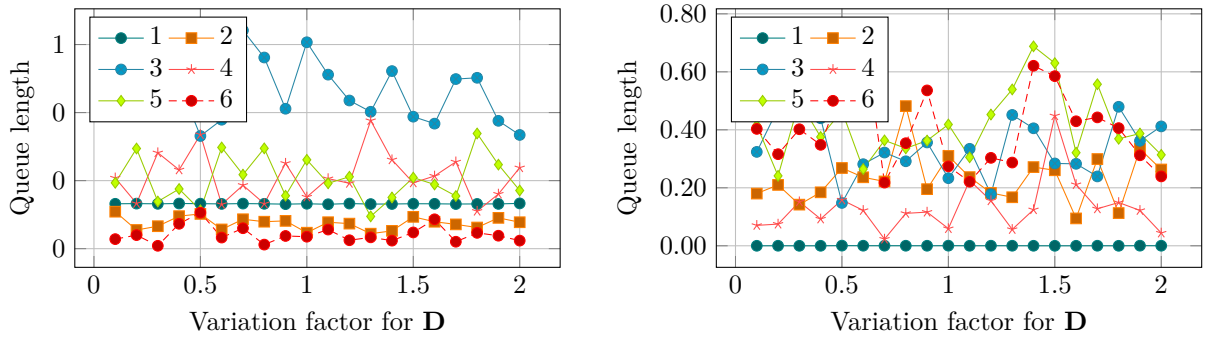

Figure 2.26: Queue lengths n^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over **D** variation

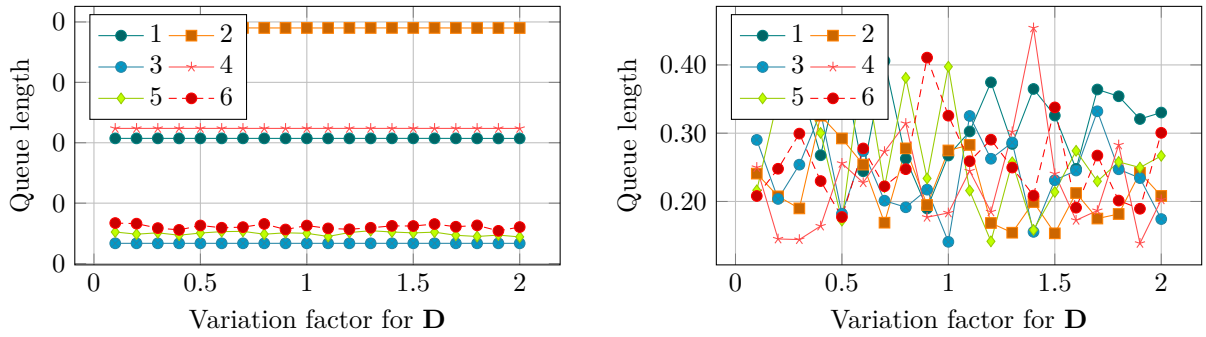

Figure 2.27: Queue lengths n^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over **D** variation

2.3.6 Required Resources (D)

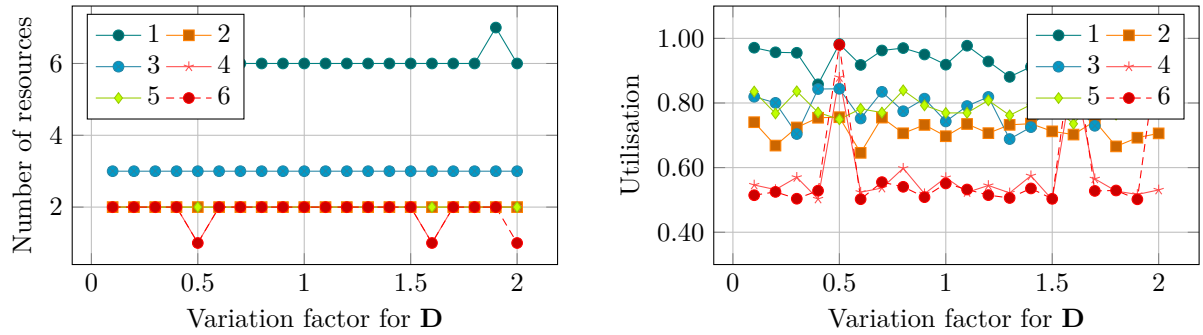

Figure 2.28: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over **D** variation (scenario 1A)

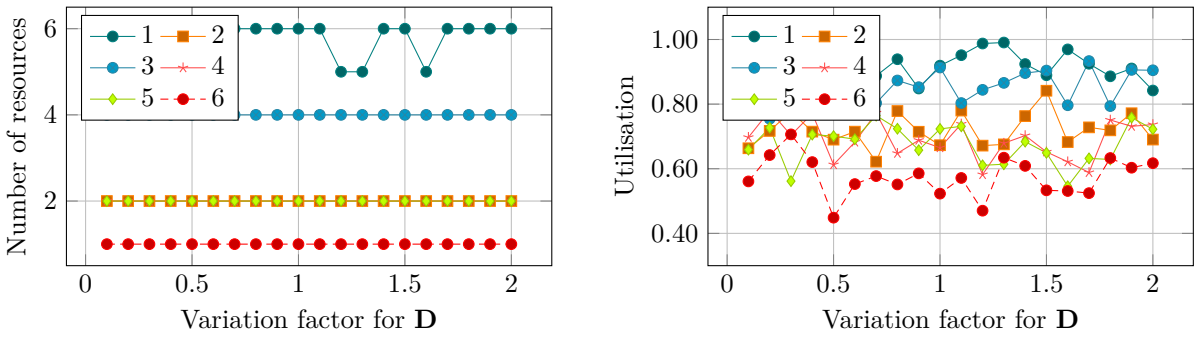

Figure 2.29: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over **D** variation (scenario 1B)

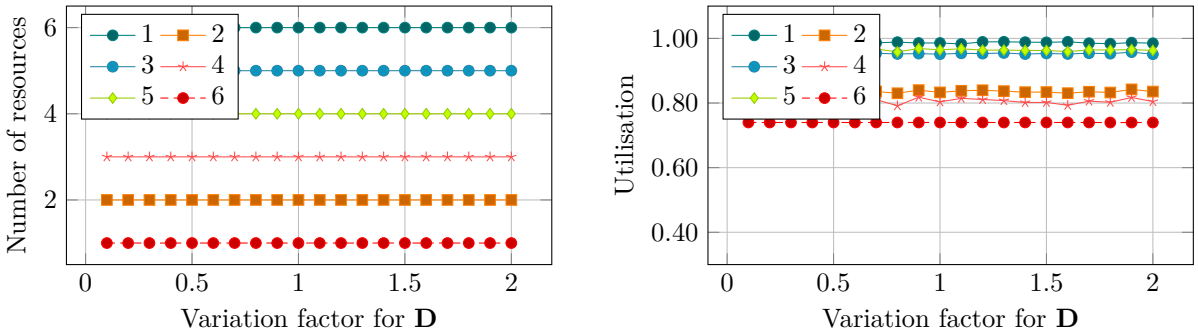

Figure 2.30: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over **D** variation (scenario 2A)

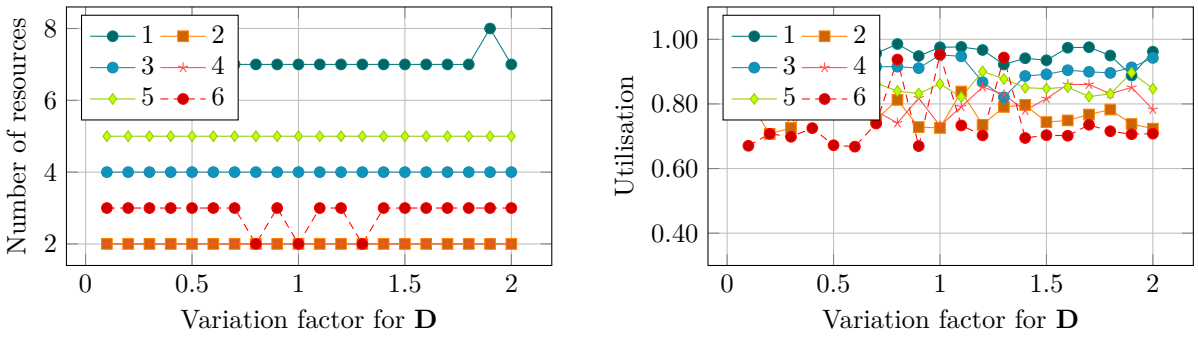

Figure 2.31: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over **D** variation (scenario 2B)

2.4 Variation of Number of AGVs

2.4.1 Throughput (n_{TS})

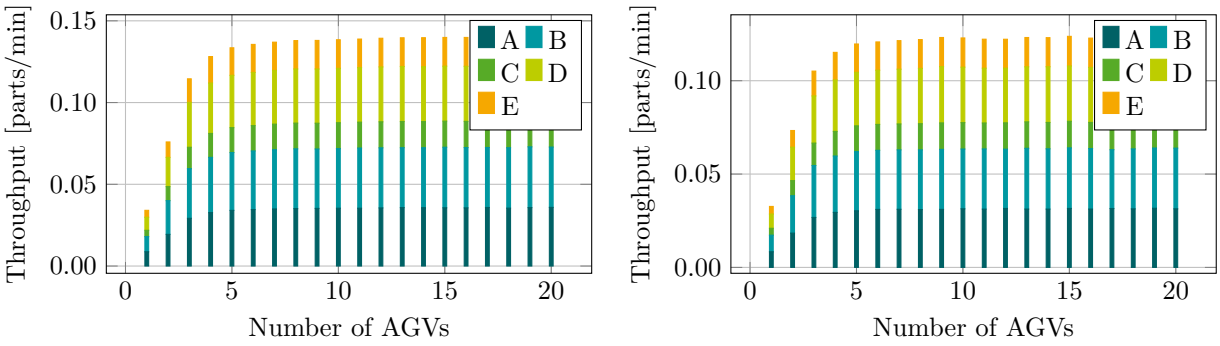

Figure 2.32: Throughput λ_j for all products for scenario 1A (left) and scenario 1B (right) over n_{TS} variation

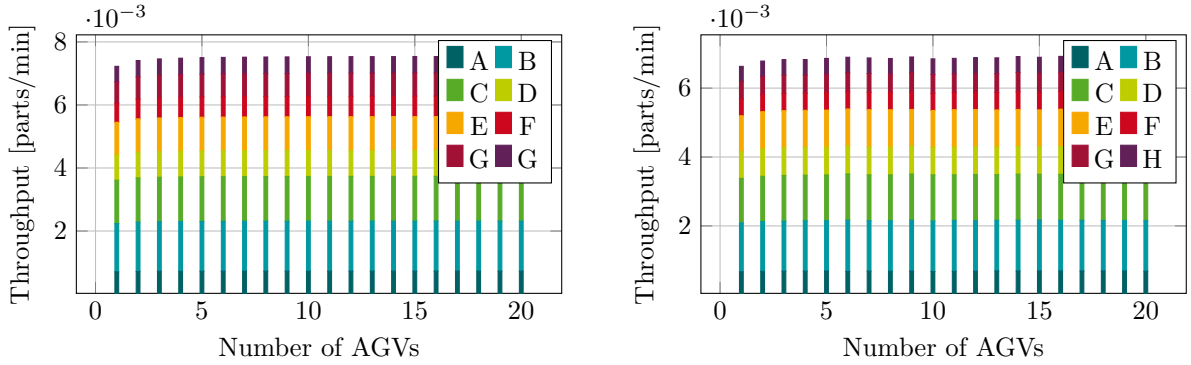

Figure 2.33: Throughput λ_j for all products for scenario 2A (left) and scenario 2B (right) over n_{TS} variation

2.4.2 Lead Time (n_{TS})

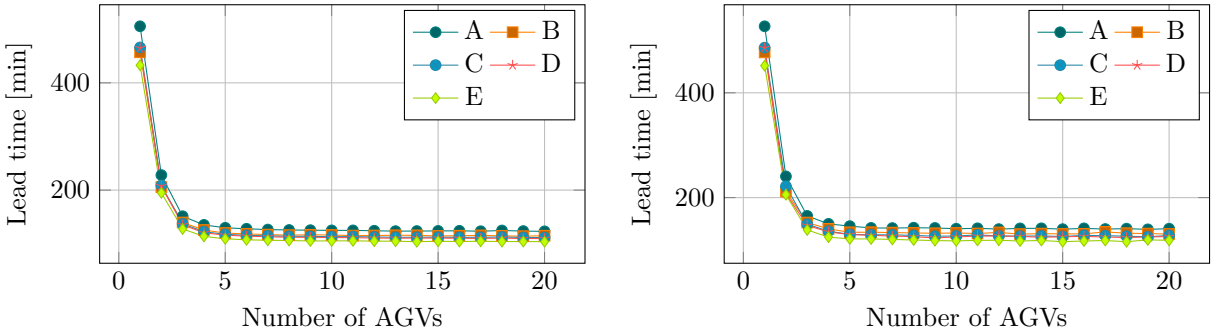

Figure 2.34: Lead time LT_j for all products for scenario 1A (left) and scenario 1B (right) over n_{TS} variation

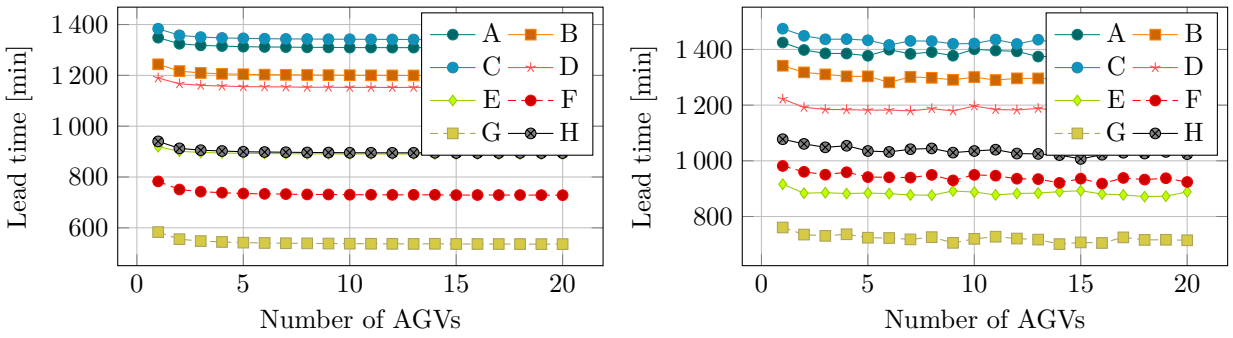

Figure 2.35: Lead time LT_j for all products for scenario 2A (left) and scenario 2B (right) over n_{TS} variation

2.4.3 Station Configuration Utilisation (n_{TS})

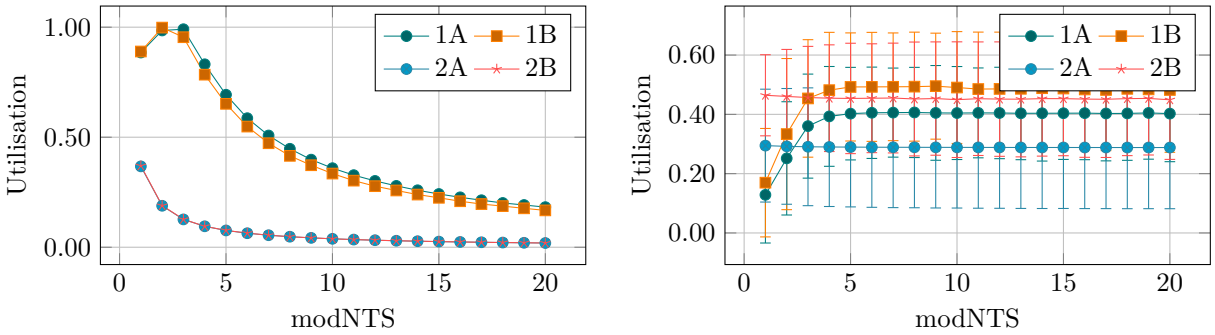

Figure 2.36: Utilisation of the transportation system ρ_{TS} (left) and mean station utilisation $\bar{\rho}_{SC}$ (right) over n_{TS} variation (all scenarios)

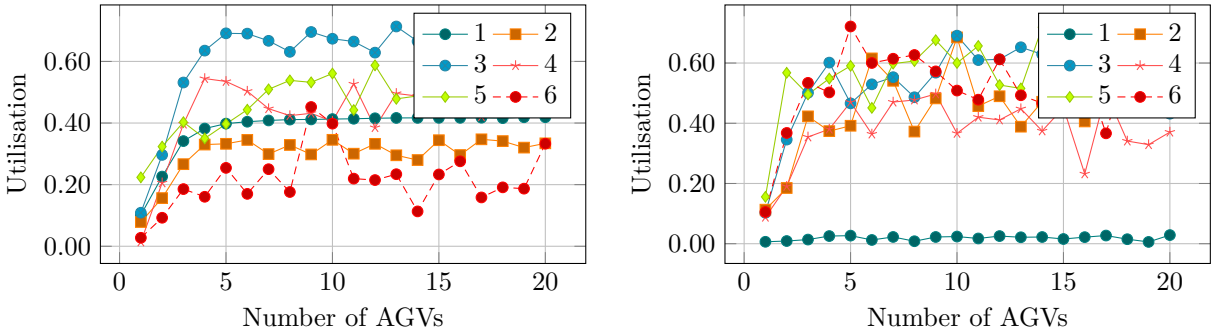

Figure 2.37: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over n_{TS} variation

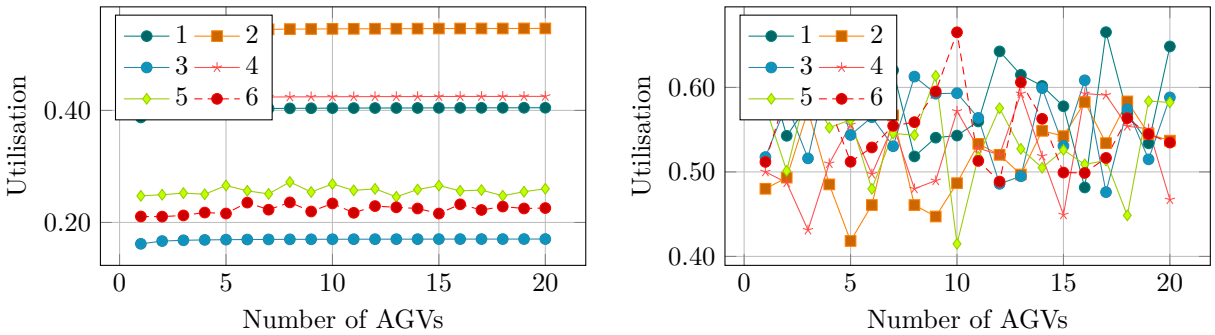

Figure 2.38: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over n_{TS} variation

2.4.4 Waiting Times (n_{TS})

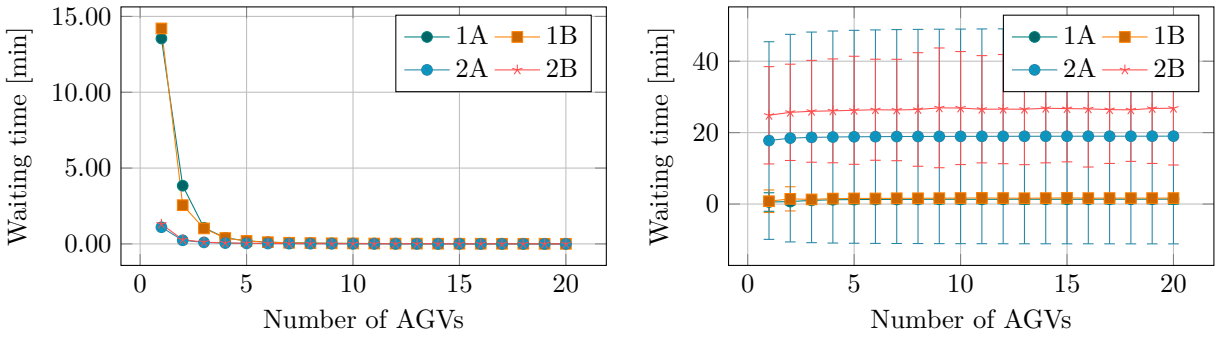

Figure 2.39: Waiting times w^Q_{TS} (left) and mean waiting time $\bar{w}^Q_{SC}$ [min] (right) over n_{TS} variation (all scenarios)

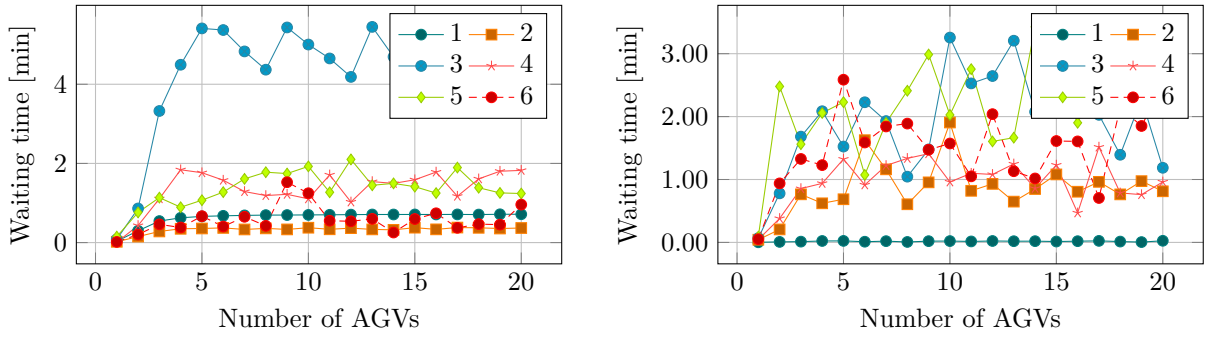

Figure 2.40: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over n_{TS} variation

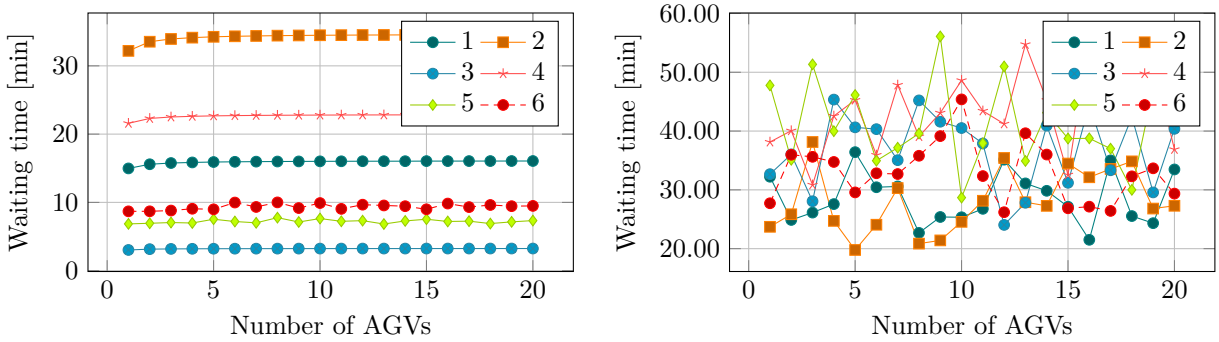

Figure 2.41: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over n_{TS} variation

2.4.5 Queue Lengths (n_{TS})

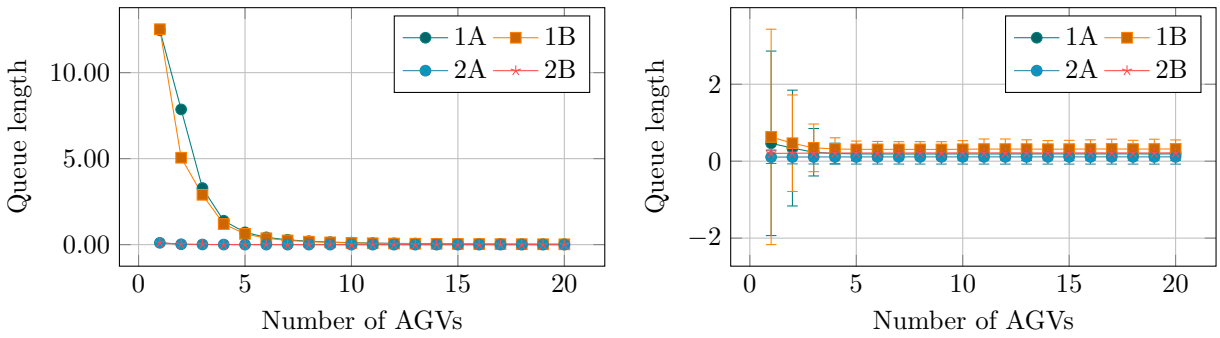

Figure 2.42: Queue length n^Q_{TS} [min] (left) and mean queue length $\bar{n}^Q_{SC}$ (right) over n_{TS} variation (all scenarios)

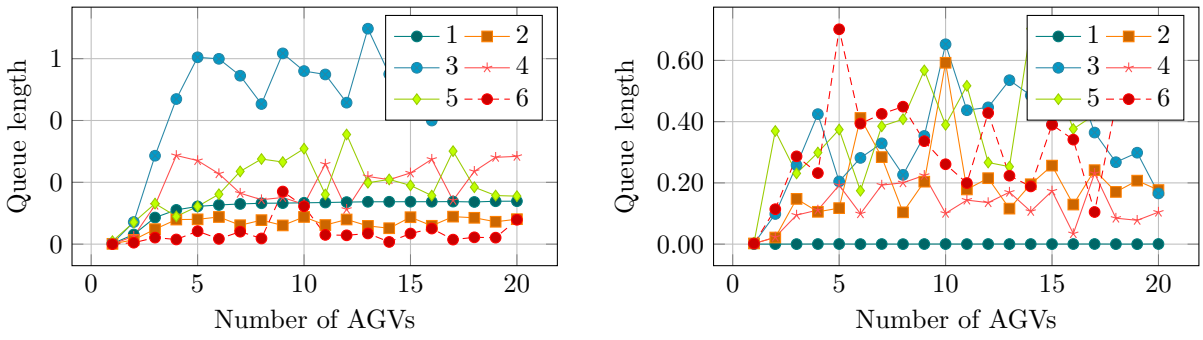

Figure 2.43: Queue lengths n_{SC}^{Q} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over n_{TS} variation

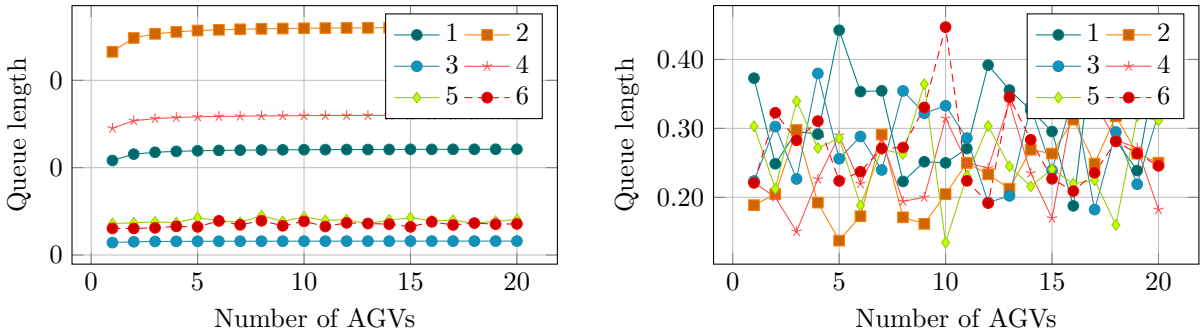

Figure 2.44: Queue lengths n_{SC}^{Q} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over n_{TS} variation

2.4.6 Required Resources (n_{TS})

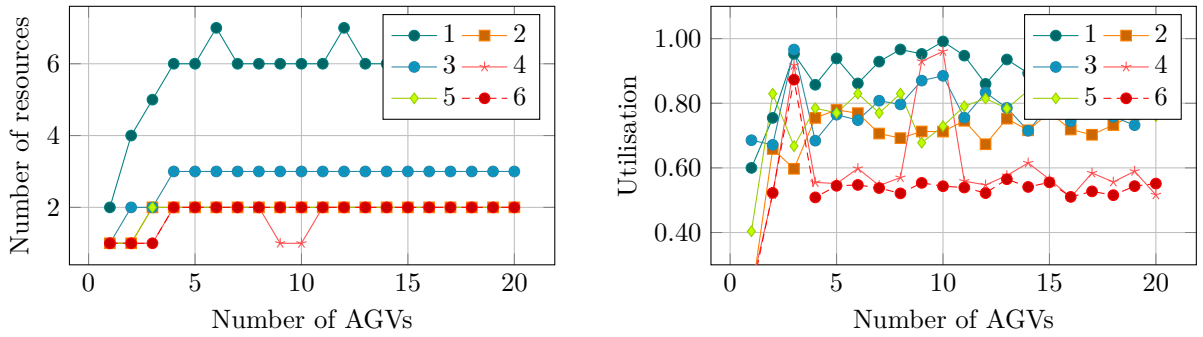

Figure 2.45: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over n_{TS} variation (scenario 1A)

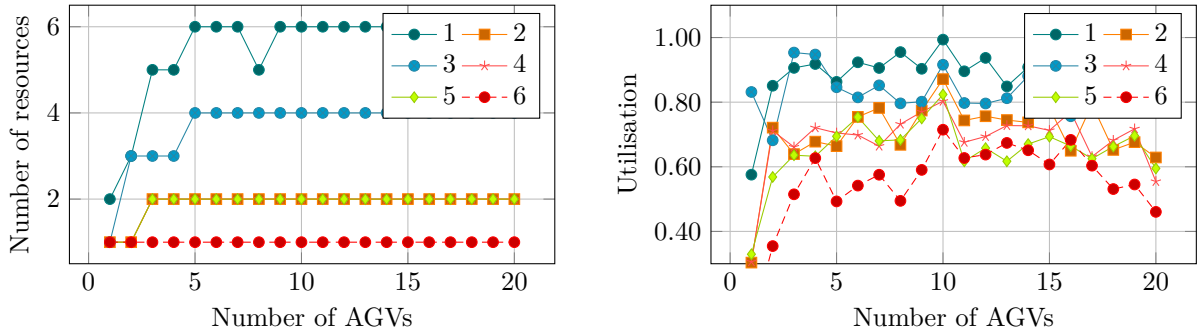

Figure 2.46: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over n_{TS} variation (scenario 1B)

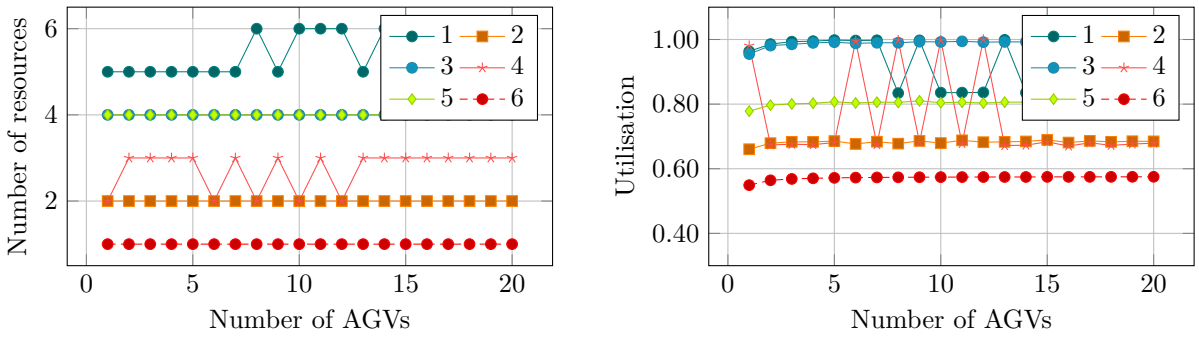

Figure 2.47: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over n_{TS} variation (scenario 2A)

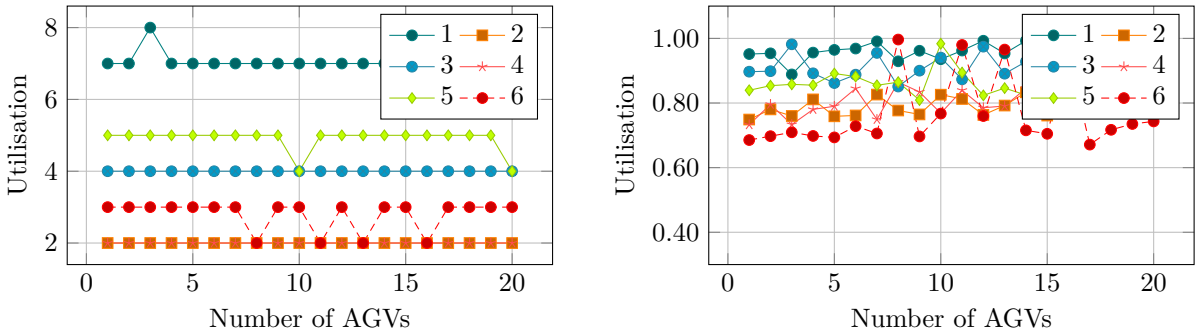

Figure 2.48: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over n_{TS} variation (scenario 2B)

2.5 Variation of Transport System Speed v_{TS}

2.5.1 Throughput (v_{TS})

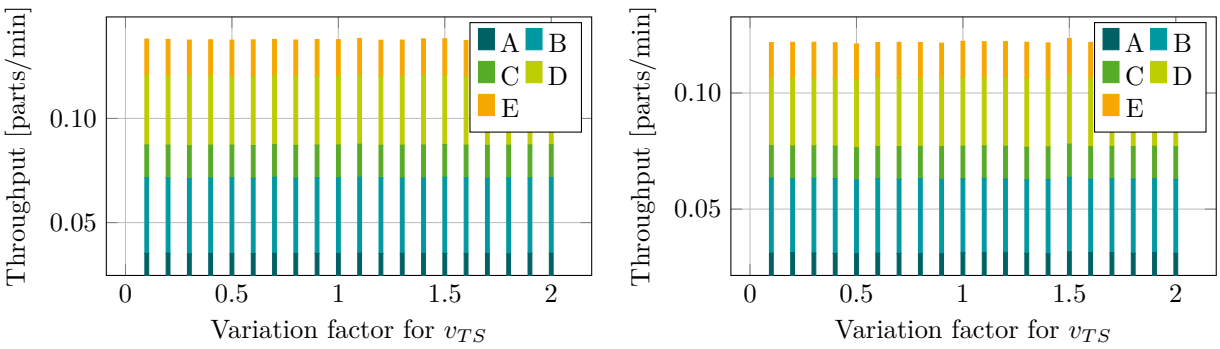

Figure 2.49: Throughput λ_j for all products for scenario 1A (left) and scenario 1B (right) over v_{TS} variation

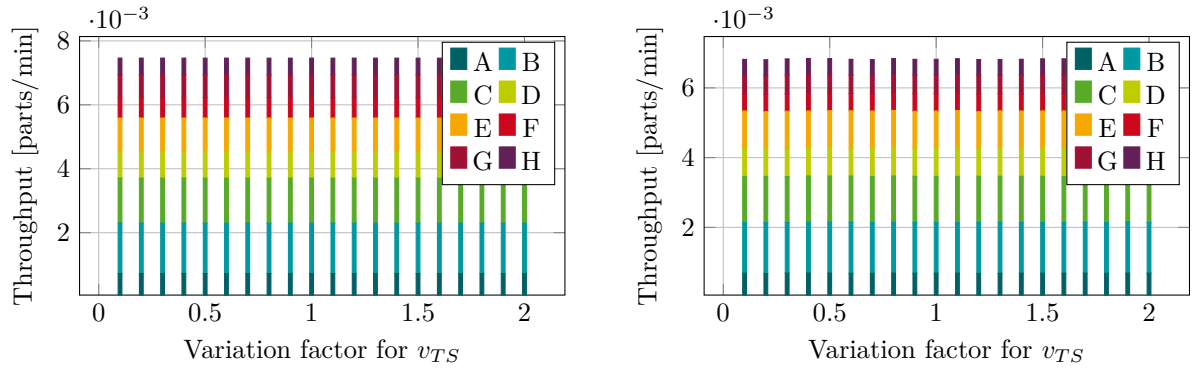

Figure 2.50: Throughput λ_j for all products for scenario 2A (left) and scenario 2B (right) over v_{TS} variation

2.5.2 Lead Time (v_{TS})

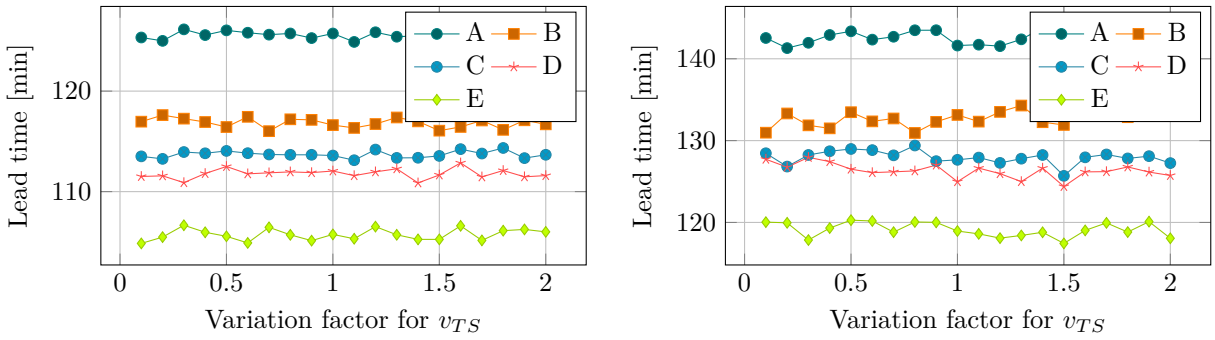

Figure 2.51: Lead time LT_j for all products for scenario 1A (left) and scenario 1B (right) over v_{TS} variation

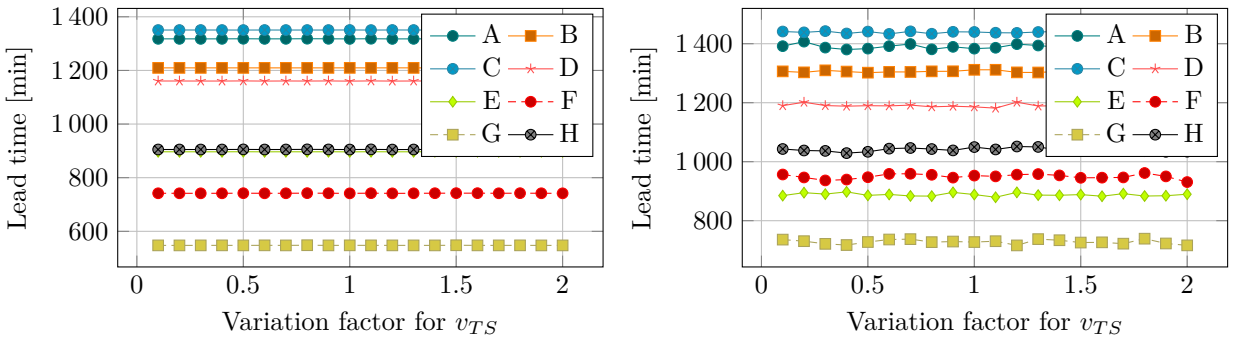

Figure 2.52: Lead time LT_j for all products for scenario 2A (left) and scenario 2B (right) over v_{TS} variation

2.5.3 Station Configuration Utilisation (v_{TS})

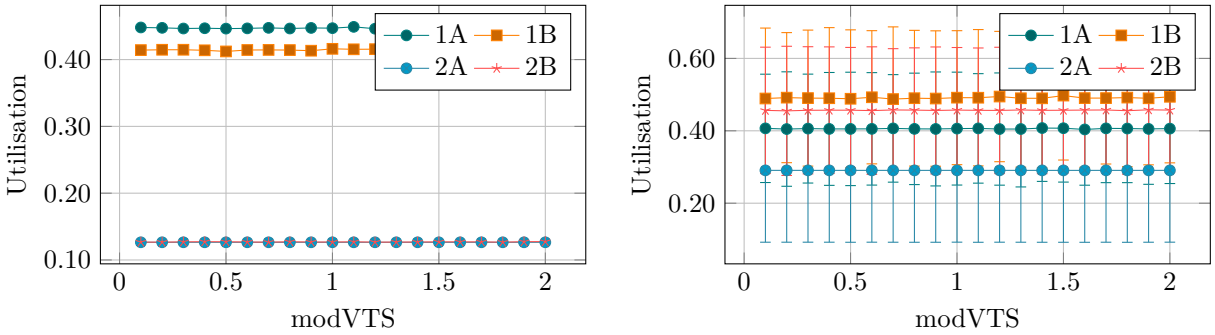

Figure 2.53: Utilisation of the transportation system ρ_{TS} (left) and mean station utilisation $\bar{\rho}_{SC}$ (right) over v_{TS} variation (all scenarios)

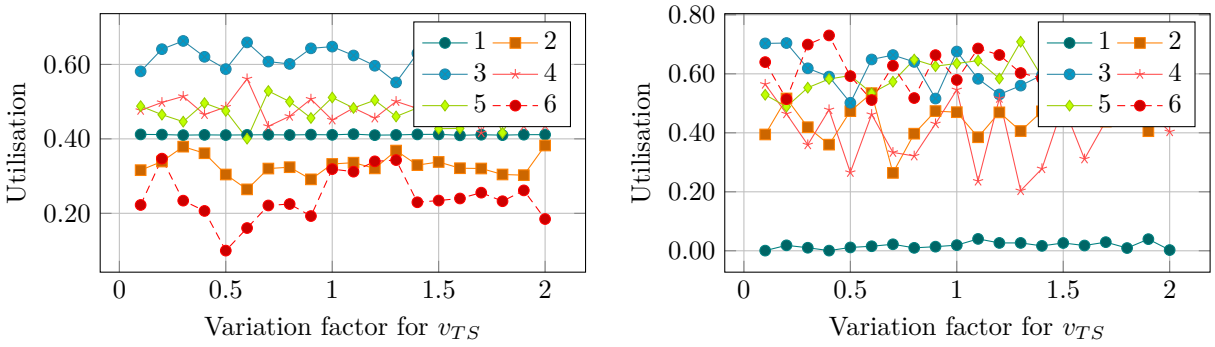

Figure 2.54: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over v_{TS} variation

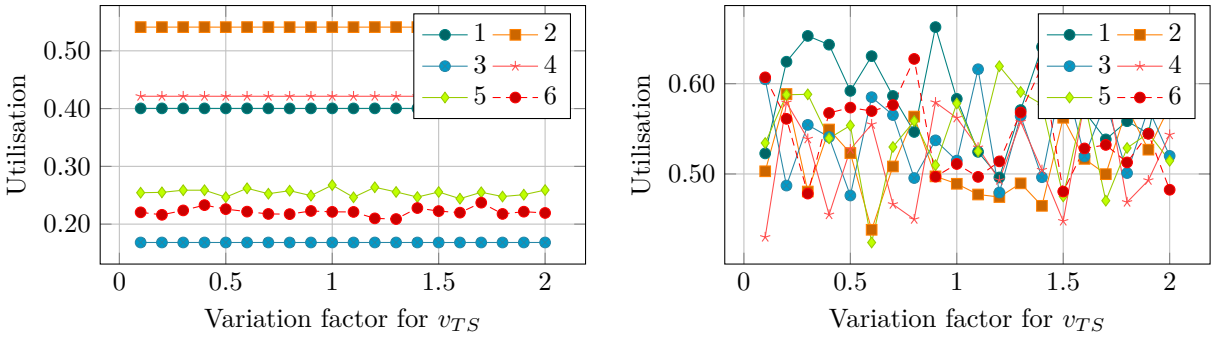

Figure 2.55: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over v_{TS} variation

2.5.4 Waiting Times (v_{TS})

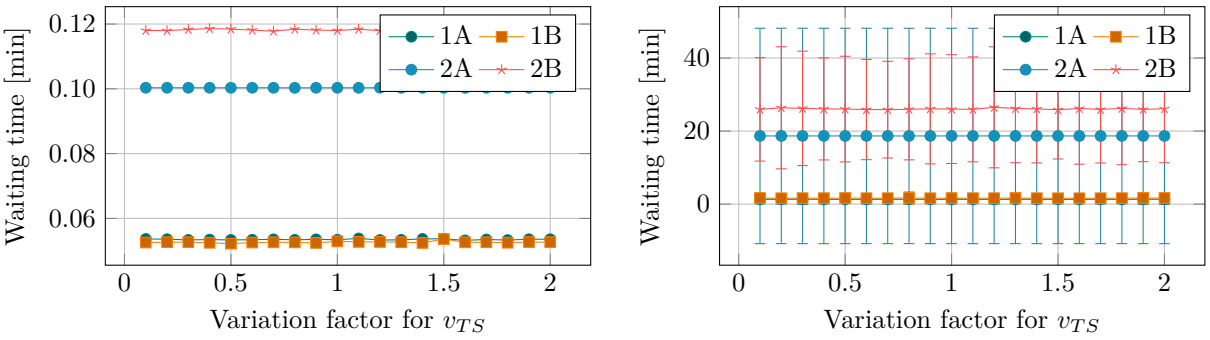

Figure 2.56: Waiting times w^Q_{TS} (left) and mean waiting time $\bar{w}^Q_{SC}$ [min] (right) over v_{TS} variation (all scenarios)

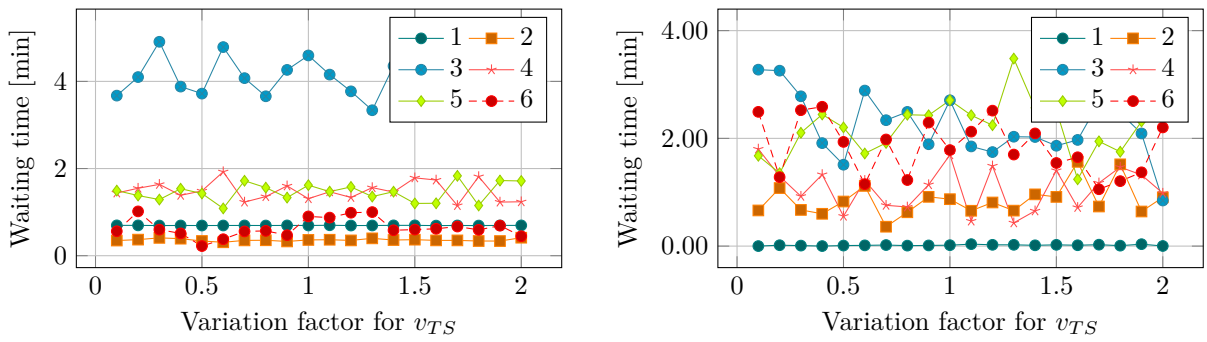

Figure 2.57: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over v_{TS} variation

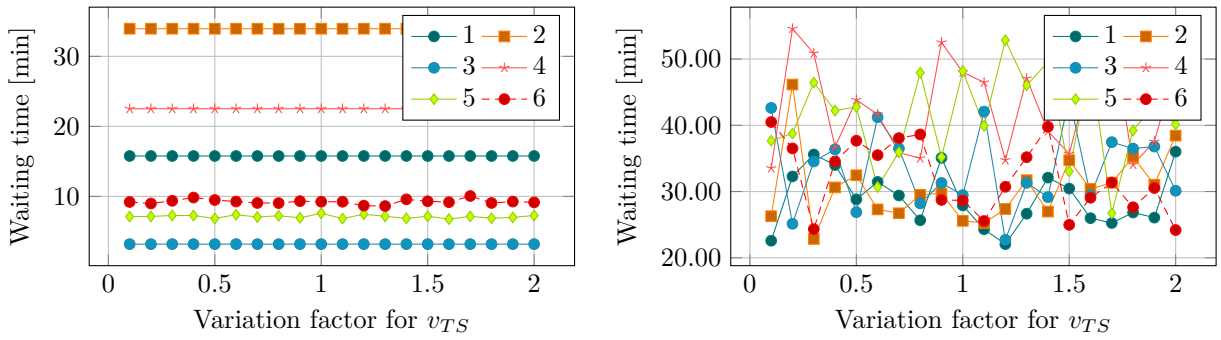

Figure 2.58: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over v_{TS} variation

2.5.5 Queue Lengths (v_{TS})

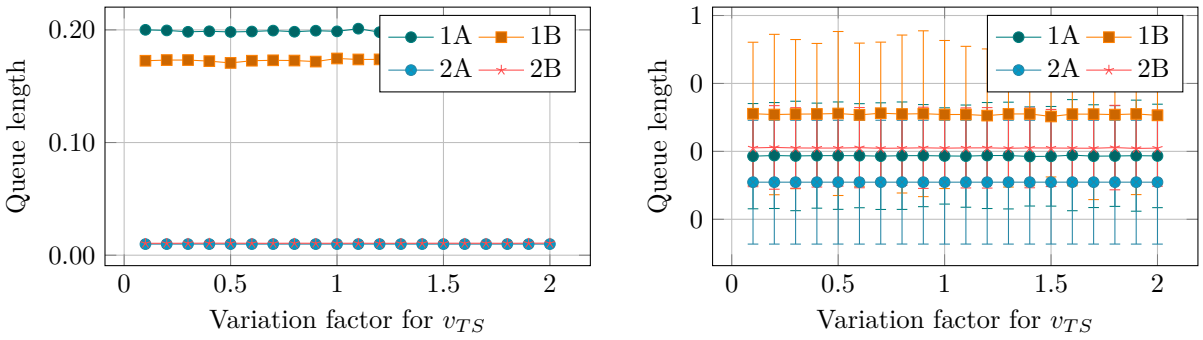

Figure 2.59: Queue length n^Q_{TS} [min] (left) and mean queue length $\bar{n}^Q_{SC}$ (right) over v_{TS} variation (all scenarios)

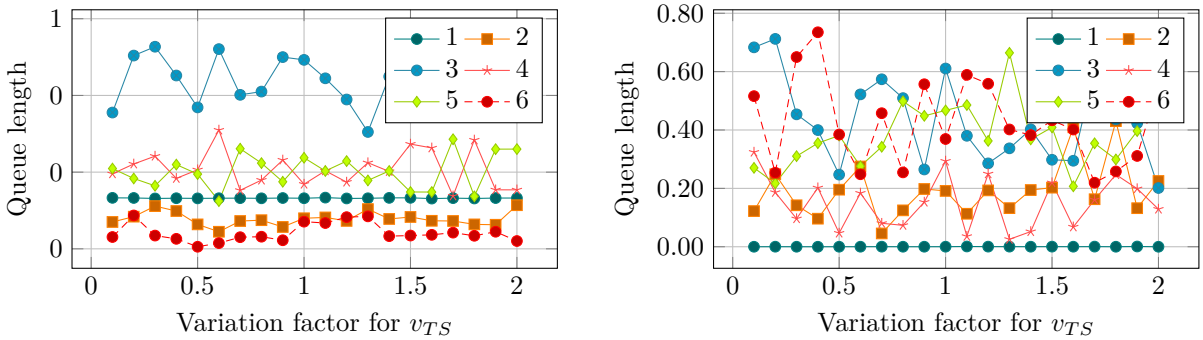

Figure 2.60: Queue lengths n^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over v_{TS} variation

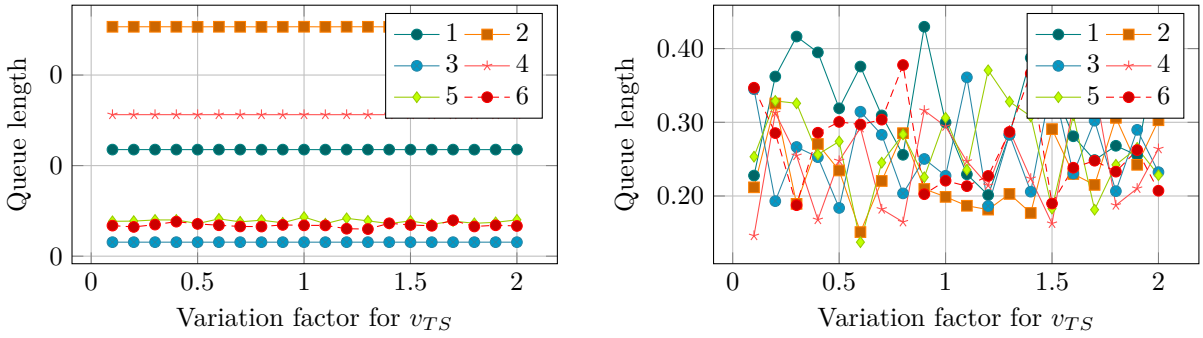

Figure 2.61: Queue lengths n^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over v_{TS} variation

2.5.6 Required Resources (v_{TS})

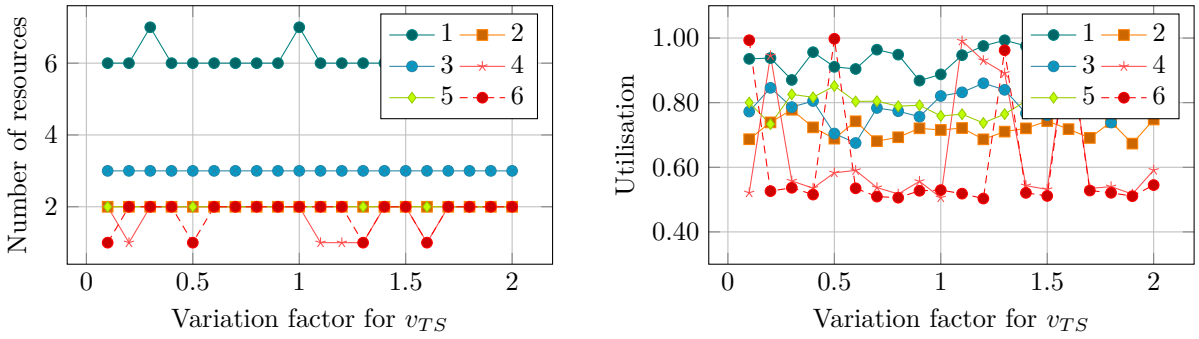

Figure 2.62: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over v_{TS} variation (scenario 1A)

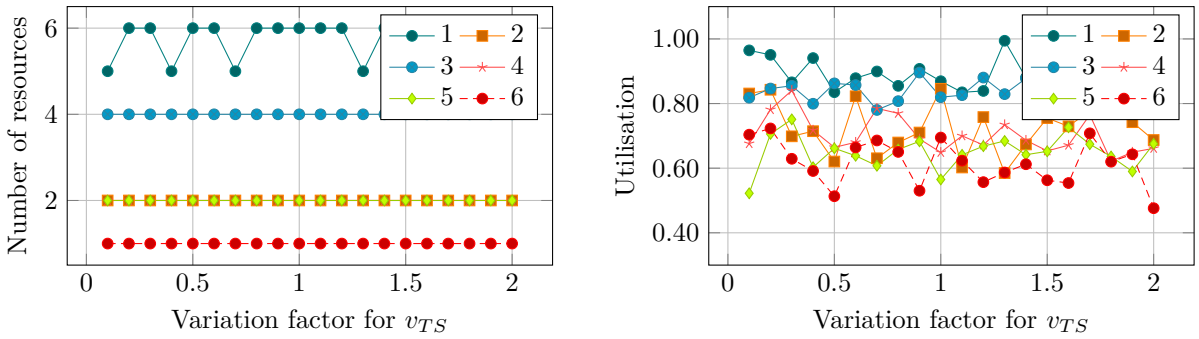

Figure 2.63: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over v_{TS} variation (scenario 1B)

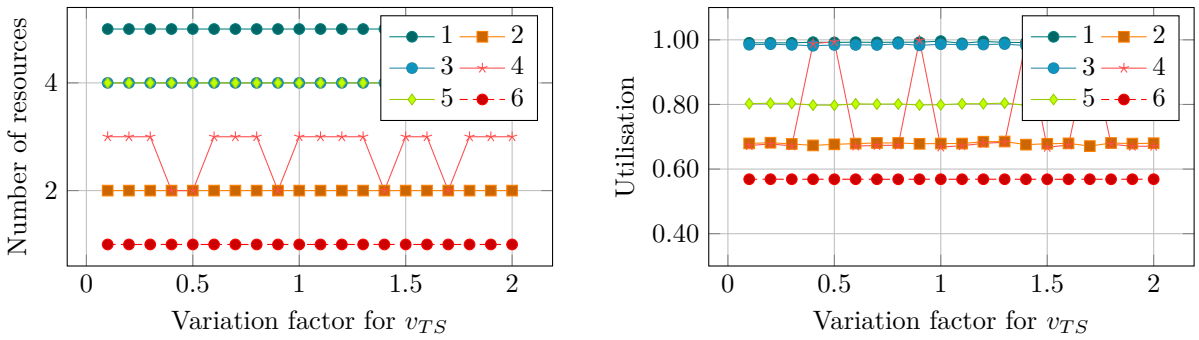

Figure 2.64: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over v_{TS} variation (scenario 2A)

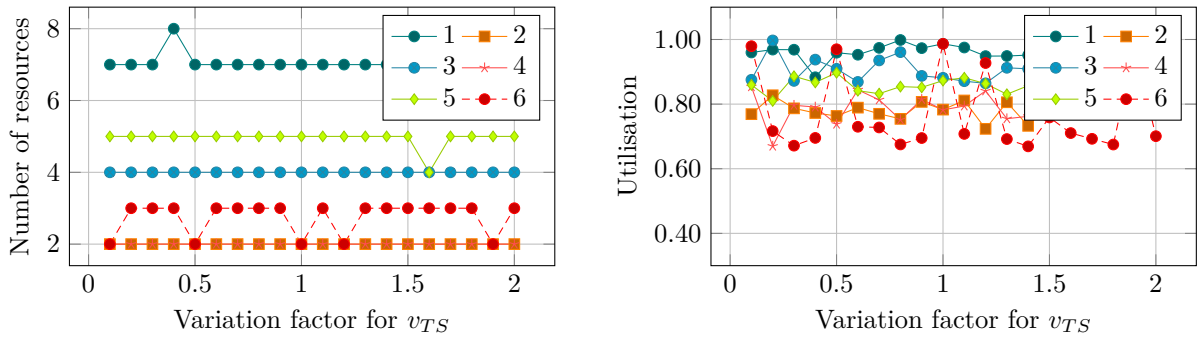

Figure 2.65: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over v_{TS} variation (scenario 2B)

2.6 Variation of Processing Times ($\mathbf{T}_{(P,PC)}$)

2.6.1 Throughput ($\mathbf{T}_{(P,PC)}$)

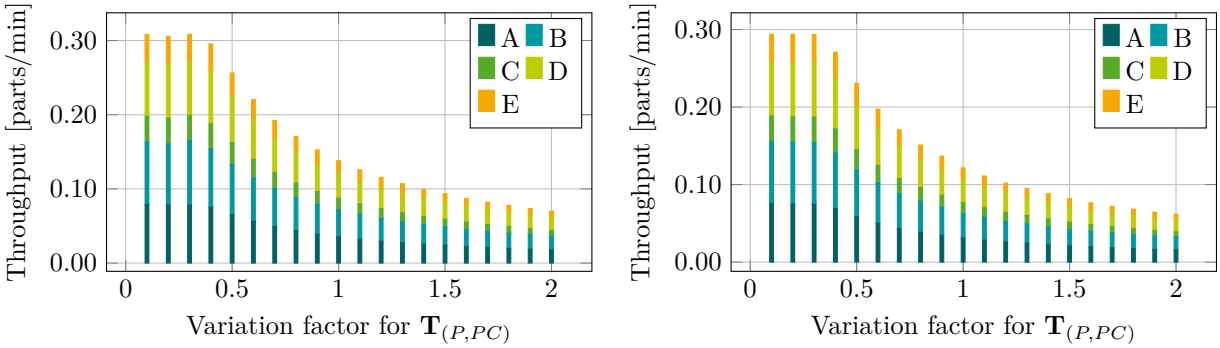

Figure 2.66: Throughput λ_j for all products for scenario 1A (left) and scenario 1B (right) over $\mathbf{T}_{(P,PC)}$ variation

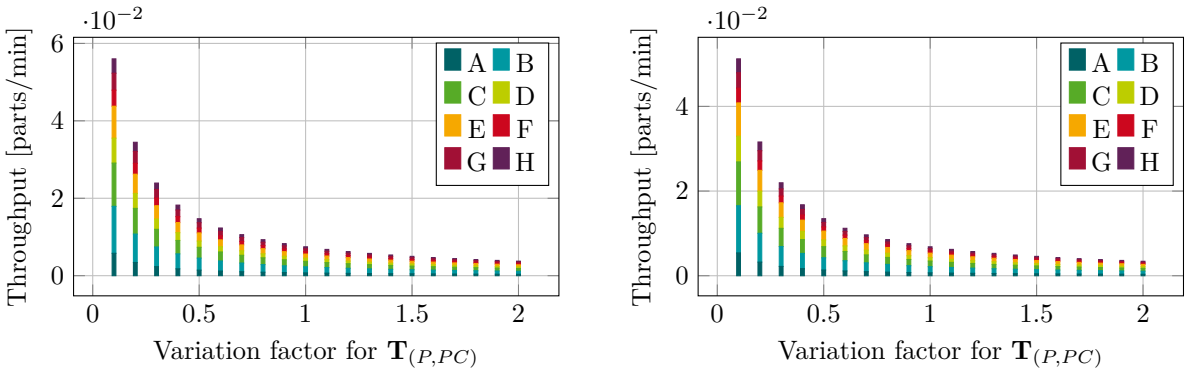

Figure 2.67: Throughput λ_j for all products for scenario 2A (left) and scenario 2B (right) over $\mathbf{T}_{(P,PC)}$ variation

2.6.2 Lead Time ($\mathbf{T}_{(P,PC)}$)

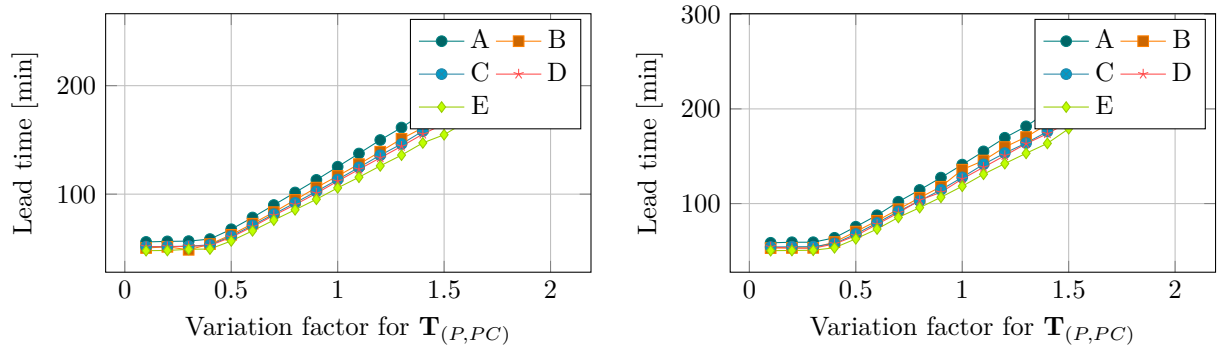

Figure 2.68: Lead time LT_j for all products for scenario 1A (left) and scenario 1B (right) over $\mathbf{T}_{(P,PC)}$ variation

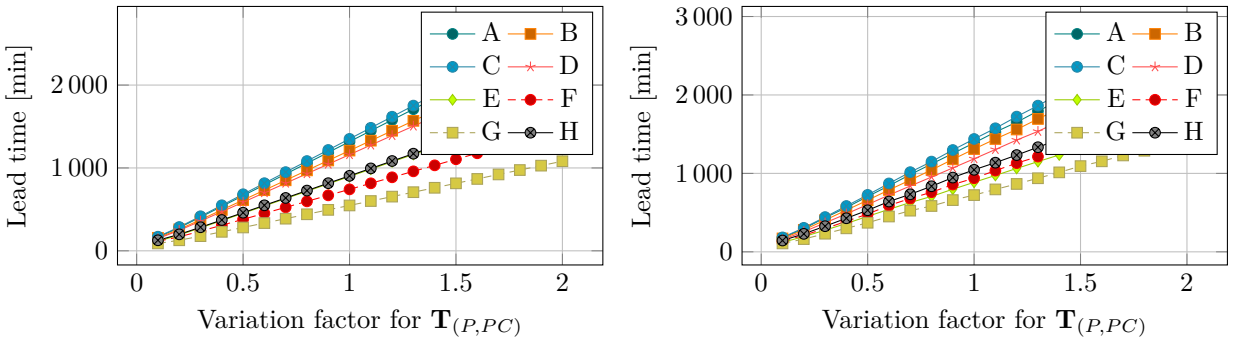

Figure 2.69: Lead time LT_j for all products for scenario 2A (left) and scenario 2B (right) over $\mathbf{T}_{(P,PC)}$ variation

2.6.3 Station Configuration Utilisation ($\mathbf{T}_{(P,PC)}$)

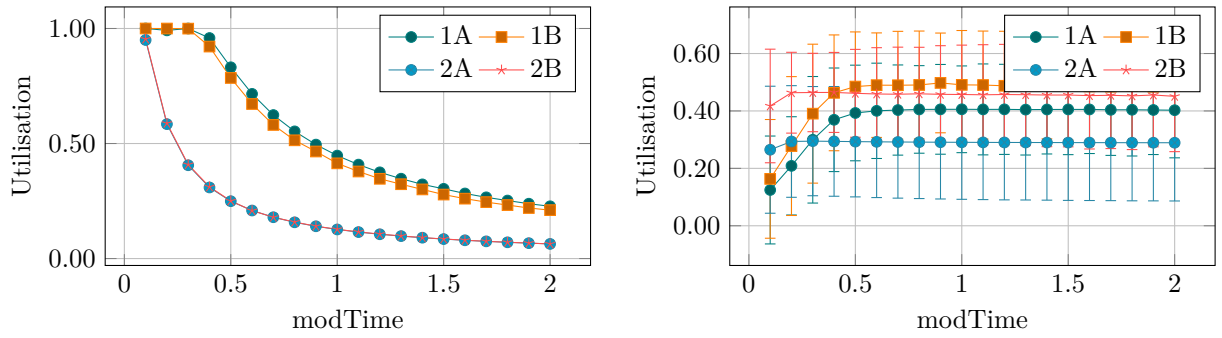

Figure 2.70: Utilisation of the transportation system ρ_{TS} (left) and mean station utilisation $\bar{\rho}_{SC}$ (right) over $\mathbf{T}_{(P,PC)}$ variation (all scenarios)

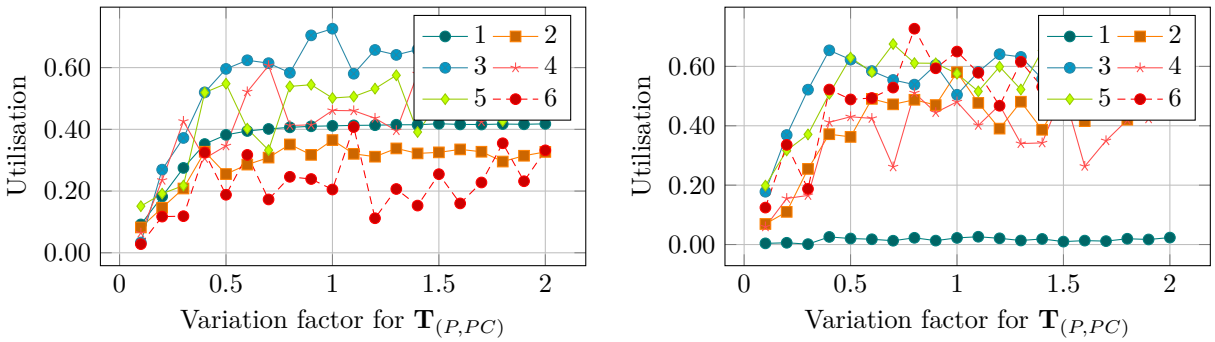

Figure 2.71: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over $\mathbf{T}_{(P,PC)}$ variation

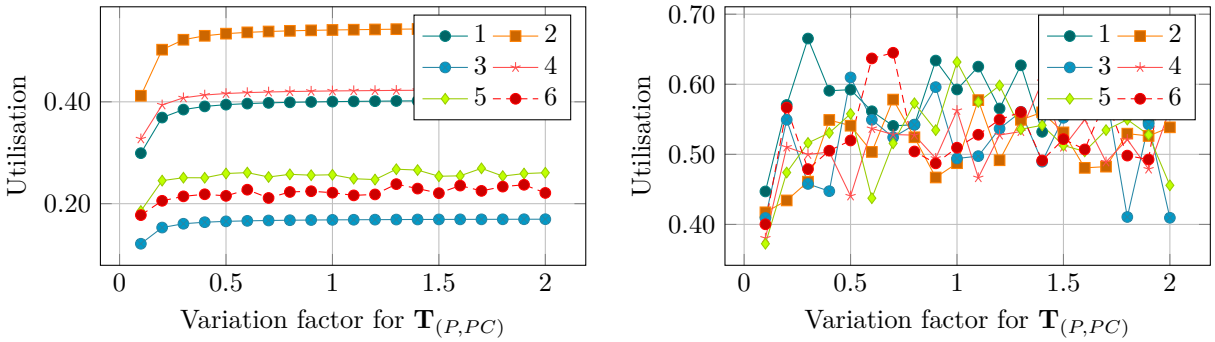

Figure 2.72: Station configuration utilisation ρ_{SC} of SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over $\mathbf{T}_{(P,PC)}$ variation

2.6.4 Waiting Times ($\mathbf{T}_{(P,PC)}$)

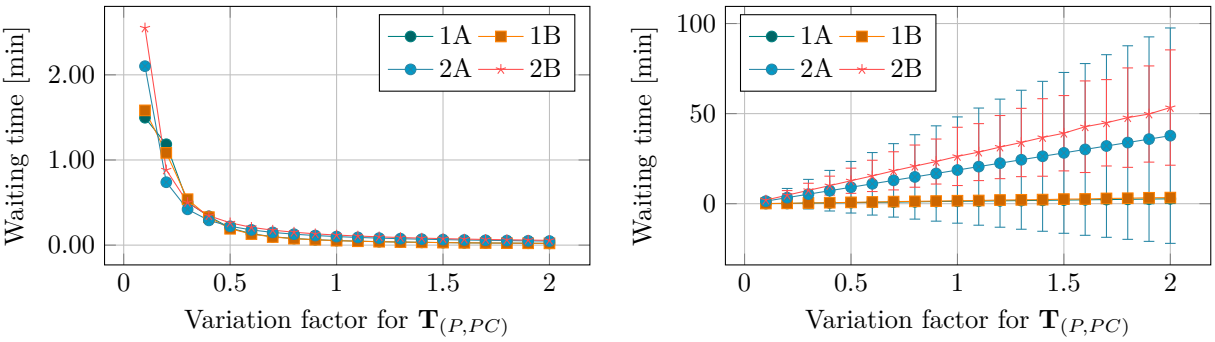

Figure 2.73: Waiting times w^Q_{TS} (left) and mean waiting time $\bar{w}^Q_{SC}$ [min] (right) over $\mathbf{T}_{(P,PC)}$ variation (all scenarios)

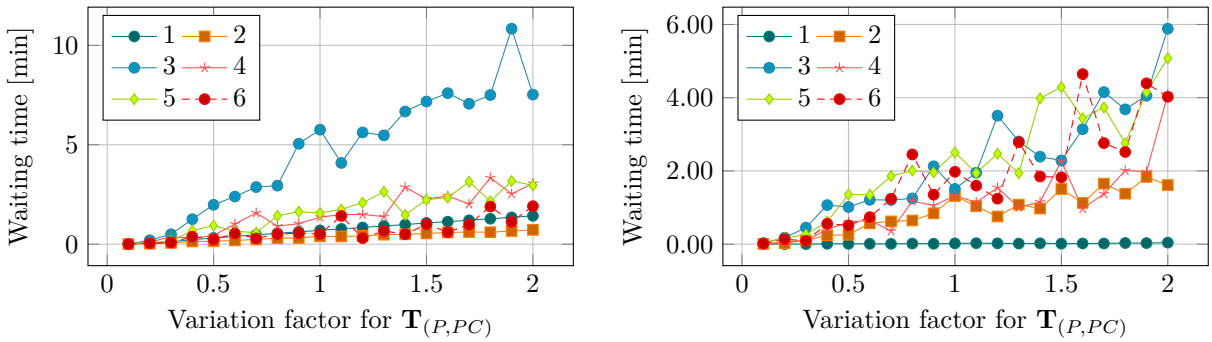

Figure 2.74: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over $\mathbf{T}_{(P,PC)}$ variation

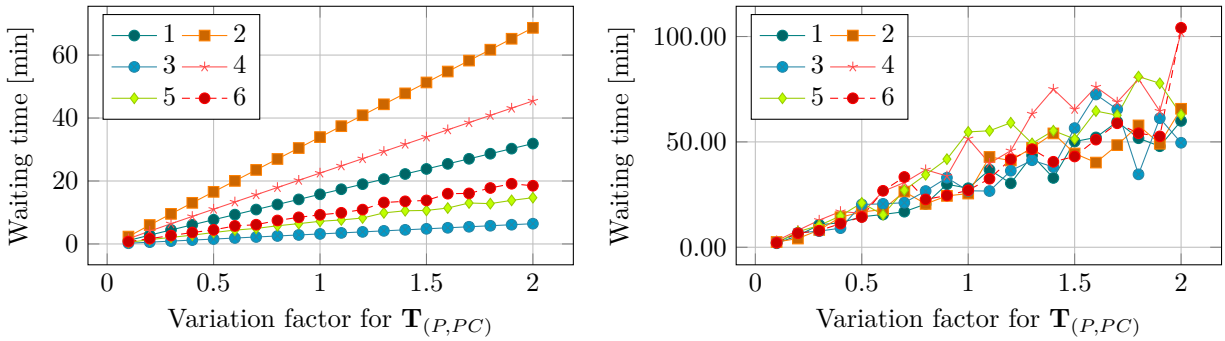

Figure 2.75: Waiting time w^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over $\mathbf{T}_{(P,PC)}$ variation

2.6.5 Queue Lengths ($\mathbf{T}_{(P,PC)}$)

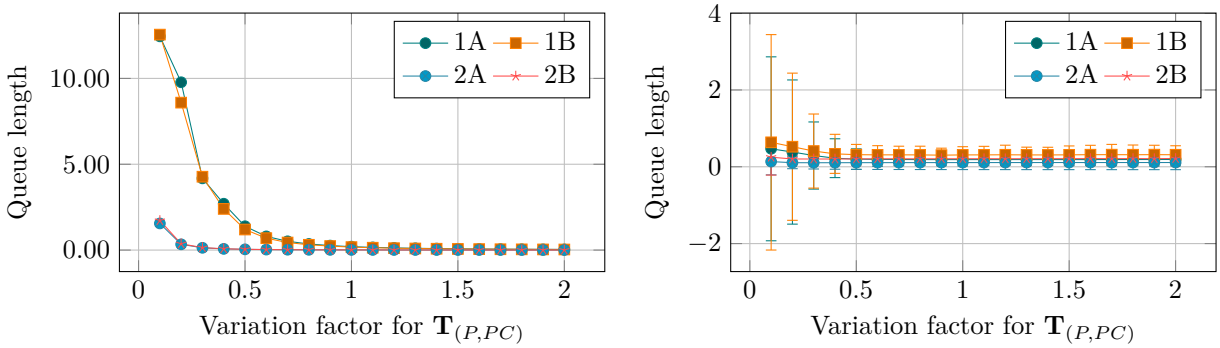

Figure 2.76: Queue length n^Q_{TS} [min] (left) and mean queue length $\bar{n}^Q_{SC}$ (right) over $\mathbf{T}_{(P,PC)}$ variation (all scenarios)

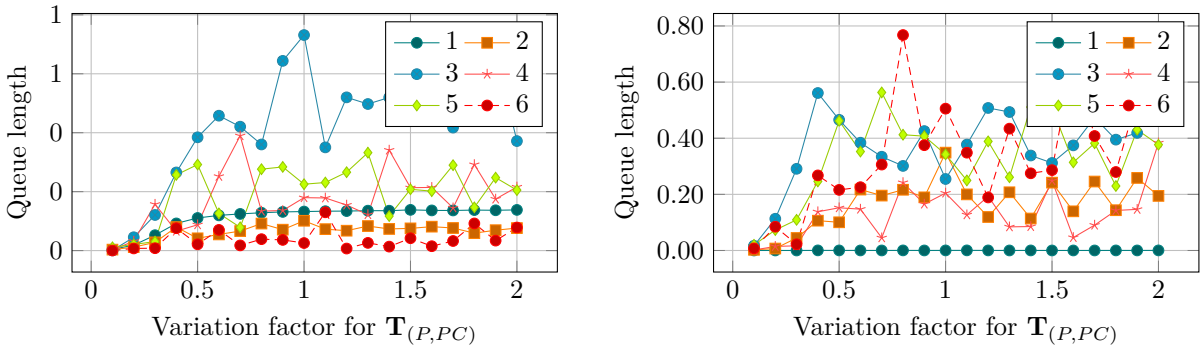

Figure 2.77: Queue lengths n^Q_{SC} at SC_1 to SC_6 for scenario 1A (left) and scenario 1B (right) over $\mathbf{T}_{(P,PC)}$ variation

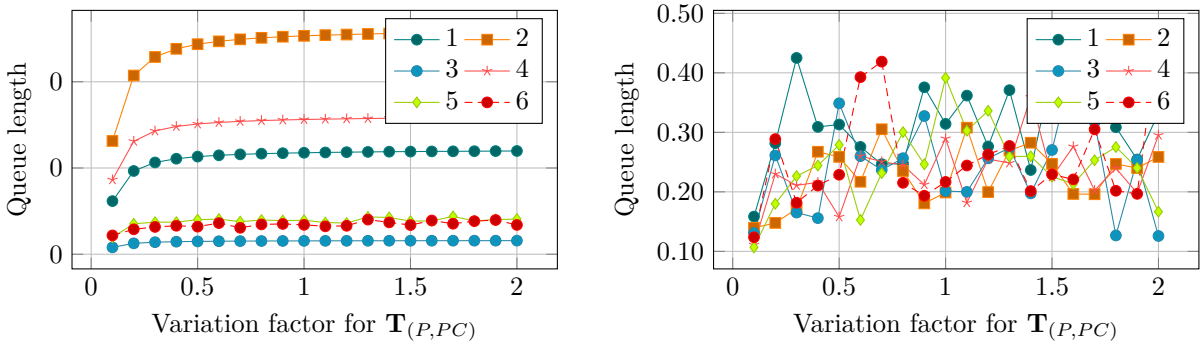

Figure 2.78: Queue lengths n^Q_{SC} at SC_1 to SC_6 for scenario 2A (left) and scenario 2B (right) over $\mathbf{T}_{(P,PC)}$ variation

2.6.6 Required Resources ($\mathbf{T}_{(P,PC)}$)

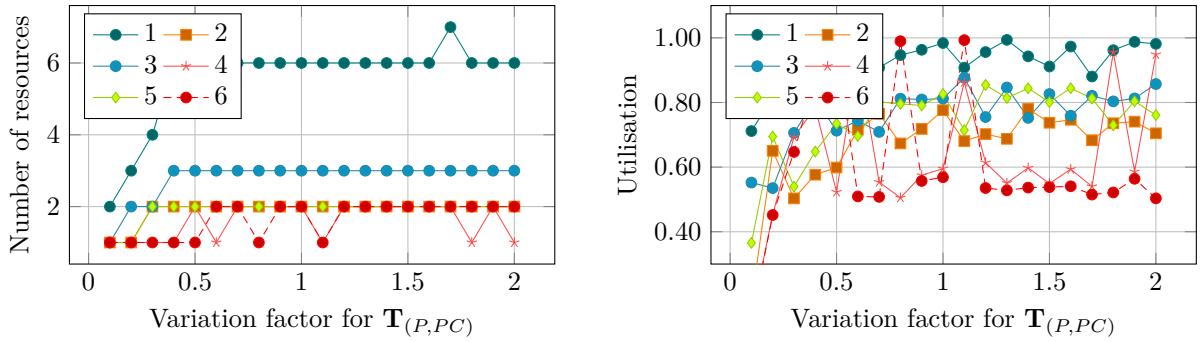

Figure 2.79: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over $\mathbf{T}_{(P,PC)}$ variation (scenario 1A)

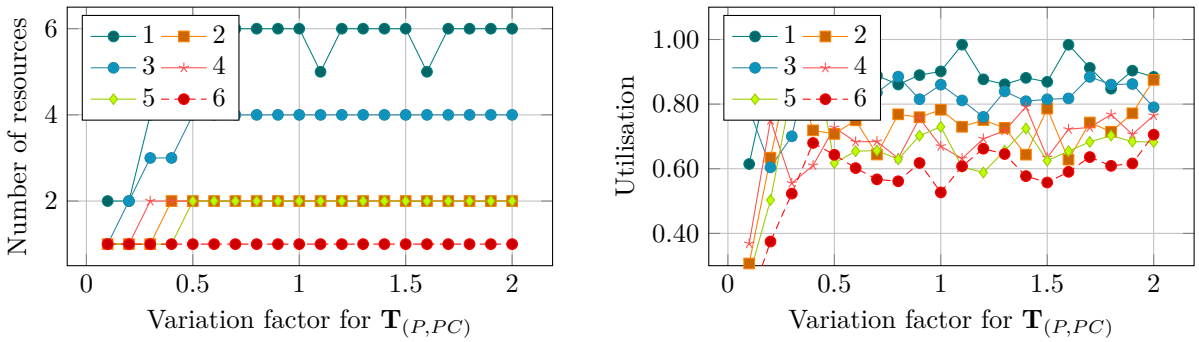

Figure 2.80: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over $\mathbf{T}_{(P,PC)}$ variation (scenario 1B)

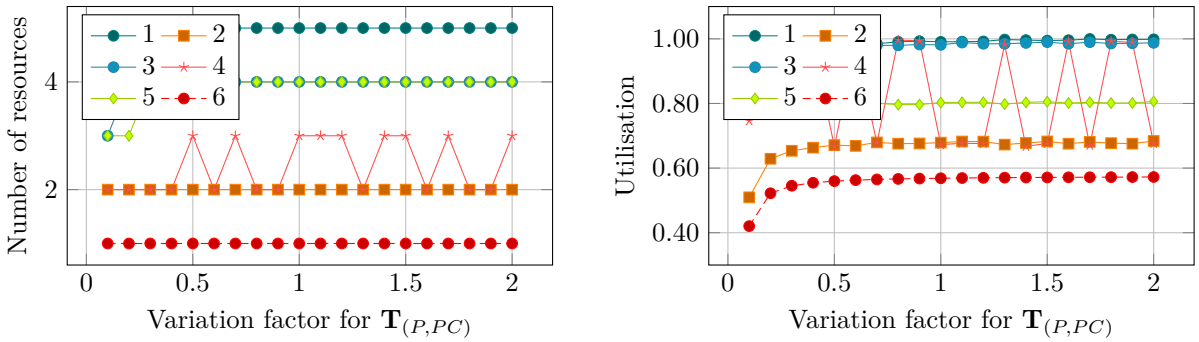

Figure 2.81: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over $\mathbf{T}_{(P,PC)}$ variation (scenario 2A)

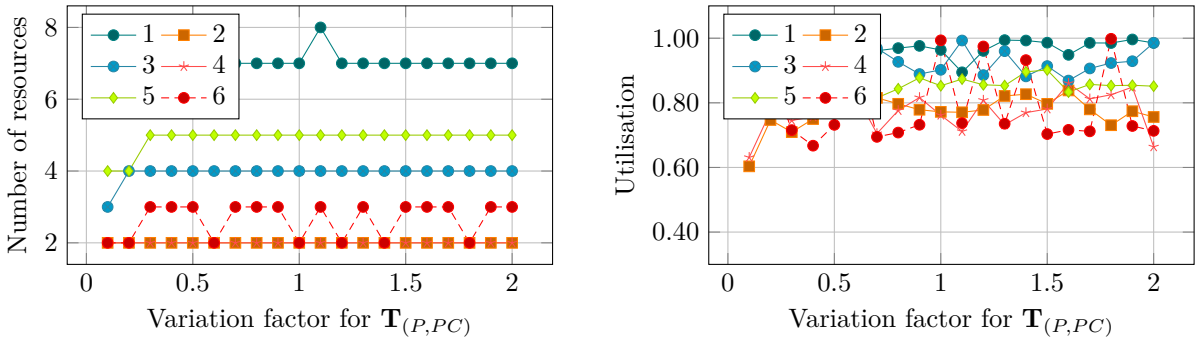

Figure 2.82: Number of required resources (left) and resource utilisation ρ_l (right) for r_1 to r_6 over $\mathbf{T}_{(P,PC)}$ variation (scenario 2B)

2.7 Variation of Production Program ($\vec{p}_P$)

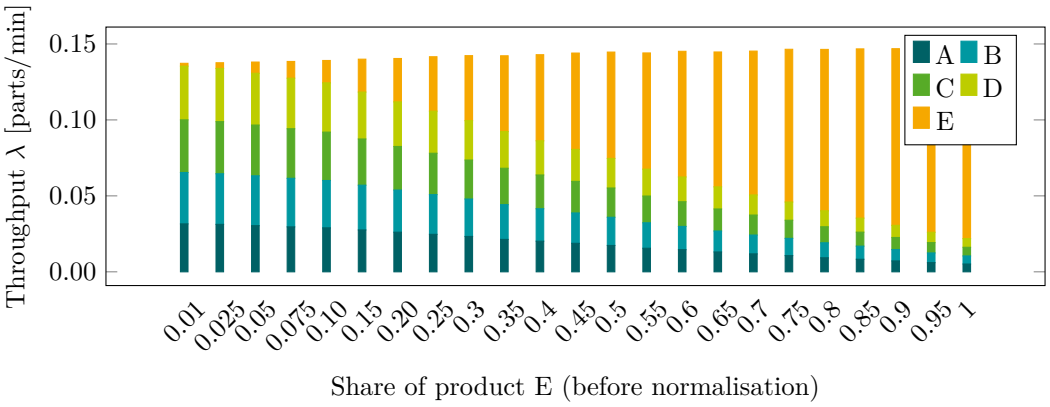

Figure 2.83: Throughput λ of all products over variation of share of product E in production program (modified scenario 1A)

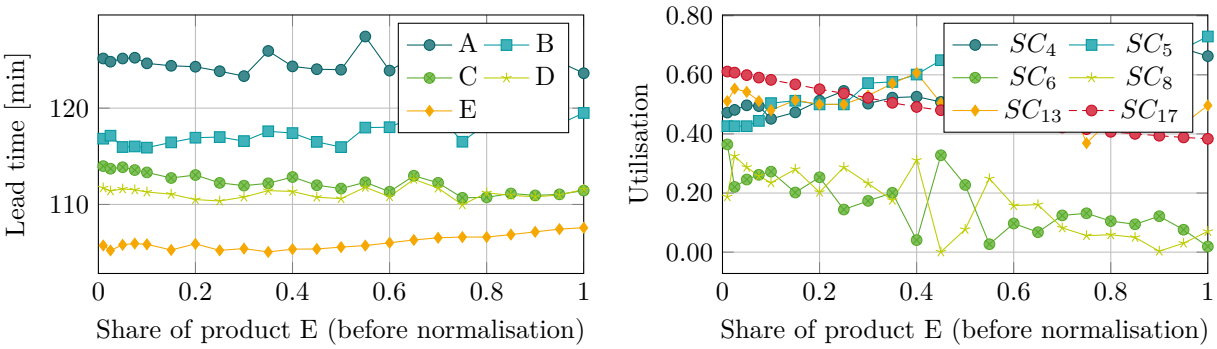

Figure 2.84: Lead time LT_j for all products (left) and selected station configuration utilisations ρ_{SC} (right) over variation of share of product E in production program f_E (modified scenario 1A)

2.8 Two Factor Variation WIP and Processing Times ($\mathbf{T}_{(P,PC)}$)

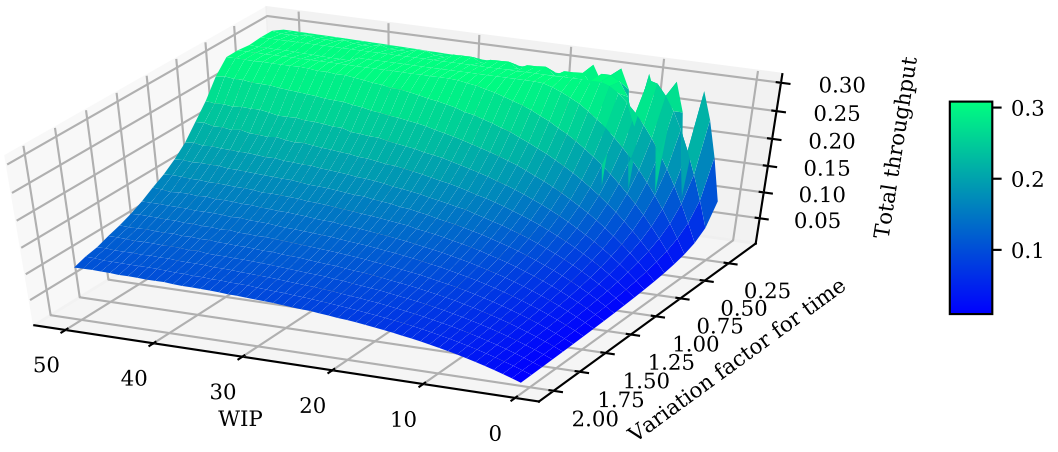

Figure 2.85: Surface plot of total throughput over modification factor for processing time and WIP (scenario 1A)

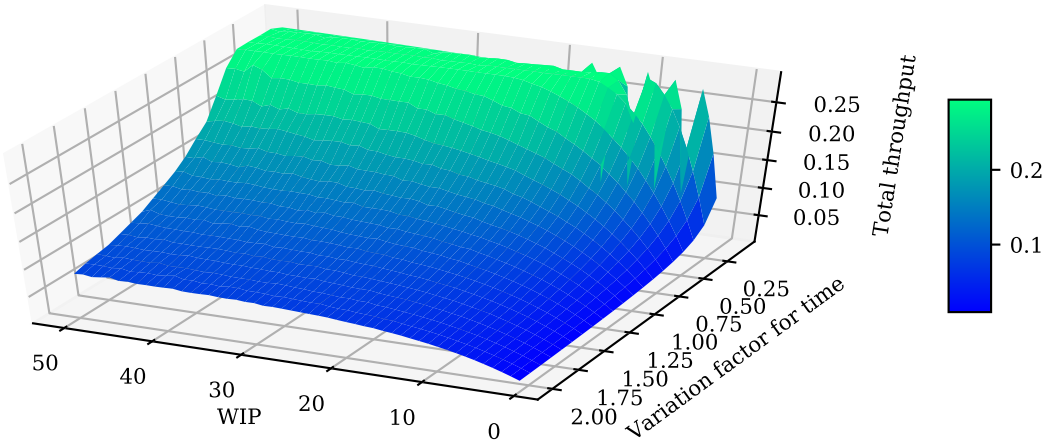

Figure 2.86: Surface plot of total throughput over modification factor for processing time and WIP (scenario 1B)

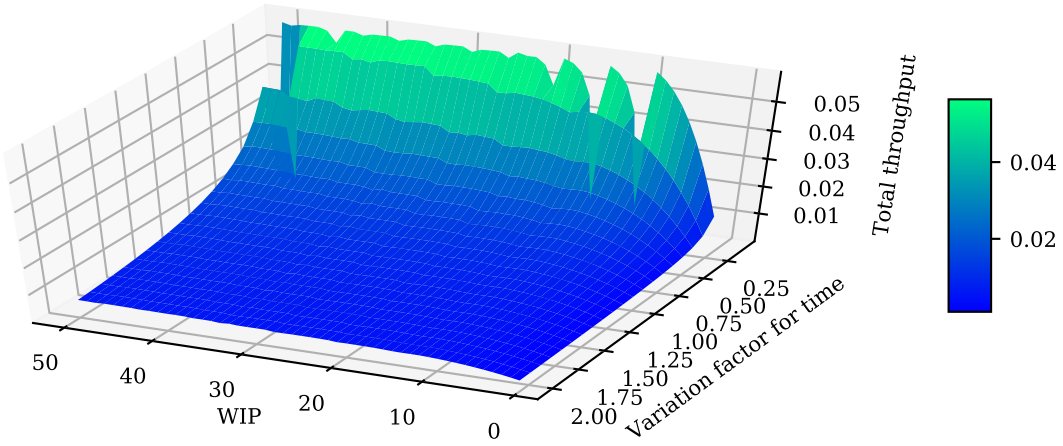

Figure 2.87: Surface plot of total throughput over modification factor for processing time and WIP (scenario 2A)

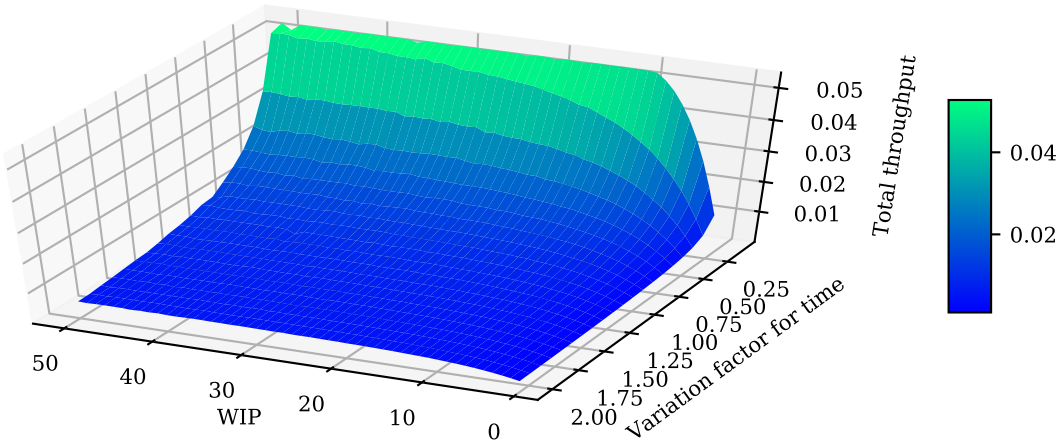

Figure 2.88: Surface plot of total throughput over modification factor for processing time and WIP (scenario 2B)

λ_A

Time / WIP	0.5	1.0	1.5
0.5	-7,9%	-8,1%	-8,2%
1.0	-7,8%	-7,5%	-7,5%
1.5	-7,3%	-6,9%	-7,0%

λ_B

Time / WIP	0.5	1.0	1.5
0.5	-1,9%	-1,8%	-1,7%
1.0	0,0%	-0,4%	-0,3%
1.5	1,3%	-0,1%	0,7%

λ_C

Time / WIP	0.5	1.0	1.5
0.5	3,4%	3,3%	3,4%
1.0	2,1%	2,1%	2,2%
1.5	1,0%	0,9%	0,9%

λ_D

Time / WIP	0.5	1.0	1.5
0.5	4,7%	4,9%	4,8%
1.0	3,6%	3,8%	3,6%
1.5	2,4%	2,9%	3,0%

λ_E

Time / WIP	0.5	1.0	1.5
0.5	10,6%	10,4%	10,4%
1.0	9,4%	9,3%	9,5%
1.5	8,6%	10,0%	8,5%

Figure 2.89: Deviations of product shares in production program f_j and throughput (scenario 1A)

λ_A

Time / WIP	0.5	1.0	1.5
0.5	-7,7%	-7,1%	-7,7%
1.0	-7,6%	-7,4%	-8,0%
1.5	-7,4%	-7,3%	-7,4%

λ_B

Time / WIP	0.5	1.0	1.5
0.5	-2,0%	-2,6%	-2,5%
1.0	0,4%	-2,0%	-0,7%
1.5	-0,9%	-1,1%	0,4%

λ_C

Time / WIP	0.5	1.0	1.5
0.5	3,4%	4,0%	4,5%
1.0	1,6%	1,9%	2,2%
1.5	2,3%	1,7%	0,9%

λ_D

Time / WIP	0.5	1.0	1.5
0.5	4,7%	4,4%	4,7%
1.0	3,0%	4,8%	3,5%
1.5	3,6%	3,4%	3,1%

λ_E

Time / WIP	0.5	1.0	1.5
0.5	10,3%	10,3%	10,3%
1.0	9,7%	10,8%	11,7%
1.5	10,2%	11,6%	9,6%

Figure 2.90: Deviations of product shares in production program f_j and throughput (scenario 1B)

λ_A

Time / WIP	0.5	1.0	1.5
0.5	-20,8%	-21,2%	-21,3%
1.0	-18,3%	-18,6%	-18,7%
1.5	-17,1%	-17,5%	-17,6%

λ_B

Time / WIP	0.5	1.0	1.5
0.5	-12,7%	-13,0%	-13,1%
1.0	-11,2%	-11,4%	-11,4%
1.5	-11,0%	-11,2%	-11,3%

λ_C

Time / WIP	0.5	1.0	1.5
0.5	-22,2%	-22,6%	-22,7%
1.0	-20,3%	-20,6%	-20,7%
1.5	-19,5%	-19,7%	-19,7%

λ_D

Time / WIP	0.5	1.0	1.5
0.5	-6,3%	-6,6%	-6,7%
1.0	-7,3%	-7,6%	-7,7%
1.5	-9,2%	-9,6%	-9,8%

λ_E

Time / WIP	0.5	1.0	1.5
0.5	28,4%	28,3%	28,3%
1.0	20,0%	19,6%	19,4%
1.5	11,3%	10,7%	10,4%

λ_F

Time / WIP	0.5	1.0	1.5
0.5	40,3%	41,6%	42,0%
1.0	43,1%	44,5%	44,9%
1.5	53,6%	55,6%	55,9%

λ_G

Time / WIP	0.5	1.0	1.5
0.5	91,9%	94,7%	95,7%
1.0	92,9%	95,7%	96,7%
1.5	105,0%	108,4%	109,8%

λ_H

Time / WIP	0.5	1.0	1.5
0.5	21,6%	22,1%	22,3%
1.0	18,1%	18,4%	18,5%
1.5	12,5%	12,5%	12,3%

Figure 2.91: Deviations of product shares in production program f_j and throughput (scenario 2A)

λ_A

WIP \ Time	0.5	1.0	1.5
0.5	-19,2%	-19,8%	-19,7%
1.0	-16,2%	-15,8%	-15,5%
1.5	-12,5%	-12,2%	-12,4%

λ_B

WIP \ Time	0.5	1.0	1.5
0.5	-12,1%	-12,3%	-12,6%
1.0	-10,0%	-10,0%	-10,4%
1.5	-9,2%	-9,4%	-8,6%

λ_C

WIP \ Time	0.5	1.0	1.5
0.5	-21,2%	-21,8%	-21,6%
1.0	-18,1%	-18,3%	-19,0%
1.5	-16,1%	-16,6%	-16,5%

λ_D

WIP \ Time	0.5	1.0	1.5
0.5	-2,6%	-3,1%	-2,9%
1.0	-1,3%	-2,2%	-2,5%
1.5	-0,4%	-1,1%	-1,5%

λ_E

WIP \ Time	0.5	1.0	1.5
0.5	33,5%	34,1%	34,8%
1.0	32,3%	30,6%	30,8%
1.5	30,4%	30,4%	29,1%

λ_F

WIP \ Time	0.5	1.0	1.5
0.5	30,6%	32,2%	30,9%
1.0	23,2%	23,7%	25,5%
1.5	17,8%	18,0%	17,7%

λ_G

WIP \ Time	0.5	1.0	1.5
0.5	76,5%	77,4%	78,2%
1.0	59,1%	62,0%	63,3%
1.5	49,1%	50,7%	51,4%

λ_H

WIP \ Time	0.5	1.0	1.5
0.5	16,3%	18,4%	17,4%
1.0	11,4%	13,4%	15,0%
1.5	8,2%	10,3%	10,5%

Figure 2.92: Deviations of product shares in production program f_j and throughput (scenario 2B)

2.9 Reconfiguration Efforts

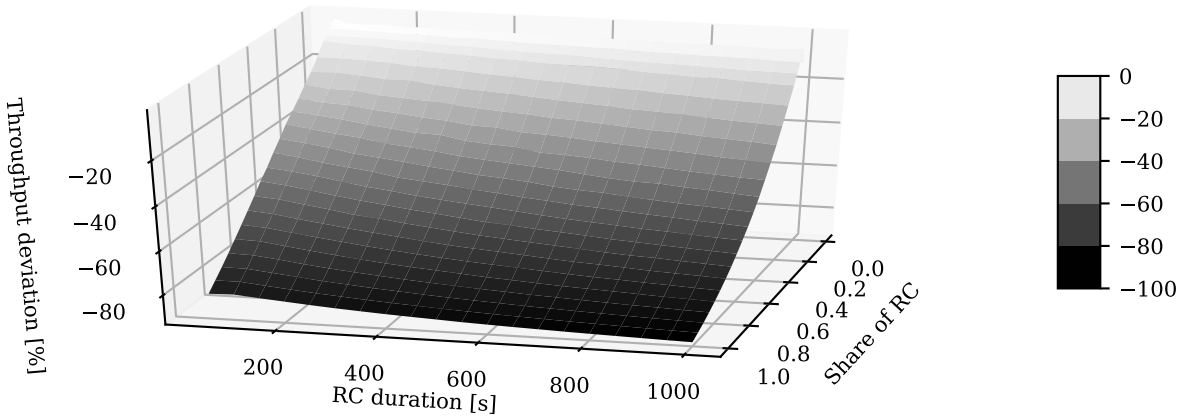

Figure 2.93: Impact of reconfiguration efforts on total throughput λ_{tot} (scenario 1A). Share of RC refers to the value of f_{RC} prior to normalisation.

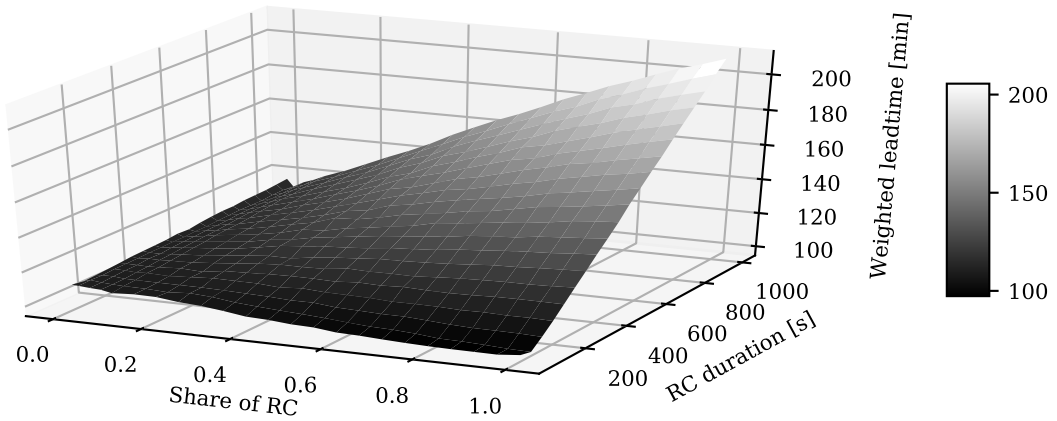

Figure 2.94: Effects of reconfiguration efforts on weighted lead time LT_w for products over production program and reconfiguration time variation (scenario 1A)

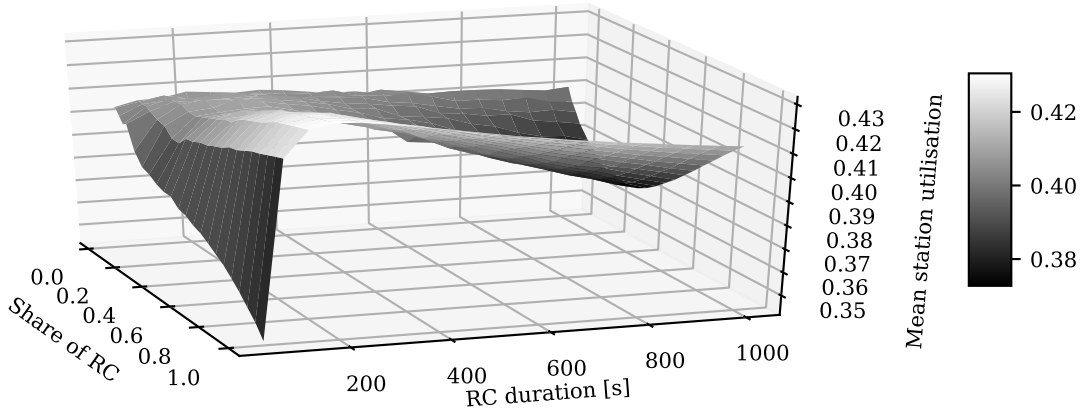

Figure 2.95: Effects of reconfiguration efforts on mean station utilisation $\bar{\rho}_{SC}$ over production program and reconfiguration time variation (scenario 1A)

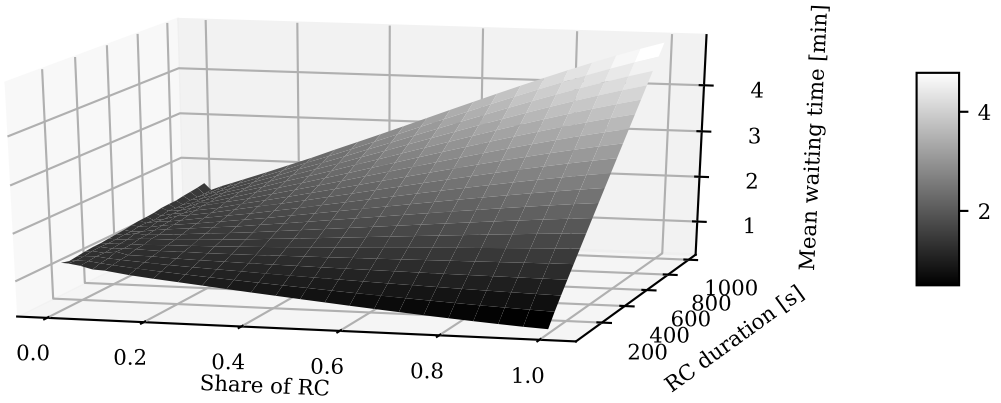

Figure 2.96: Effects of reconfiguration efforts on mean waiting time at stations $\bar{w}_{SC}^{q}$ over production program and reconfiguration time variation (scenario 1A)

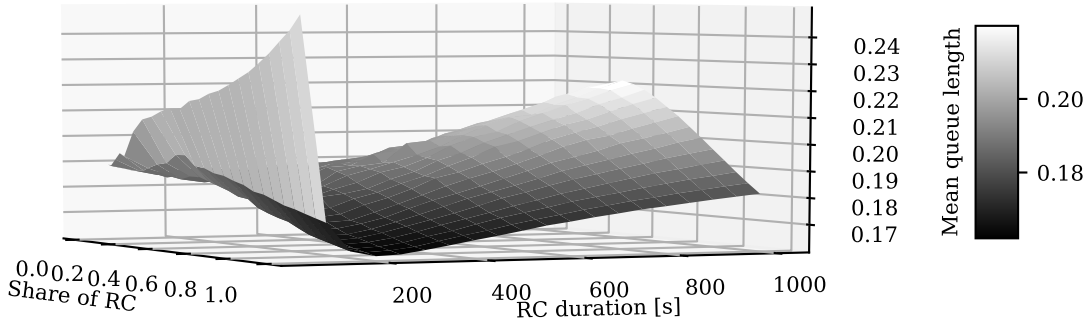

Figure 2.97: Effects of reconfiguration efforts on mean queue length time at stations $\bar{n}_{SC}^{q}$ over production program and reconfiguration time variation (scenario 1A)

3

Results of Model Comparison

The stochastic model and the DES Model (JaamSim) are compared in Table **??**.

Table 3.1: Comparison of stochastic model and JaamSim model

Similarities	
• Based on queuing theory • Similar level of detail (system of abstract stations, orders, and transport system) • Similar input data (work plans of different products, relative frequencies of products, capabilities of stations, and transport routes) • Assembly sequence restriction are not taken into consideration • FIFO input buffer with infinite capacity before each station • Closed queue model	
Differences	
Stochastic Model	JaamSim Model
Analytical method using EMVA for long periods	Discrete event simulation for any period
Scheduling by Monte Carlo simulation with randomly generated stochastic flow charts	Scheduling based on JaamSim function “JavaRandom”, random assignment of jobs to a station that provides a missing process and is not blocked (i.e. queue not full)
Operating times at stations result from average standard processing times with variability	Deterministic operating times are assigned by events
Transportation time based on the average transportation route and variance of all transportation routes	Discrete-event simulation of the transport including empty run to the starting point of the transport
Consideration of a stable system over a long (indefinite) period	Consideration of any system for a defined period with a defined job list and possibility to encounter deadlocks

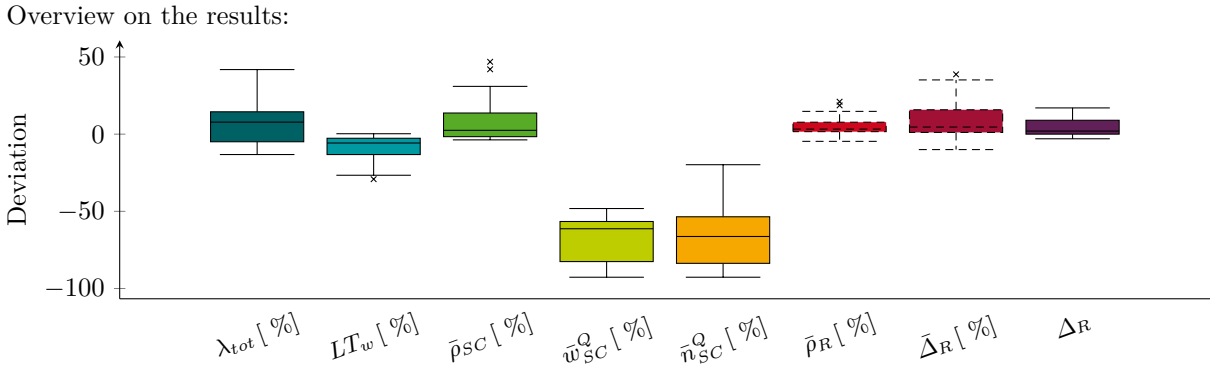

Figure 3.1: Box plot of model result deviations for selected key figures (all experiments, $n = 36$). Relative deviations are indicated with %. Δ_R is indicated as absolute deviation.

3.1 Two Factor Variation of Main Key Figures

LT_A

WIP \ Time	0.5	1.0	1.5
0.5	-29,4%	-19,0%	-14,7%
1.0	-20,2%	-15,6%	-12,6%
1.5	-12,6%	-12,2%	-11,0%

LT_B

WIP \ Time	0.5	1.0	1.5
0.5	-27,6%	-17,3%	-12,7%
1.0	-19,5%	-13,3%	-10,7%
1.5	-12,1%	-10,2%	-9,3%

LT_C

WIP \ Time	0.5	1.0	1.5
0.5	-29,7%	-18,6%	-13,7%
1.0	-20,2%	-14,4%	-11,4%
1.5	-12,3%	-10,9%	-11,0%

LT_D

WIP \ Time	0.5	1.0	1.5
0.5	-30,1%	-19,2%	-14,2%
1.0	-20,5%	-15,2%	-11,5%
1.5	-12,3%	-11,3%	-10,1%

LT_E

WIP \ Time	0.5	1.0	1.5
0.5	-29,7%	-18,0%	-13,4%
1.0	-19,7%	-14,4%	-10,1%
1.5	-11,0%	-10,5%	-6,9%

LT_w

WIP \ Time	0.5	1.0	1.5
0.5	-29,2%	-18,5%	-13,8%
1.0	-20,0%	-14,7%	-11,5%
1.5	-12,2%	-11,2%	-10,0%

λ_A

WIP \ Time	0.5	1.0	1.5
0.5	30,6%	13,3%	7,0%
1.0	15,9%	8,9%	4,9%
1.5	6,2%	5,3%	3,8%

λ_B

WIP \ Time	0.5	1.0	1.5
0.5	39,2%	21,1%	14,6%
1.0	25,8%	17,3%	13,2%
1.5	16,0%	13,1%	12,5%

λ_C

WIP \ Time	0.5	1.0	1.5
0.5	46,7%	27,5%	20,6%
1.0	28,4%	20,3%	16,0%
1.5	15,7%	14,2%	12,7%

λ_D

WIP \	0.5	1.0	1.5
0.5	48,4%	29,3%	22,2%
1.0	30,2%	22,3%	17,5%
1.5	17,2%	16,5%	15,0%

λ_E

WIP \	0.5	1.0	1.5
0.5	56,7%	35,9%	28,6%
1.0	37,4%	28,7%	24,2%
1.5	24,3%	24,4%	21,1%

λ_{tot}

WIP \ Time	0.5	1.0	1.5
0.5	41,8%	23,3%	16,6%
1.0	25,7%	17,8%	13,5%
1.5	14,5%	13,1%	11,7%

$\bar{\rho}_{SC}$

WIP \ Time	0.5	1.0	1.5
0.5	46,9%	23,0%	14,6%
1.0	31,0%	17,7%	11,9%
1.5	19,4%	12,9%	10,4%

$\bar{\rho}_R$

WIP \ Time	0.5	1.0	1.5
0.5	27,3%	21,0%	14,3%
1.0	38,7%	35,1%	25,0%
1.5	23,6%	15,1%	18,6%

$\bar{\Delta}_R$

WIP \ Time	0.5	1.0	1.5
0.5	11,0	9,0	6,0
1.0	17,0	17,0	12,0
1.5	14,0	10,0	13,0

$\bar{w}_{SC}^{Q}$

WIP \ Time	0.5	1.0	1.5
0.5	-48,7%	-60,2%	-62,7%
1.0	-61,9%	-72,1%	-72,9%
1.5	-70,7%	-77,2%	-79,0%

$\bar{n}_{SC}^{Q}$

WIP \ Time	0.5	1.0	1.5
0.5	-42,7%	-66,3%	-70,9%
1.0	-58,2%	-77,6%	-79,4%
1.5	-64,6%	-81,8%	-84,0%

Figure 3.2: Model comparison key figure overview for two factor variation (scenario 1A)

LT_A

WIP \ Time	0.5	1.0	1.5
0.5	-27,0%	-18,4%	-14,3%
1.0	-16,2%	-11,3%	-8,7%
1.5	-5,4%	-2,8%	-1,0%

LT_B

WIP \ Time	0.5	1.0	1.5
0.5	-24,9%	-15,1%	-11,4%
1.0	-15,6%	-8,2%	-7,3%
1.5	-2,8%	0,0%	0,4%

LT_C

WIP \ Time	0.5	1.0	1.5
0.5	-27,4%	-17,7%	-14,4%
1.0	-14,9%	-9,8%	-7,9%
1.5	-4,8%	-1,7%	0,9%

LT_D

WIP \ Time	0.5	1.0	1.5
0.5	-27,4%	-17,9%	-13,2%
1.0	-16,0%	-10,5%	-7,9%
1.5	-5,3%	-1,7%	1,2%

LT_E

WIP \ Time	0.5	1.0	1.5
0.5	-27,4%	-17,4%	-13,7%
1.0	-16,1%	-10,9%	-9,9%
1.5	-5,2%	-2,3%	1,0%

LT_w

WIP \ Time	0.5	1.0	1.5
0.5	-26,6%	-17,2%	-13,2%
1.0	-15,8%	-10,1%	-8,2%
1.5	-4,6%	-1,6%	0,3%

λ_A

WIP \ Time	0.5	1.0	1.5
0.5	26,4%	12,7%	6,9%
1.0	10,3%	3,5%	0,7%
1.5	-2,4%	-5,2%	-7,1%

λ_B

WIP \ Time	0.5	1.0	1.5
0.5	34,2%	18,2%	12,9%
1.0	19,9%	9,6%	8,8%
1.5	4,5%	1,2%	0,8%

λ_C

WIP \ Time	0.5	1.0	1.5
0.5	41,7%	26,3%	21,1%
1.0	21,4%	14,0%	12,1%
1.5	7,9%	4,2%	1,3%

λ_D

WIP \ Time	0.5	1.0	1.5
0.5	43,4%	26,7%	21,2%
1.0	23,0%	17,2%	13,4%
1.5	9,2%	5,8%	3,5%

λ_E

WIP \ Time	0.5	1.0	1.5
0.5	50,9%	33,7%	27,6%
1.0	30,8%	23,7%	22,3%
1.5	16,1%	14,1%	9,9%

λ_{tot}

WIP \ Time	0.5	1.0	1.5
0.5	36,9%	21,3%	15,8%
1.0	19,4%	11,8%	9,5%
1.5	5,4%	2,3%	0,3%

$\overline{\rho}_{SC}$

WIP \ Time	0.5	1.0	1.5
0.5	42,0%	20,8%	13,7%
1.0	24,4%	11,6%	7,9%
1.5	9,5%	2,5%	-1,3%

$\overline{\rho}_R$

WIP \ Time	0.5	1.0	1.5
0.5	20,0%	24,0%	10,0%
1.0	15,8%	4,6%	7,5%
1.5	7,7%	3,5%	-1,9%

$\overline{\Delta}_R$

WIP \ Time	0.5	1.0	1.5
0.5	8,0	9,0	5,0
1.0	11,0	4,0	5,0
1.5	5,0	3,0	-2,0

$\overline{w}^{Q}_{SC}$

WIP \ Time	0.5	1.0	1.5
0.5	-51,0%	-54,1%	-59,8%
1.0	-48,3%	-55,7%	-59,6%
1.5	-48,2%	-49,1%	-53,4%

$\overline{n}^{Q}_{SC}$

WIP \ Time	0.5	1.0	1.5
0.5	-19,8%	-44,5%	-52,8%
1.0	-24,9%	-47,1%	-53,5%
1.5	-25,3%	-42,9%	-48,2%

Figure 3.3: Model comparison key figure overview for two factor variation (scenario 1B)

LT_A

WIP \ Time	0.5	1.0	1.5
0.5	-1,1%	-1,5%	-0,4%
1.0	0,1%	-1,4%	-0,9%
1.5	-5,4%	-6,5%	-5,3%

LT_B

WIP \ Time	0.5	1.0	1.5
0.5	0,6%	0,4%	0,0%
1.0	-0,1%	-0,4%	-0,2%
1.5	-5,0%	-5,8%	-6,2%

LT_C

WIP \ Time	0.5	1.0	1.5
0.5	0,3%	0,0%	-0,8%
1.0	0,5%	-0,8%	0,5%
1.5	-5,0%	-5,0%	-4,9%

LT_D

WIP \ Time	0.5	1.0	1.5
0.5	-0,8%	-2,3%	-0,1%
1.0	-2,8%	-2,2%	-1,9%
1.5	-6,0%	-7,2%	-7,4%

LT_E

WIP \ Time	0.5	1.0	1.5
0.5	-3,1%	-2,2%	-2,2%
1.0	-6,4%	-6,2%	-7,6%
1.5	-8,9%	-11,0%	-11,2%

LT_F

WIP \ Time	0.5	1.0	1.5
0.5	0,1%	-0,5%	1,6%
1.0	-0,1%	-0,1%	-0,9%
1.5	3,4%	7,1%	5,7%

LT_G

WIP \ Time	0.5	1.0	1.5
0.5	0,7%	0,9%	1,1%
1.0	-0,1%	-1,6%	-3,0%
1.5	7,1%	9,5%	5,6%

LT_H

WIP \ Time	0.5	1.0	1.5
0.5	0,0%	0,1%	-0,5%
1.0	-0,8%	-3,6%	-2,9%
1.5	-10,8%	-9,6%	-10,1%

LT_w

WIP \ Time	0.5	1.0	1.5
0.5	-0,3%	-0,6%	-0,4%
1.0	-0,9%	-1,6%	-1,3%
1.5	-5,4%	-5,9%	-6,0%

λ_A

WIP \ Time	0.5	1.0	1.5
0.5	-15,4%	-15,4%	-15,6%
1.0	-12,8%	-12,3%	-12,7%
1.5	-7,0%	-6,7%	-6,7%

λ_B

WIP \ Time	0.5	1.0	1.5
0.5	-6,8%	-6,5%	-6,7%
1.0	-5,2%	-4,5%	-4,8%
1.5	-0,1%	0,4%	0,5%

λ_C

WIP \ Time	0.5	1.0	1.5
0.5	-16,8%	-16,7%	-16,9%
1.0	-14,8%	-14,3%	-14,7%
1.5	-9,4%	-9,1%	-8,9%

λ_D

WIP \ Time	0.5	1.0	1.5
0.5	0,1%	0,3%	0,2%
1.0	-1,0%	-0,4%	-0,9%
1.5	1,9%	2,2%	2,2%

λ_E

WIP \ Time	0.5	1.0	1.5
0.5	37,2%	37,8%	37,7%
1.0	28,1%	28,9%	28,3%
1.5	24,9%	25,1%	25,0%

λ_F

WIP \ Time	0.5	1.0	1.5
0.5	49,8%	52,0%	52,3%
1.0	52,6%	55,6%	55,6%
1.5	72,3%	75,9%	76,5%

λ_G

WIP \ Time	0.5	1.0	1.5
0.5	104,9%	109,0%	109,9%
1.0	105,8%	110,8%	111,2%
1.5	129,9%	135,6%	137,5%

λ_H

WIP \ Time	0.5	1.0	1.5
0.5	29,8%	31,1%	31,2%
1.0	26,0%	27,6%	27,3%
1.5	26,3%	27,1%	27,2%

λ_{tot}

WIP \ Time	0.5	1.0	1.5
0.5	6,8%	7,5%	7,4%
1.0	6,8%	7,8%	7,5%
1.5	12,3%	13,1%	13,3%

$\bar{\rho}_{SC}$

WIP \ Time	0.5	1.0	1.5
0.5	-1,1%	-2,8%	-3,6%
1.0	-0,7%	-2,0%	-3,0%
1.5	4,4%	2,8%	2,2%

$\bar{\rho}_R$

WIP \ Time	0.5	1.0	1.5
0.5	0,0%	2,2%	2,2%
1.0	-2,2%	1,1%	3,3%
1.5	3,3%	5,6%	5,6%

$\bar{\Delta}_R$

WIP \ Time	0.5	1.0	1.5
0.5	0,0	1,0	1,0
1.0	-1,0	0,0	1,0
1.5	1,0	2,0	2,0

$\bar{w}_{SC}^{Q}$

WIP \ Time	0.5	1.0	1.5
0.5	-82,6%	-82,6%	-83,5%
1.0	-87,6%	-88,6%	-88,3%
1.5	-92,6%	-92,7%	-92,7%

$\bar{n}_{SC}^{Q}$

WIP \ Time	0.5	1.0	1.5
0.5	-83,5%	-83,7%	-84,7%
1.0	-88,2%	-89,2%	-89,0%
1.5	-92,6%	-92,7%	-92,6%

Figure 3.4: Model comparison key figure overview for two factor variation (scenario 2A)

LT_A

WIP \ Time	0.5	1.0	1.5
0.5	-0,8%	-1,3%	-2,6%
1.0	-1,1%	-3,5%	-3,2%
1.5	-2,3%	-2,9%	-1,5%

LT_B

WIP \ Time	0.5	1.0	1.5
0.5	-2,3%	-2,3%	-2,5%
1.0	-4,8%	-5,7%	-6,3%
1.5	-2,2%	-4,5%	-4,7%

LT_C

WIP \ Time	0.5	1.0	1.5
0.5	-1,6%	-2,3%	-2,5%
1.0	-4,6%	-5,7%	-3,2%
1.5	-2,7%	-2,5%	-3,4%

LT_D

WIP \ Time	0.5	1.0	1.5
0.5	-3,3%	-4,6%	-5,4%
1.0	-5,5%	-6,2%	-5,6%
1.5	-3,2%	-7,5%	-4,7%

LT_E

WIP \ Time	0.5	1.0	1.5
0.5	-3,2%	-4,9%	-4,6%
1.0	-9,1%	-9,5%	-7,6%
1.5	-7,2%	-8,2%	-4,6%

LT_F

WIP \ Time	0.5	1.0	1.5
0.5	0,2%	-2,0%	-0,4%
1.0	-3,6%	-6,4%	-5,0%
1.5	-5,1%	-5,0%	-5,4%

LT_G

WIP \ Time	0.5	1.0	1.5
0.5	-3,4%	-3,8%	-6,2%
1.0	-9,1%	-5,6%	-12,4%
1.5	-6,9%	-9,4%	-3,4%

LT_H

WIP \ Time	0.5	1.0	1.5
0.5	2,9%	-2,3%	-0,3%
1.0	-0,9%	-3,5%	-5,8%
1.5	-4,1%	-3,7%	-1,2%

LT_w

WIP \ Time	0.5	1.0	1.5
0.5	-1,7%	-2,7%	-2,9%
1.0	-4,6%	-5,7%	-5,2%
1.5	-3,3%	-4,6%	-3,7%

λ_A

WIP \ Time	0.5	1.0	1.5
0.5	-13,2%	-12,8%	-12,4%
1.0	-8,6%	-9,9%	-7,1%
1.5	-6,6%	-4,9%	-6,0%

λ_B

WIP \ Time	0.5	1.0	1.5
0.5	-5,6%	-4,7%	-4,7%
1.0	-1,9%	2,7%	-1,5%
1.5	-3,1%	-1,9%	-1,9%

λ_C

WIP \ Time	0.5	1.0	1.5
0.5	-15,2%	-14,8%	-14,4%
1.0	-10,5%	-7,1%	-10,8%
1.5	-10,3%	-9,5%	-10,3%

λ_D

WIP \ Time	0.5	1.0	1.5
0.5	4,6%	5,3%	5,9%
1.0	7,6%	0,7%	7,2%
1.5	6,3%	7,2%	5,6%

λ_E

WIP \ Time	0.5	1.0	1.5
0.5	43,3%	45,8%	46,9%
1.0	44,2%	45,4%	43,8%
1.5	39,2%	41,3%	38,5%

λ_F

WIP \ Time	0.5	1.0	1.5
0.5	40,2%	43,7%	42,7%
1.0	34,3%	34,9%	37,9%
1.5	25,6%	27,8%	26,2%

λ_G

WIP \ Time	0.5	1.0	1.5
0.5	89,4%	92,7%	94,2%
1.0	73,4%	60,9%	79,4%
1.5	59,1%	63,2%	62,3%

λ_H

WIP \ Time	0.5	1.0	1.5
0.5	24,8%	28,6%	28,0%
1.0	21,4%	24,6%	26,4%
1.5	15,4%	19,5%	18,5%

λ_{tot}

WIP \ Time	0.5	1.0	1.5
0.5	7,4%	8,7%	9,1%
1.0	9,1%	10,0%	10,0%
1.5	6,8%	8,4%	7,3%

$\bar{\rho}_{SC}$

WIP \ Time	0.5	1.0	1.5
0.5	-2,0%	-3,1%	-3,7%
1.0	0,8%	-0,4%	-1,6%
1.5	-0,3%	-1,4%	-3,2%

$\bar{\rho}_R$

WIP \ Time	0.5	1.0	1.5
0.5	-6,7%	-10,0%	6,7%
1.0	1,7%	1,7%	3,3%
1.5	-1,4%	-3,1%	-0,9%

$\bar{\Delta}_R$

WIP \ Time	0.5	1.0	1.5
0.5	-2	-3	1
1.0	1,0	1,0	1,0
1.5	0,0	-1,0	0,0

$\bar{w}_{SC}^{Q}$

WIP \ Time	0.5	1.0	1.5
0.5	-58,3%	-56,4%	-59,7%
1.0	-61,3%	-65,4%	-59,3%
1.5	-59,1%	-57,5%	-56,6%

$\bar{n}_{SC}^{Q}$

WIP \ Time	0.5	1.0	1.5
0.5	-65,8%	-64,2%	-67,9%
1.0	-67,6%	-72,2%	-65,6%
1.5	-65,5%	-63,4%	-62,4%

Figure 3.5: Model comparison key figure overview for two factor variation (scenario 2B)

3.2 Station Utilisations

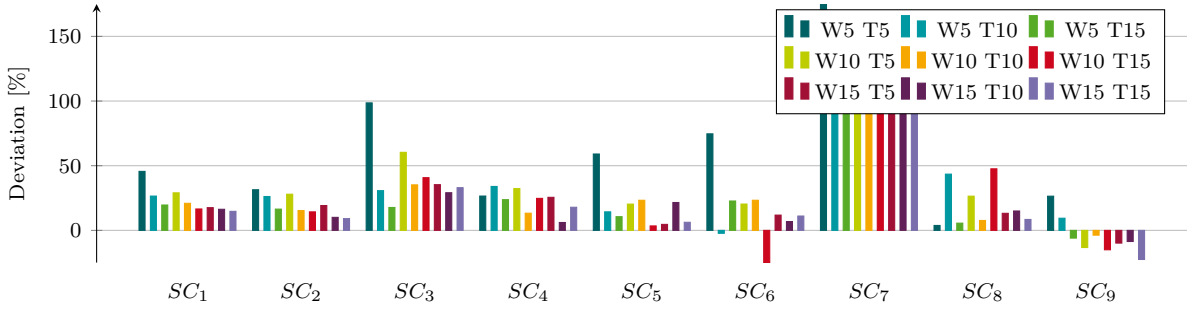

Figure 3.6: Deviations in station utilisation during model comparison for SC_1 to SC_9 (scenario 1A)

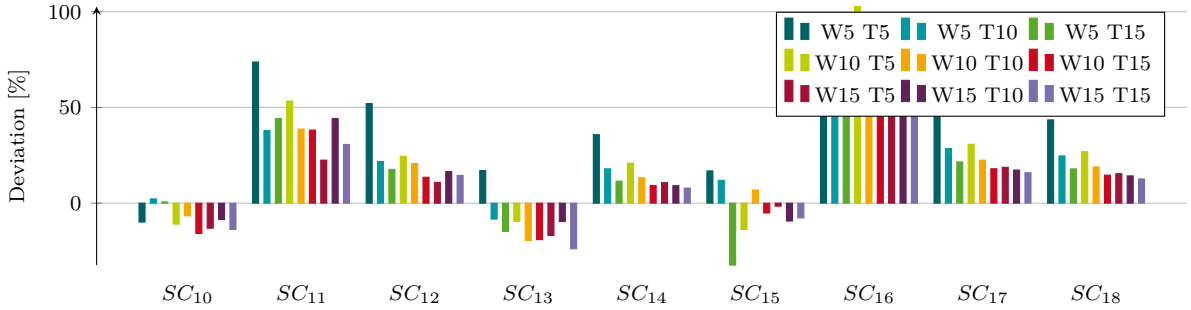

Figure 3.7: Deviations in station utilisation during model comparison for SC_{10} to SC_{18} (scenario 1A)

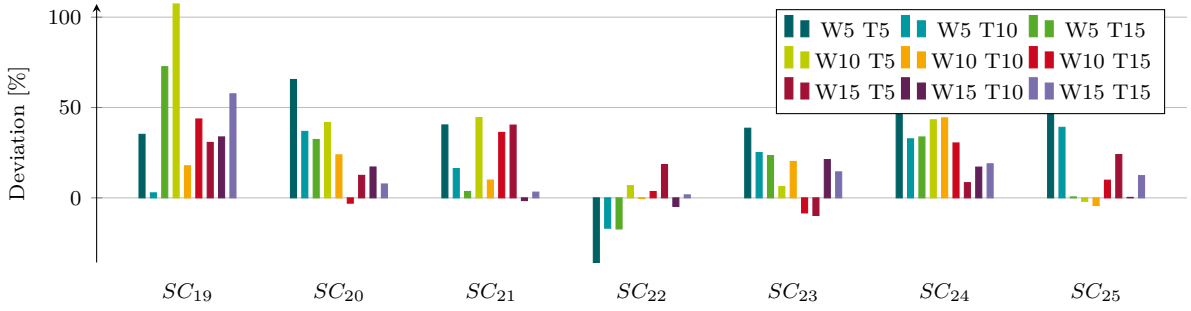

Figure 3.8: Deviations in station utilisation during model comparison for SC_{19} to SC_{25} (scenario 1A)

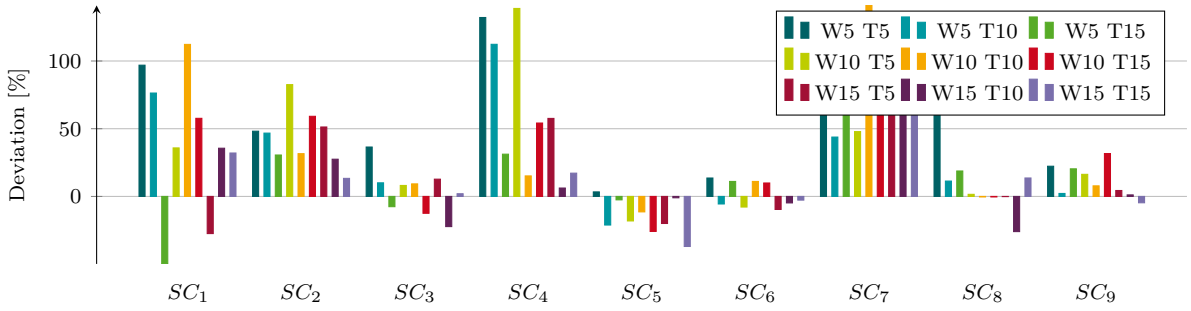

Figure 3.9: Deviations in station utilisation during model comparison for SC_1 to SC_9 (scenario 1B)

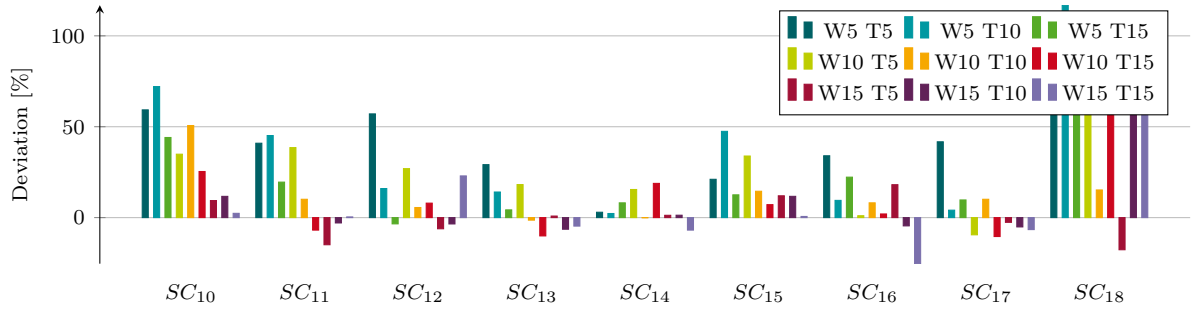

Figure 3.10: Deviations in station utilisation during model comparison for SC_{10} to SC_{18} (scenario 1B)

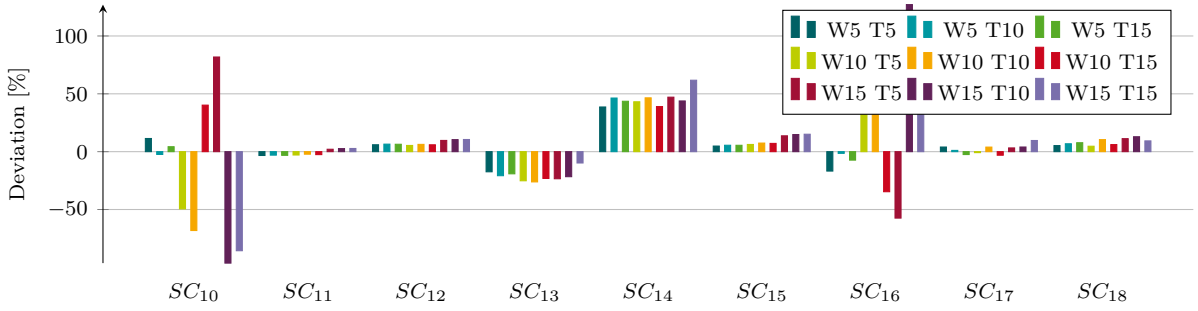

Figure 3.11: Deviations in station utilisation during model comparison for SC_{10} to SC_{18} (scenario 2A)

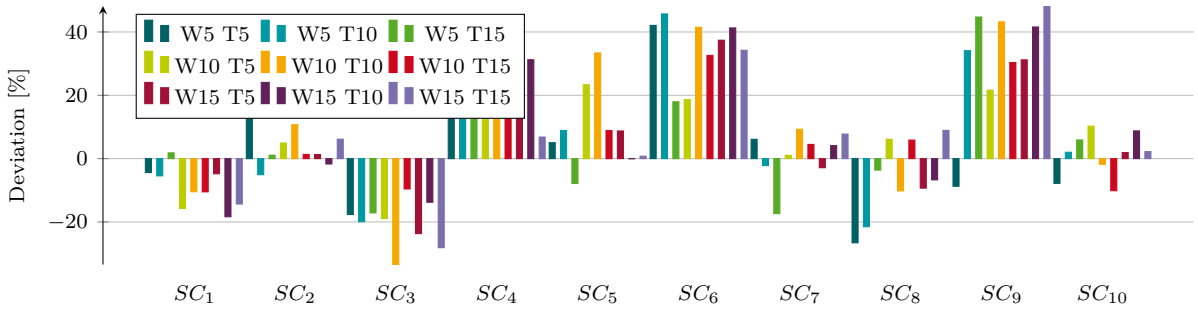

Figure 3.12: Deviations in station utilisation during model comparison for SC_1 to SC_{10} (scenario 2B)

3.3 Waiting Times at Stations

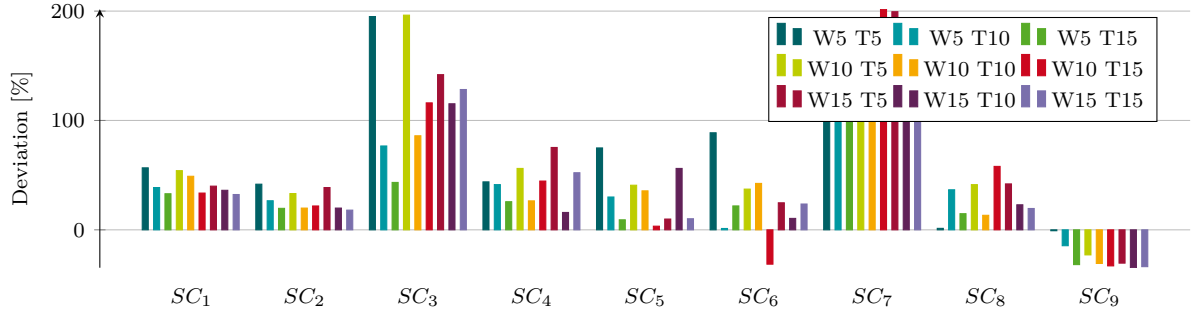

Figure 3.13: Deviations in waiting time during model comparison for SC_1 to SC_9 (scenario 1A)

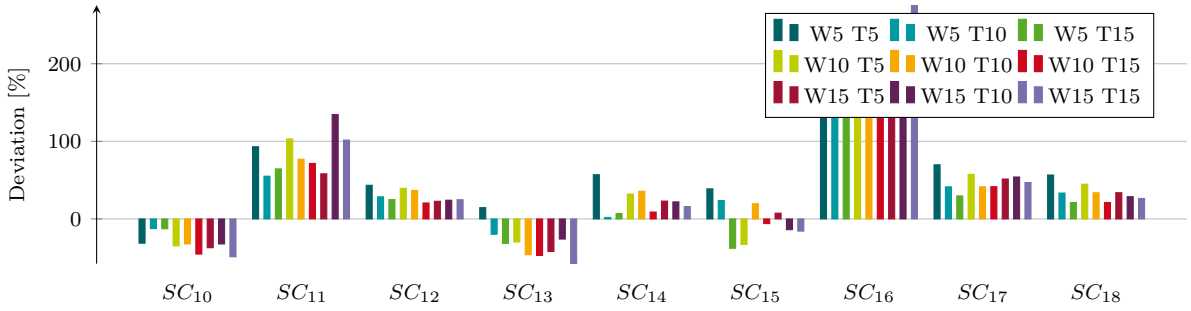

Figure 3.14: Deviations in waiting time during model comparison for SC_{10} to SC_{18} (scenario 1A)

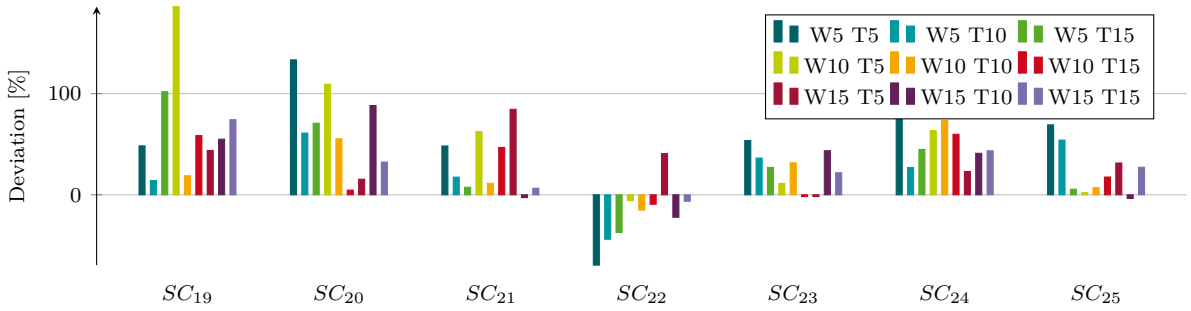

Figure 3.15: Deviations in waiting time during model comparison for SC_{19} to SC_{25} (scenario 1A)

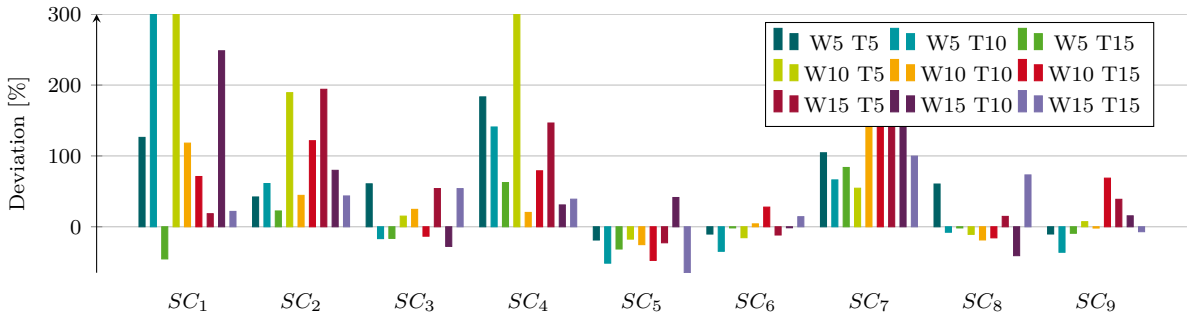

Figure 3.16: Deviations in waiting time during model comparison for SC_1 to SC_9; note that values for SC_1 to SC_3 exceed 300% (scenario 1B)

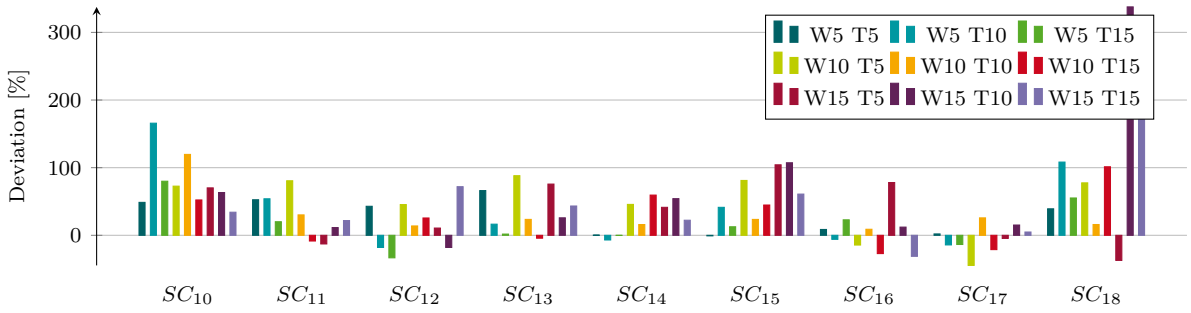

Figure 3.17: Deviations in waiting time during model comparison for SC_{10} to SC_{18} (scenario 1B)

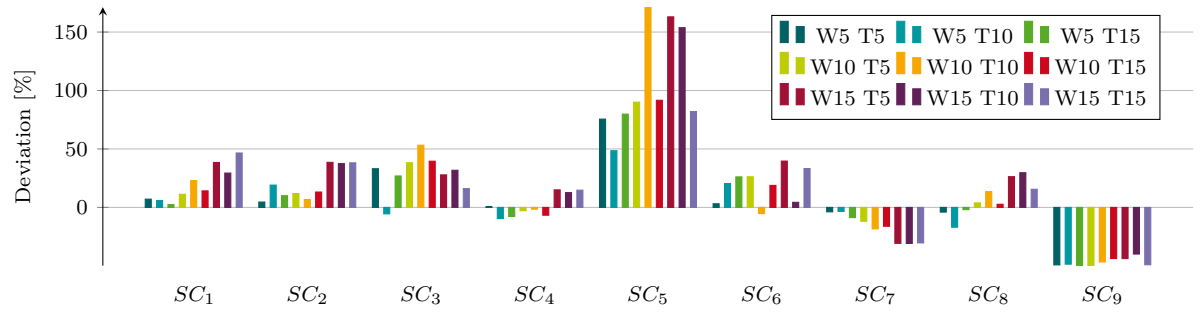

Figure 3.18: Deviations in waiting time during model comparison for SC_1 to SC_9 (scenario 2A)

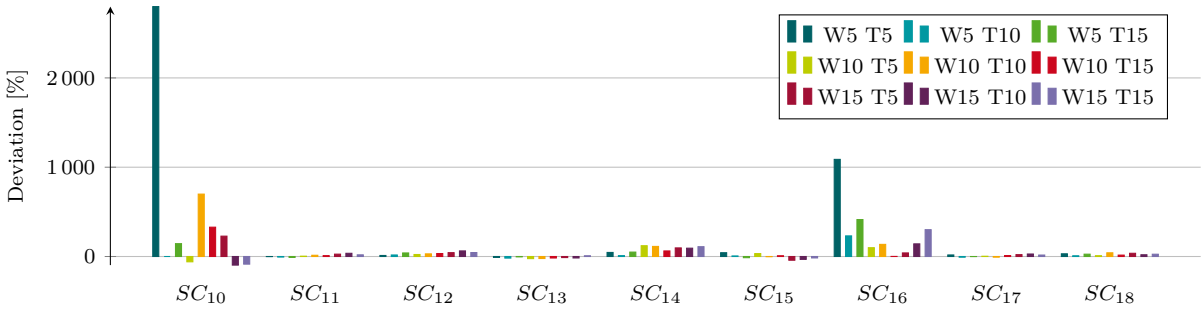

Figure 3.19: Deviations in waiting time during model comparison for SC_{10} to SC_{18} (scenario 2A)

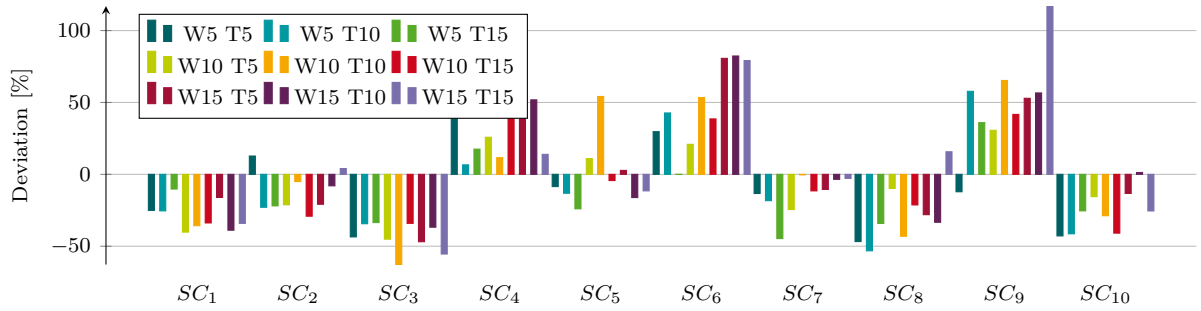

Figure 3.20: Deviations in waiting time during model comparison for SC_1 to SC_{10} (scenario 2B)

3.4 Queue Lengths at Stations

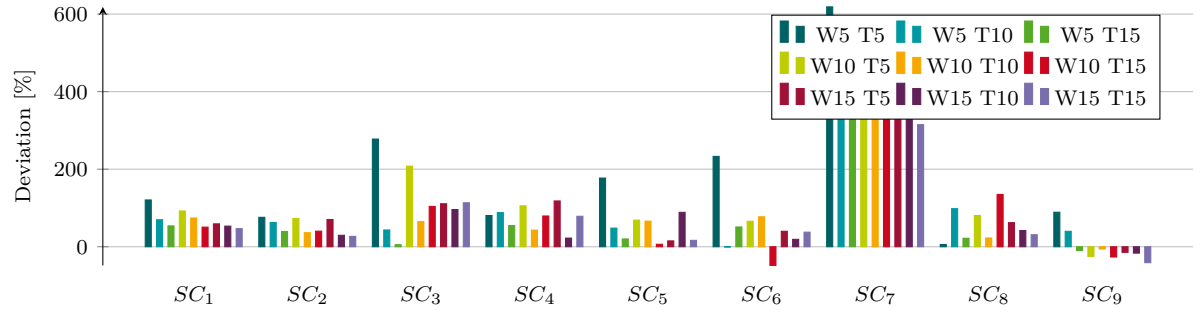

Figure 3.21: Deviations in queue length during model comparison for SC_1 to SC_9 (scenario 1A)

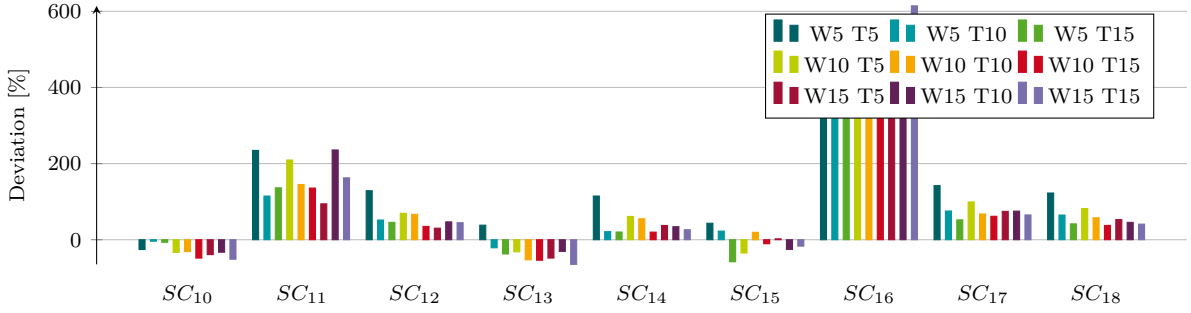

Figure 3.22: Deviations in queue length during model comparison for SC_{10} to SC_{18} (scenario 1A)

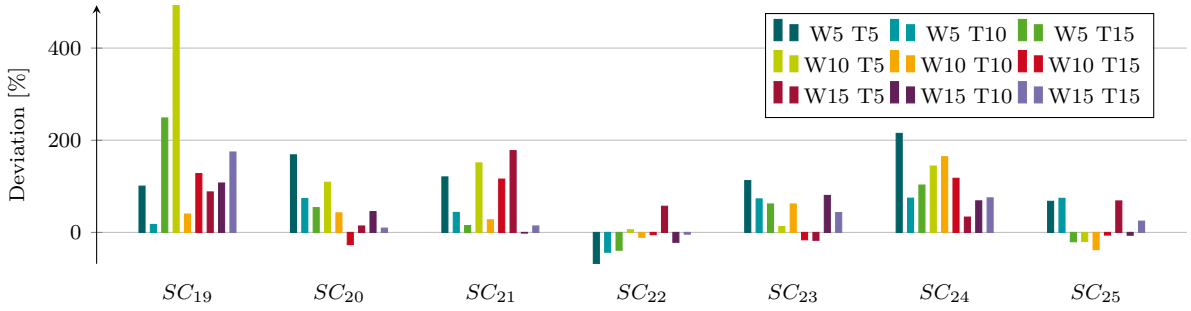

Figure 3.23: Deviations in queue length during model comparison for SC_{19} to SC_{25} (scenario 1A)

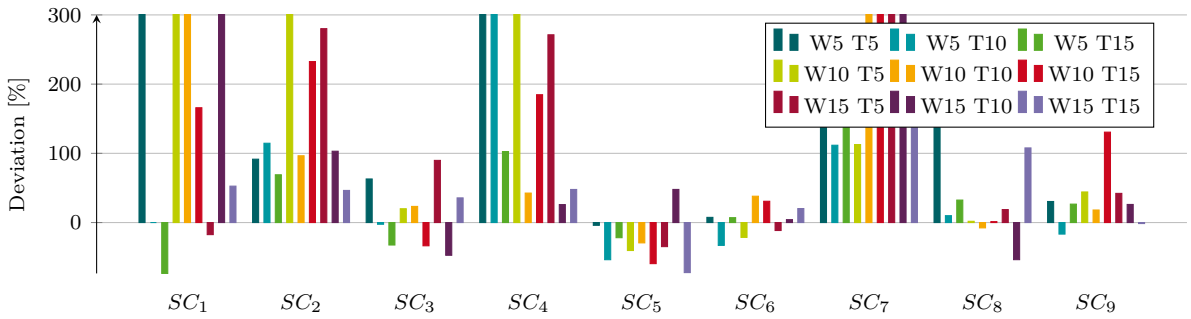

Figure 3.24: Deviations in queue length during model comparison for SC_1 to SC_9; note that values for SC_1 to SC_3 exceed 300% (scenario 1B)

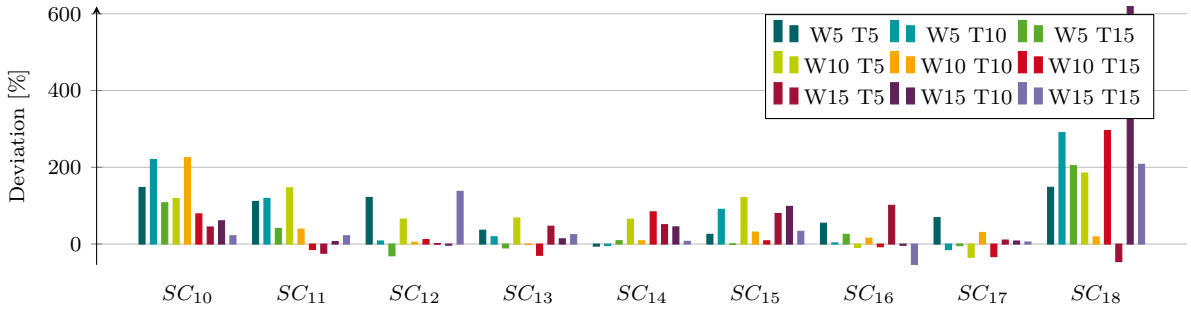

Figure 3.25: Deviations in queue length during model comparison for SC_{10} to SC_{18} (scenario 1B)

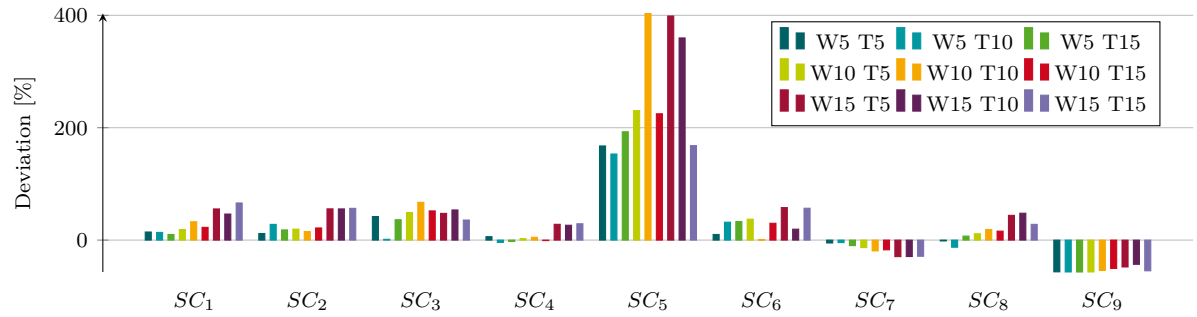

Figure 3.26: Deviations in queue length during model comparison for SC_1 to SC_9 (scenario 2A)

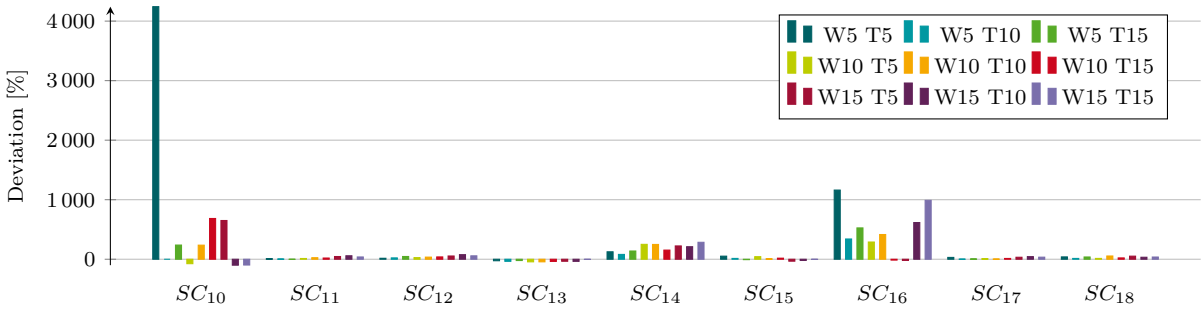

Figure 3.27: Deviations in queue length during model comparison for SC_1 to SC_9 (scenario 2A)

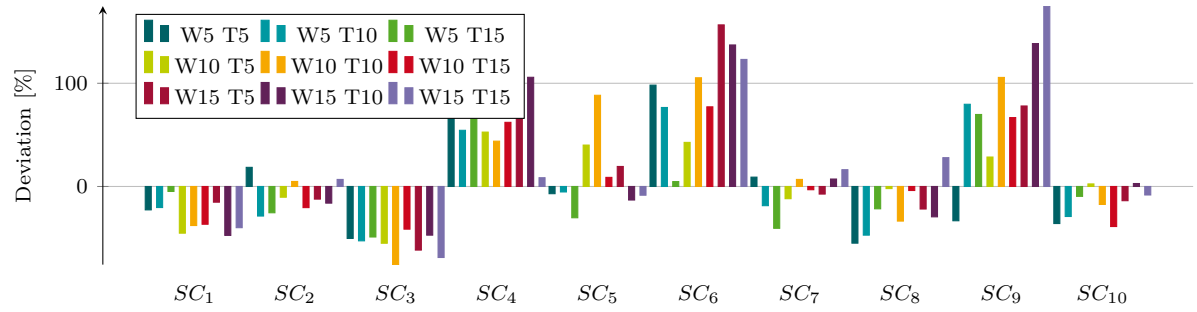

Figure 3.28: Deviations in queue length during model comparison for SC_1 to SC_{10} (scenario 2B)

3.5 Required Resources

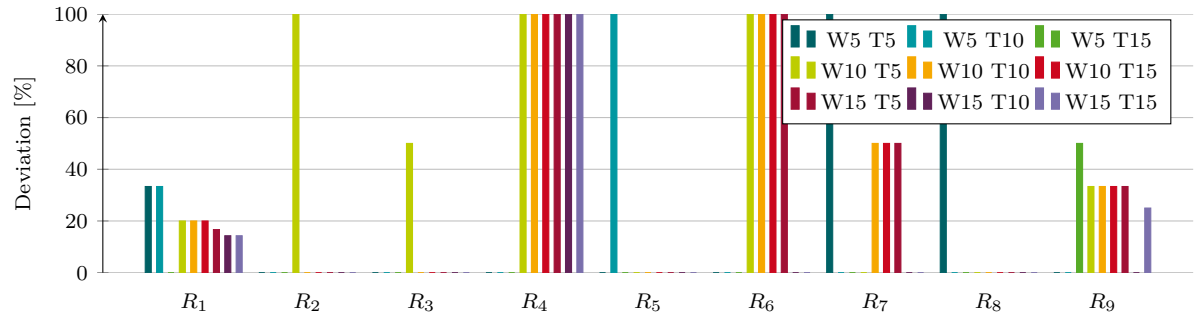

Figure 3.29: Deviations in required resources during model comparison for R_1 to R_9 (scenario 1A)

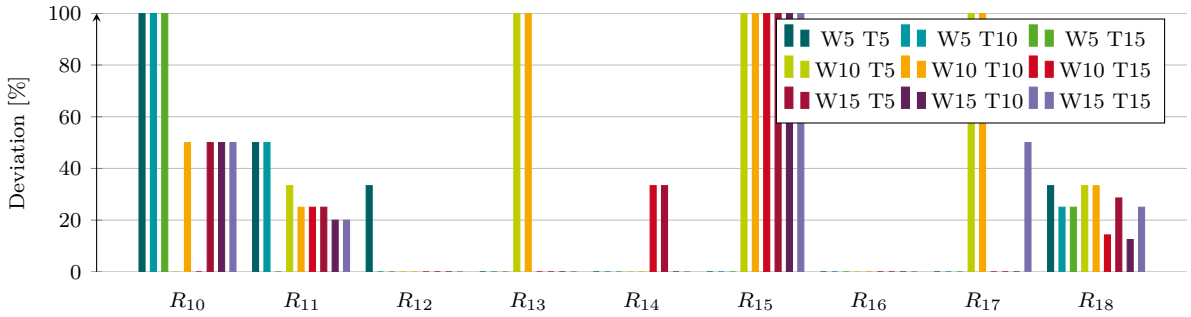

Figure 3.30: Deviations in required resources during model comparison for R_{10} to R_{18} (scenario 1A)

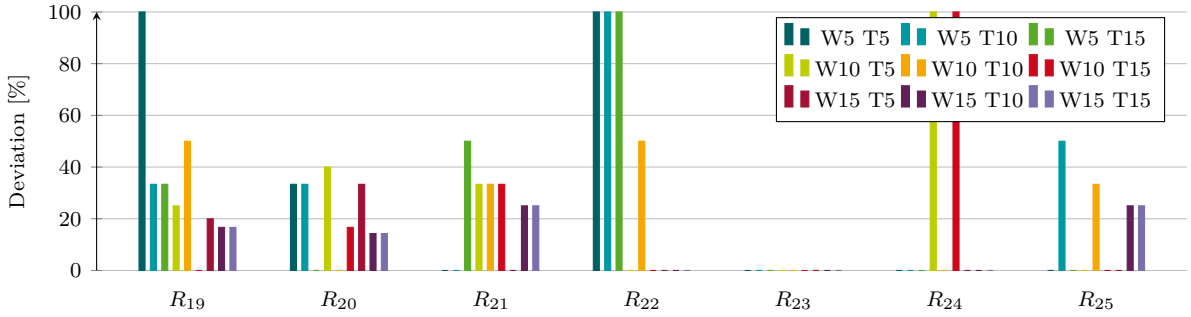

Figure 3.31: Deviations in required resources during model comparison for R_{19} to R_{25} (scenario 1A)

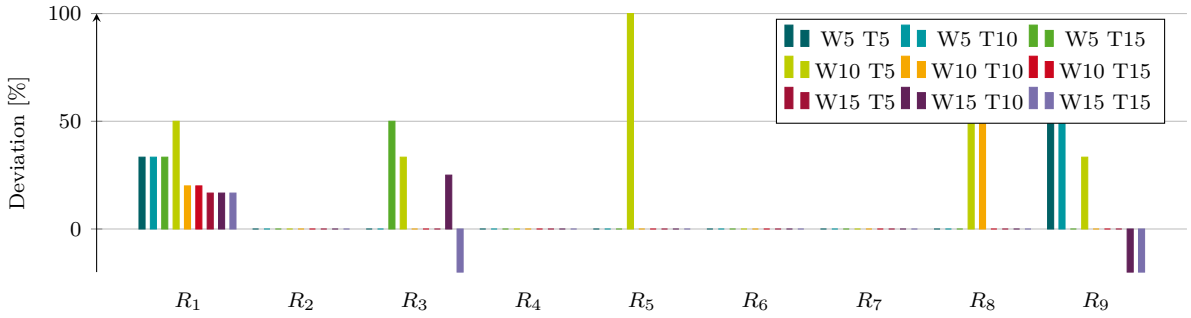

Figure 3.32: Deviations in required resources during model comparison for R_1 to R_9 (scenario 1B)

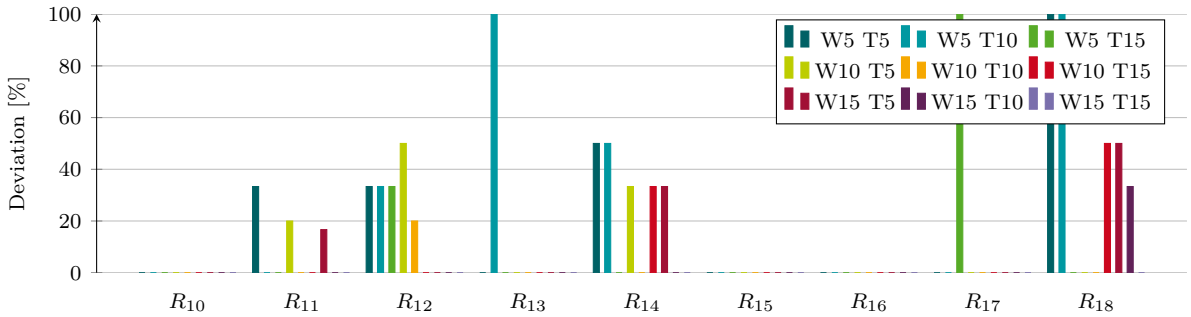

Figure 3.33: Deviations in required resources during model comparison for R_{10} to R_{18} (scenario 1B)

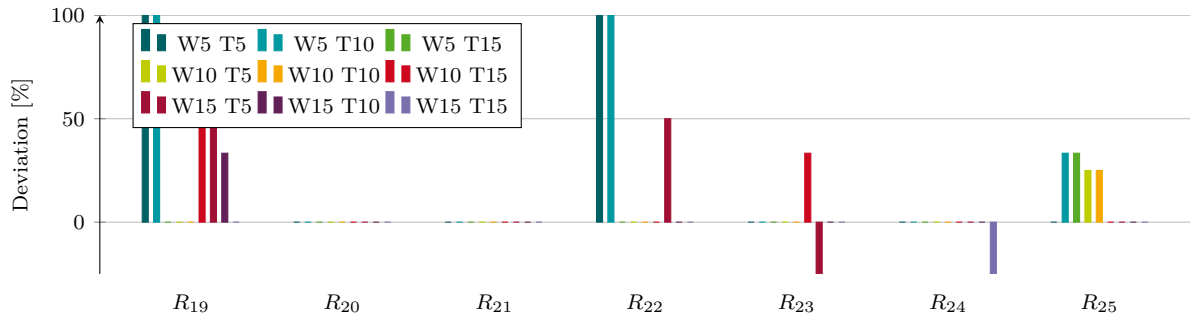

Figure 3.34: Deviations in required resources during model comparison for R_{19} to R_{25} (scenario 1B)

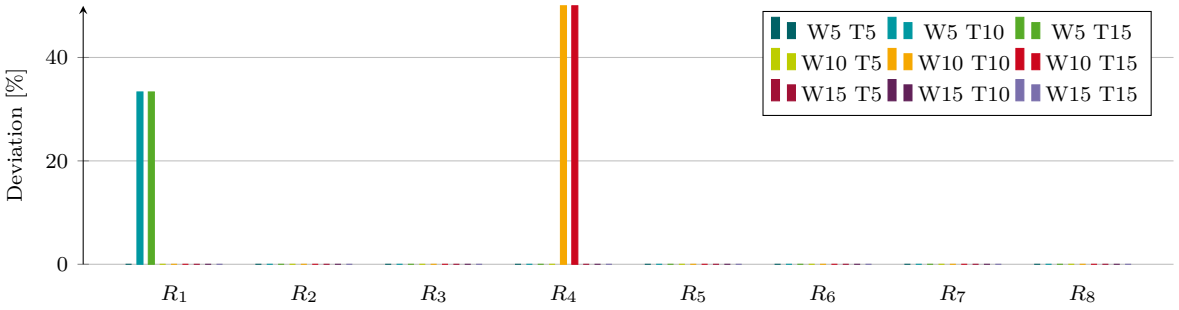

Figure 3.35: Deviations in required resources during model comparison for R_1 to R_8 (scenario 2A)

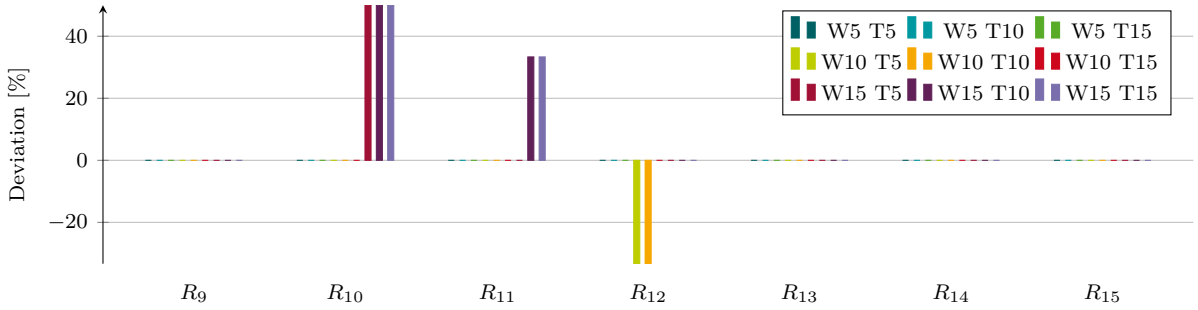

Figure 3.36: Deviations in required resources during model comparison for R_9 to R_{15} (scenario 2A)

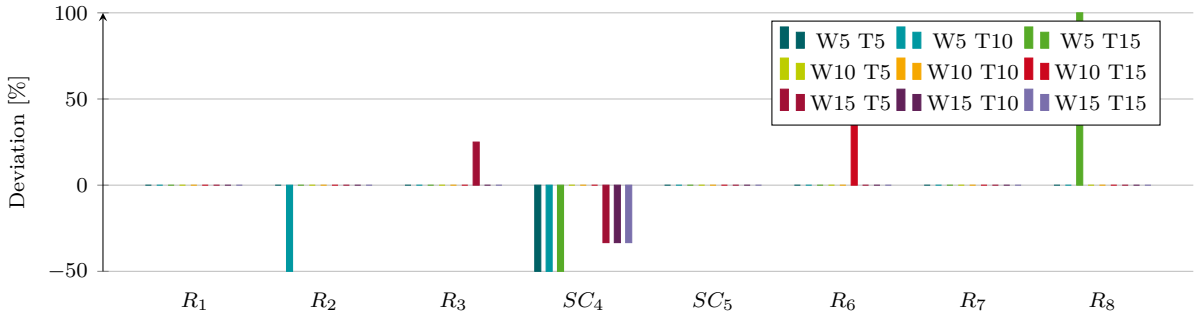

Figure 3.37: Deviations in required resources during model comparison for R_1 to R_8 (scenario 2B)

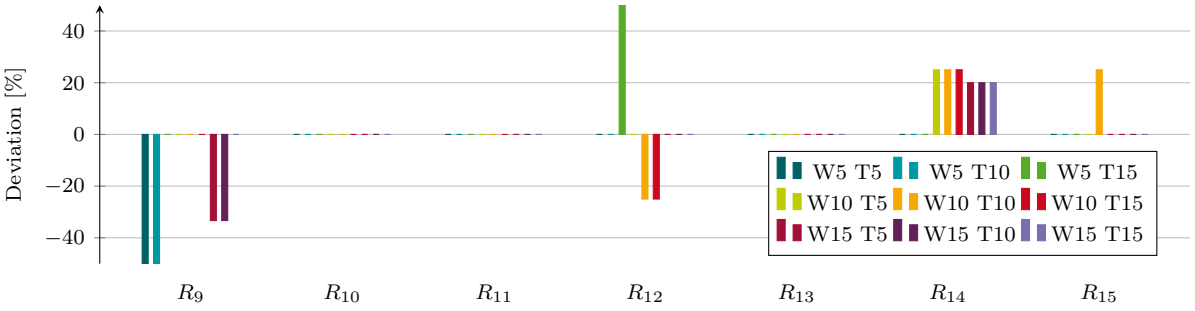

Figure 3.38: Deviations in required resources during model comparison for R_9 to R_{15} (scenario 2B)

3.6 Resource Utilisation

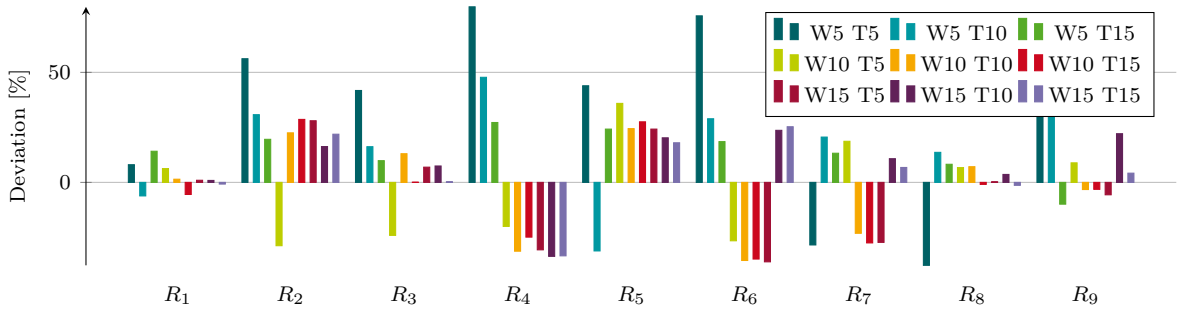

Figure 3.39: Deviations in required resources during model comparison for R_1 to R_9 (scenario 1A)

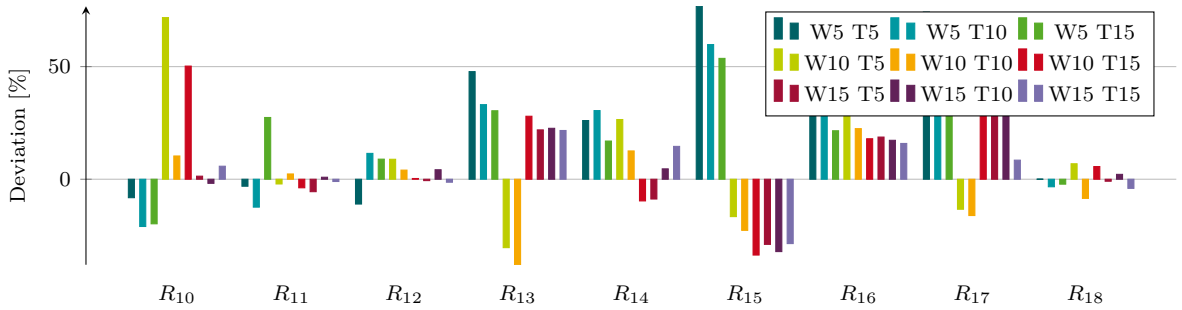

Figure 3.40: Deviations in required resources during model comparison for R_{10} to R_{18} (scenario 1A)

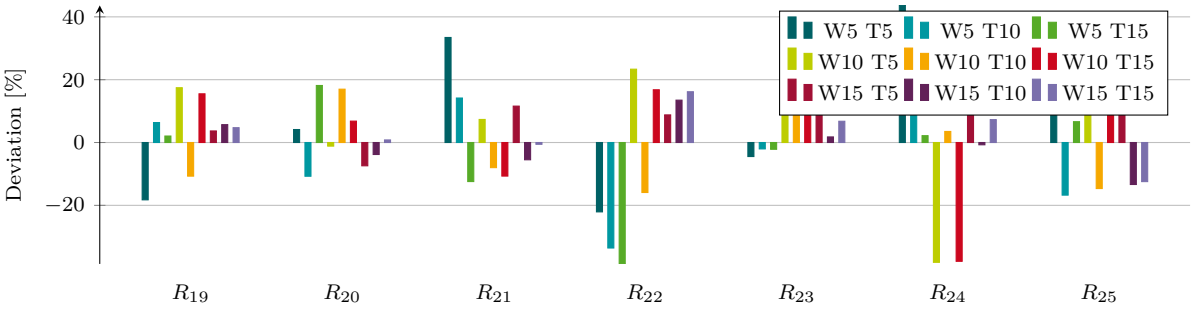

Figure 3.41: Deviations in required resources during model comparison for R_{19} to R_{25} (scenario 1A)

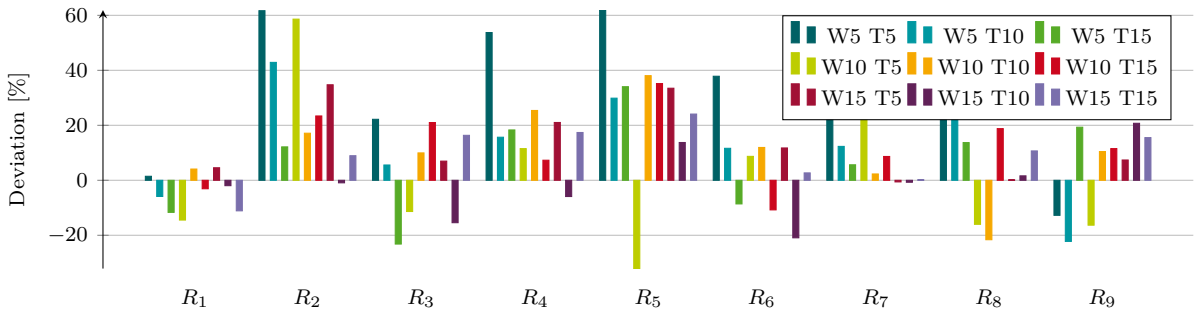

Figure 3.42: Deviations in required resources during model comparison for R_1 to R_9 (scenario 1B)

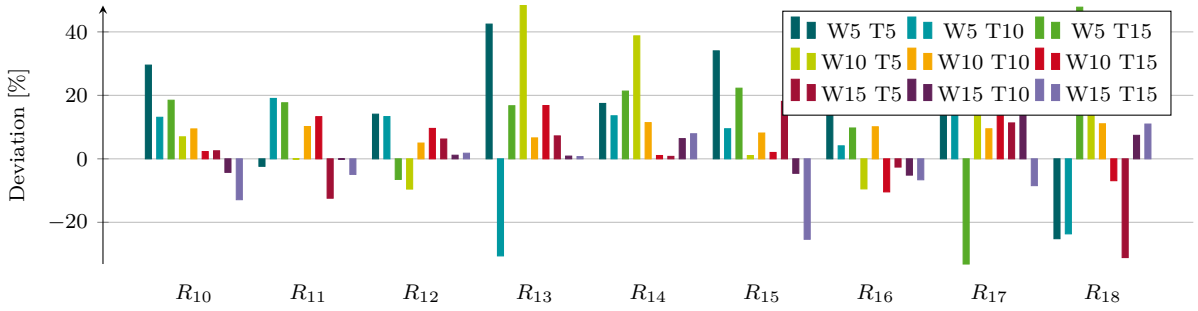

Figure 3.43: Deviations in required resources during model comparison for R_{10} to R_{18} (scenario 1B)

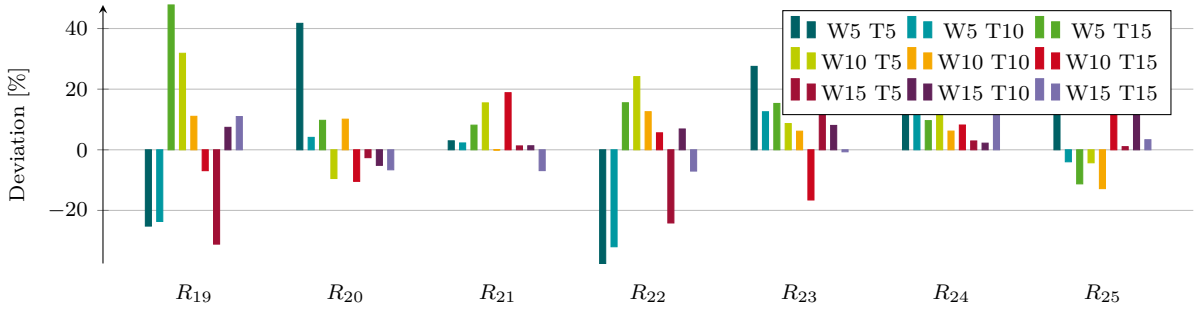

Figure 3.44: Deviations in required resources during model comparison for R_{19} to R_{25} (scenario 1B)

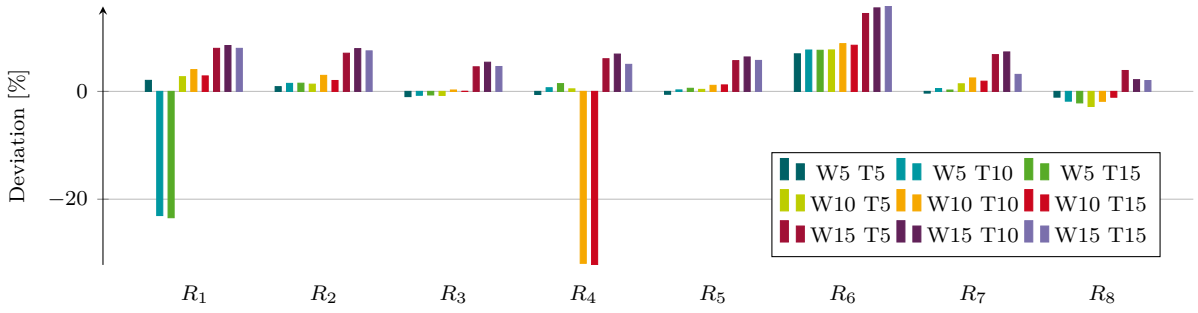

Figure 3.45: Deviations in resources utilisation during model comparison for R_1 to R_8 (scenario 2A)

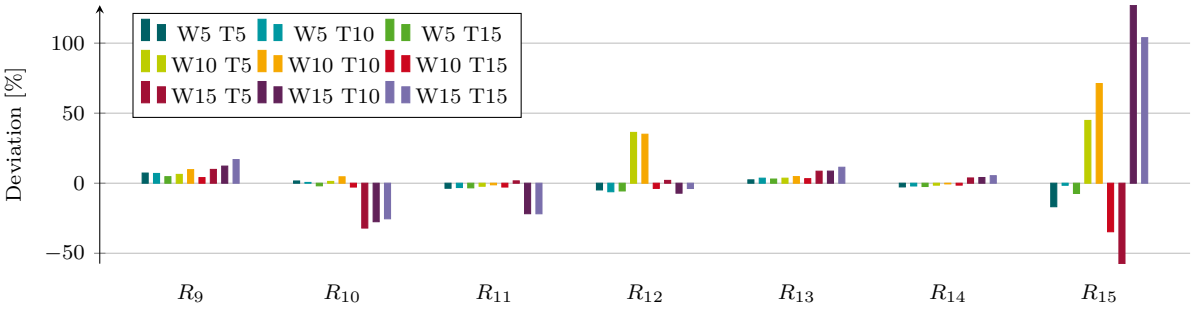

Figure 3.46: Deviations in resources utilisation during model comparison for R_9 to R_{15} (scenario 2A)

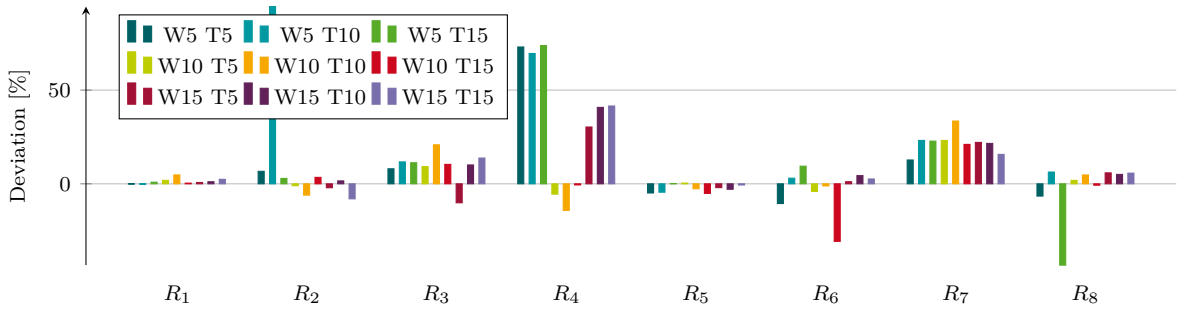

Figure 3.47: Deviations in resources utilisation during model comparison for R_1 to R_8 (scenario 2B)

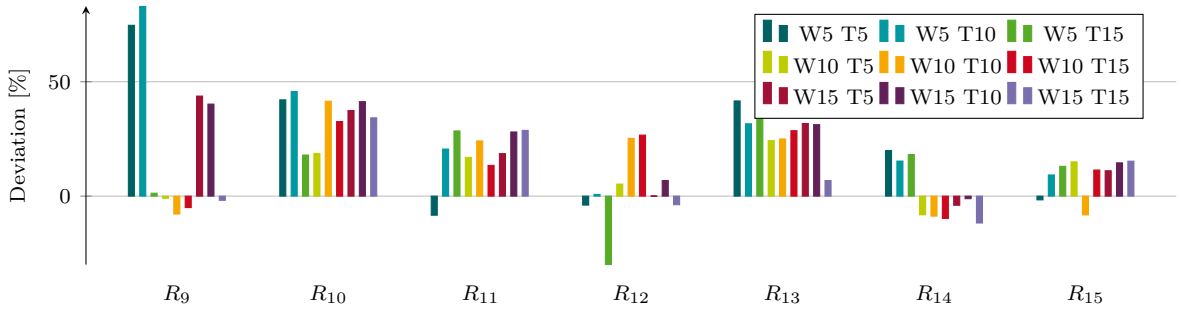

Figure 3.48: Deviations in resources utilisation during model comparison for R_9 to R_{15} (scenario 2B)

3.7 Comparison of Throughputs

Table 3.2: Comparative analysis of throughputs between stochastic and JaamSim model (scenario 1A; WIP and processing times are not modified)

	p_A	p_B	p_C	p_D	p_E
f_p	0.276	0.265	0.112	0.232	0.115
λ_p Stochastic Model	0.0352	0.0364	0.0158	0.0333	0.0174
Ratio WIP	0.276	0.265	0.112	0.232	0.115
Share of λ_{tot}	0.255	0.264	0.114	0.241	0.126
Deviation throughput	-7.60%	-0.52%	2.46%	3.80%	9.42%
λ_p JaamSim	0.0324	0.0311	0.0131	0.0272	0.0135
Ratio WIP	0.301	0.261	0.109	0.224	0.105
Products plan	1041.7	1000.0	420.9	875.0	433.4
Product actual	1041	999	422	875	434
Ratio in output	0.276	0.265	0.112	0.232	0.115
Deviation f_p	-0.1%	-0.1%	0.3%	0.0%	0.1%
Δ λ_p models	8.89%	17.29%	20.34%	22.25%	28.67%

Table 3.3: Comparative analysis of throughputs between stochastic and JaamSim model (scenario 1B; WIP and processing times are not modified)

	p_A	p_B	p_C	p_D	p_E
f_p	0.276	0.265	0.112	0.232	0.115
λ_p Stochastic Model	0.0313	0.0318	0.0140	0.0298	0.0156
Ratio WIP	0.276	0.265	0.112	0.232	0.115
Share of λ_{tot}	0.256	0.260	0.114	0.243	0.127
Deviation throughput	-7.46%	-2.08%	2.23%	4.81%	10.84%
λ_p JaamSim	0.0302	0.0290	0.0122	0.0254	0.0126
Ratio WIP	0.301	0.264	0.109	0.221	0.104
Products plan	1041.7	1000.0	420.9	875.0	433.4
Product actual	1041	999	422	875	434
Ratio in output	0.276	0.265	0.112	0.232	0.115
Deviation f_p	-0.1%	-0.1%	0.3%	0.0%	0.1%
Δ λ_p models	3.55%	9.61%	13.99%	17.20%	23.75%

Table 3.4: Comparative analysis of throughputs between stochastic and JaamSim model (scenario 2A; WIP and processing times are not modified)

	p_A	p_B	p_C	p_D	p_E	p_F	p_G	p_H
f_p	0.119	0.238	0.238	0.119	0.119	0.059	0.049	0.059
λ_p Stochastic Model	0.00072	0.00157	0.00141	0.00082	0.00106	0.00064	0.00072	0.00052
Ratio in WIP	0.119	0.238	0.238	0.119	0.119	0.059	0.049	0.059
Share of λ_{tot}	0.097	0.211	0.189	0.110	0.142	0.085	0.096	0.070
Deviation throughput	-18.64%	-11.36%	-20.62%	-7.60%	19.59%	44.50%	95.72%	18.44%
λ_p JaamSim	0.00082	0.00165	0.00164	0.00082	0.00082	0.00041	0.00034	0.00041
Ratio in WIP	0.138	0.251	0.281	0.122	0.099	0.038	0.024	0.048
Number products plan	249.9	499.8	499.8	249.9	249.9	123.9	102.9	123.9
Number product actual	250	500	499	250	250	124	103	124
Ratio in actual output	0.119	0.238	0.238	0.119	0.119	0.059	0.049	0.059
Deviation from f_p	0.0%	0.0%	-0.2%	0.0%	0.0%	0.1%	0.1%	0.1%
Δ λ_p models	-12.33%	-4.48%	-14.30%	-0.44%	28.87%	55.65%	110.78%	27.57%

Table 3.5: Comparative analysis of throughputs between stochastic and JaamSim model (scenario 2B; WIP and processing times are not modified)

	p_A	p_B	p_C	p_D	p_E	p_F	p_G	p_H
f_j	0.119	0.238	0.238	0.119	0.119	0.059	0.049	0.059
λ_j Stochastic Model	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.000
Ratio WIP	0.119	0.238	0.238	0.119	0.119	0.059	0.049	0.059
Share of λ_{tot}	0.100	0.214	0.195	0.116	0.155	0.073	0.079	0.067
Deviation throughput	-15.76 %	-9.98 %	-18.27 %	-2.24 %	30.61 %	23.67 %	61.97 %	13.47 %
λ_j JaamSim	0.00076	0.00143	0.00143	0.00079	0.00073	0.00037	0.00034	0.00037
Ratio WIP	0.137	0.246	0.272	0.126	0.091	0.047	0.032	0.049
Products plan	249.9	499.8	499.8	249.9	249.9	123.9	102.9	123.9
Product actual	250	500	499	250	250	124	103	124
Ratio in output	0.119	0.238	0.238	0.119	0.119	0.059	0.049	0.059
Deviation f_j	0.0 %	0.0 %	-0.2 %	0.0 %	0.0 %	0.1 %	0.1 %	0.1 %
Δ λ_j both models	-9.87 %	2.71 %	-7.14 %	0.68 %	45.39 %	34.88 %	60.86 %	24.64 %