Department of Industrial Engineering
University of Stellenbosch

Simulasie 442 : Simulation 442
2025

MEMORANDUM

Tutoriaal 12 *Tutorial 12*	Punt: 91 *Mark:*	Ingeedatum: **24-10-2025** (10:00) B3003 *Due date:*

Instruksies:	Formatteer alle syfers sinvol. Ontwikkel die modelle individueel. U mag in groepe van **twee** of minder werk om die vrae te beantwoord. Handig slegs een dokument in. Gebruik Tecnomatix en Excel vir u berekenings. **Hierdie tutoriaal en prakties is verpligtend**. **Indien u nalaat om die vereistes betyds na te kom, sal u die module sak**.
Instructions:	*Format all numbers sensibly.* *Develop the models individually.* *You may work in groups of* **two** *or less when answering the questions.* *Submit one document only.* *Use Tecnomatix and Excel for your calculations.* ***This tutorial and practical are compulsory.*** ***You will fail the module if you do not comply with the requirements, on time.***

Buffer-allocation Model

Question 1 [25]

Buffer-allocation problem		
The essence of the problem	There are m machines in a linear production line, work in progress can only be stored in buffers between machines. Thus there are $m-1$ buffers. Buffers may have different capacities (number of niches per buffer). Note: The buffer is a collection of spaces or niches. We say 'buffer size', 'buffer space' or 'niche'. Do not confuse 'Buffer' with its size. Machines are thus unequally spaced. The size of each buffer is measured in equivalent product dimensions.	[2]
Objective of the simulation	Multi objective optimisation: find the minimum number of buffer spaces (niches) while maximising the throughput, minimizing the WIP, maximising the NettProfit, minimising the energy consumed.	[1]
Input variables	1. Distributions of manufacturing times, 2. distributions of failure counts, 3. distributions of repair times, 4. buffer allocations, *i.e.* number of niches per buffer. Input variables belong to the set I and are all the data we specify for the simulation to run. The decision variables (in the next row of this table) in set D are also input variables and are part of the input variable set, *i.e.* decision variables form a subset of input variables: $D \subseteq I$. They are listed again in a subset because we want to adjust their values. We do not adjust the values of other inputs, *e.g.* the processing times – but we could, if there were reasons to do so.	[1]
Decision variables	Buffer size allocations	[1]
Output parameters	1. Throughput (avg number of product produced per shift) 2. WIP 3. Energy consumed 4. Nett profit	[2]
Assumptions made	A product made by the line is a homogeneous unit of fixed dimensions & Work-in-progress can only be stored in buffers between machines.	[2]
Validation considerations	The number of entities in the buffers may never exceed the buffer sizes allocated.	[2]
/////		
Entity	Product	[1]
Attributes	None	[1]
Resources	Machines	[1]
Conditions	Product cannot advance to next machine unless there is space in the buffer or the machine is idle.	[1]
Events	Arrival of product; failure of machine occurs, repair time interval of machine ends, product leaves system, processing of product starts on machine i (Allow others)	[1]
System State	Throughput at time T, machine utilisation at time T (Allow others)	[1]

Question 1.2

[8]

Explain at least four validation tests you conducted, using the `Throughput as guide`. *Hint*: Change buffer sizes and explain the throughput observed in terms of the buffer sizes. To do so,

- open the *Experiment Manager* and delete the experiments (the rows can be accessed by clicking on the *Define Experiments* button), or you can change the experiments' active status to "False". Add new experiments by manually changing the buffer capacities and use the *Experiment Manager* to run the validation scenarios, or
- Select the *Experiment Manager*, copy and paste it, rename it (select it and smash F2), then open the experiments definition and create your validation experiments. In the completed model provided, there is an Experiment Manager named `ExperimentManager1` which is already configured for this question.

I did 25 replications for 10 days to answer the following (your values may differ, but the order of magnitude must be similar):

(a) Make all buffers one, then the throughput, based on 25 replications, is 146 with $h = 2.76$ units ✓

(b) Make all buffers large, *e.g.* 1 000, then the throughput, based on 25 replications, is 199 with $h = 4.46$ units. I can explain this: `The first machine delivers a product every hour, on average, so it delivers 24 products per day on average, and over 10 days we expect 240 products. But failures occur every 20 products, and the repair time is 2 hours on average. The number of failure events per 240 h is 240/20 = 12 events with duration of 2 h each. We thus have 240 h-24 h=216 h production time on the first machine. We expect 216 products and the simulation gave us 199 products (25 reps.).` ✓

(c) Make the first buffer large, *e.g.* 100, and the others small, *e.g.* all equal to one, then the throughput, based on 25 replications, is 155 with $h = 3.31$ units. ✓

(d) Make the first buffer small, *e.g.* 1, and the others large, *e.g.* all equal to 100, then the throughput, based on 25 replications, is 148 with $h = 2.57$ units. ✓

We see that if we "open up" the buffers, the maximum throughput ✓is 199 units. When we strangle the system with the minimum buffer size setting, the throughput is the minimum ✓of 146 units. If the first buffer is large, then many jobs are accepted, but the downstream buffer size allocations block the first machine ✓and the throughput is 155 units. If the first buffer is small, the downstream machines are starved ✓regardless of their buffer sizes, and the throughput is 148 units. All throughput values vary between the lower bound (146) and the upper bound (199) for throughput.

Question 2 [16]

1. What are Processing Count-based (or operation-demand failures (ODF)? What type of variable is this? (Discrete/continuous/deterministic/ stochastic). [2]

2. In simulation-optimisation problems ξ refers to the stochastic elements of the optimisation problem. In the BAP model, list three of these elements that contributed to ξ. [6]

3. Suppose you can assign n niches per buffer, what is the total number of possible assignments? [2]

4. Refer to Section 6.6 in the eBook, and to (6.8). Explain what $\mathbf{x}$ and Ω in this problem are. [6]

1. It is when the failure of a machine is dictated by the number of product cycles, as opposed to operational time. ✓It is a discrete random variable. ✓

2.
   - Processing times on the five machines. ✓✓
   - The failure rates of the machines. ✓✓
   - The repair times of the machines. ✓✓

3. $n^{(m-1)}$✓✓

4. Ω is the combination of the buffer sizes (BufferPunchCapacity, BufferLatheCapacity, BufferRivitingCapacity, and BufferBendingCapacity) *e.g.* $[1, 10] \times [1, 10] \times [1, 10] \times [1, 10]$, ✓✓✓while $\mathbf{x}$ is any combination of these, *e.g.* $[10, 8, 6, 4]$✓✓✓(or the values in one row in the Experiment Manager!).

Question 3 [50]

1. Find good buffer allocations while maximising throughput. Clearly show your analysis by providing the detailed results, the confidence intervals plot, the p-value table, as well as a discussion/commentary on the analysis. You may assign any number of niches to each of the buffers, with a minimum of one niche per buffer. [10]

2. What percentage of the total search space did you explore? [Hint: determine how many solutions you actually evaluated (number of experiments), then compare that to the total possible number of solutions that can be evaluated.] [5]

3. Using the output of 3.1, list the energy consumption values with the throughput. Why is the energy consumption correlated/not correlated with the throughput? [5]

4. Find good `Nett profit` using the GA Wizard. Limit the maximum buffer size to 10. Show the buffer sizes and the `Nett profit` of the best chromosomes. [10]

5. For the Buffer-allocation problem, do a bi-objective optimisation and determine a Pareto-optimal set of solutions to the problem using the file "FilterParetoFront_Extended.xlsm" on STEMLearn. For the problem, you should minimize total 'WIP' and maximise 'Throughput'. The total WIP is calculated in the `EndSim` method – see Figure 13 in the BAP guide. Your answer should include all reasoning, labelled graphs, and interpretations. [20]

1. I created 10 experiments. Here are the results; your results will be different:

Experiment	root.bufferpunch.capacity	root.bufferlathe.capacity	root.bufferriveting.capacity	root.bufferbending.capacity	Throughput	WIP	Energy consumed	Nett profit
Exp 01	1	2	2	2	153.60	0.56	839.95	11160.13
Exp 02	2	2	2	2	161.20	0.76	851.89	11590.28
Exp 03	3	4	4	4	174.20	1.10	873.06	10737.34
Exp 04	4	4	4	4	176.95	1.27	878.09	10699.77
Exp 05	5	6	6	6	184.85	1.59	891.50	9356.26
Exp 06	6	6	6	6	184.60	1.80	892.44	9028.90
Exp 07	7	8	8	8	188.40	2.03	898.38	7294.05
Exp 08	8	8	8	8	191.20	2.15	903.95	7260.13
Exp 09	9	10	10	10	195.40	2.40	909.93	5565.18
Exp 10	10	10	10	10	196.85	2.58	913.73	5400.67

Figure 1: Results for my 10 experiments

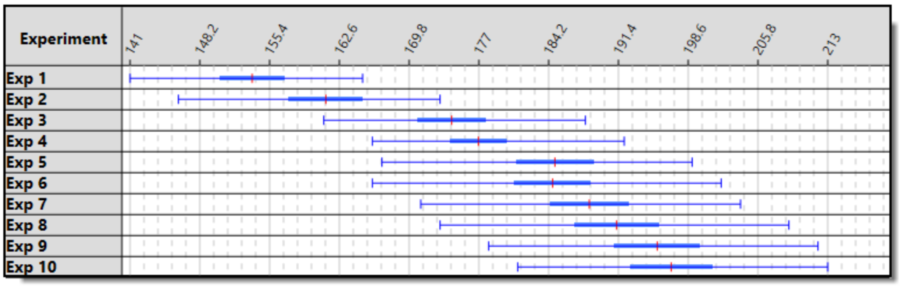


Figure 2: CI Chart for Throughput

Table of the p-values of the T-test of the output value 'Throughput'

	Exp 02	Exp 03	Exp 04	Exp 05	Exp 06	Exp 07	Exp 08	Exp 09	Exp 10
Exp 01	0.003	0	0	0	0	0	0	0	0
Exp 02		0	0	0	0	0	0	0	0
Exp 03			0.222	0	0	0	0	0	0
Exp 04				0.002	0.003	0	0	0	0
Exp 05					0.926	0.202	0.03	0.001	0
Exp 06						0.171	0.024	0.001	0
Exp 07							0.334	0.02	0.005
Exp 08								0.166	0.059
Exp 09									0.624

Figure 3: P-table for Throughput

Now we choose the best experiment based on the p-values. The question only refers to the throughput, which we must maximise. At this point, we do not consider any other output.

- **Exp10** has the best throughput, and uses $10 + 10 + 10 + 10 = 40$ buffer spaces.
- However, **Exp8** and **Exp9** are statistically similar to **Exp10** since their p-values are > 0.05, and **Exp7** is similar to **Exp8**.
- From Exp 7, 8, 9 and 10, **Exp7** uses the lowest number of buffer spaces (only $7+8+8+8 = 31$).
- Thus **Exp7** is the winner. Go **Exp7**!

2. If we allow for say 11 buffer spaces in total for the five machines and 0 as a possibility in each buffer, the size of the search space is

$$\frac{(m+n-2)!}{n!(m-2)!} = \frac{(5+11-2)!}{11!(5-2)!} = 364.$$

If we do not allow for a niche of 0, then

$$\frac{(n-1)!}{(n-m+1)!(m-2)!} = \frac{(10)!}{7!(3)!} = 120 \text{ possibilities. } \checkmark\checkmark\checkmark$$

If 18 experiments were performed, then $18/120 \times 100\% \approx 15\%$ of the search space was explored. ✓✓

Mark according to the student's choice for maximum buffer size.

3. The correlation is 0.9983, (✓Mark for calculating the correlation) which suggests the Throughput and Energy consumed are highly positively correlated (✓✓Two marks for commenting on the correlation). This makes sense because if machines are used more, the Energy consumption as well as the Throughput will increase. But if machines are used less the opposite will happen. (✓✓Two marks for explaining why it is correlated). This correlation should be obvious . . .

Experiment	Throughput	Energy consumed
Exp 1	156,3	844,58
Exp 2	192,95	906,15
Exp 3	184,6	892,44
Exp 4	196,85	913,73
Exp 5	196,5	913,16
Exp 6	184,95	893,21
Exp 7	187,15	897,61
Exp 8	192,65	910,03

Figure 4: Throughput and Energy consumed output

4. I have done this question again, because I made a mistake in the Cost calculation in the EndSim method. I subtracted one term, while I should added them. The correct '+' is shown in the figure – it was a '-'. Kudos to Michaela Seele who spotted it.

```
-- statRelativeOccupation is the percentage of time the buffer has entit
-- occupation is this percentage times the assigned buffer size.
-- Example: Say occupation is 30%, and buff size is 10, then there were
--          3 entities in the buffer.
WIP := (BufferLathe.statRelativeOccupation*BufferLathe.Capacity
        + BufferPunch.statRelativeOccupation*BufferPunch.Capacity
        + BufferBending.statRelativeOccupation*BufferBending.Capacity
        + BufferRiveting.statRelativeOccupation*BufferRiveting.Capacity)

TotalEnergyConsumed := Mill.statEnergyTotalConsumption +
                       Punch.statEnergyTotalConsumption +
                       Lathe.statEnergyTotalConsumption +
                       Bending.statEnergyTotalConsumption +
                       Riveting.statEnergyTotalConsumption

-- R300 per niche to rent.   The current Eskom tariff is ca. R2-50.
TotalCost := SumBuffers*300 + 2.5*TotalEnergyConsumed -- What we sell mi

-- We sell the product for R100/unit.
TotalIncome := 100*Throughput

NettProfit := TotalIncome - TotalCost
```

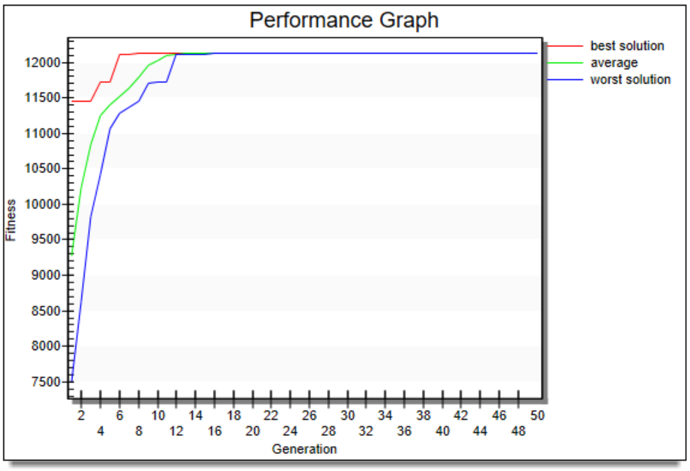
5. Marks for process: Specify the GA settings so that the reader/client knows them:

Settings of the Genetic Algorithm

Direction of the Optimization: Maximum
Number of Generations: 50
Size of Generation: 30
Observations per individual: 10

Show the fitness progress:

Evolution of the fitness values of the generations



Show the five best chromosomes:

12126.5045495884

string	table 0 Individual	real 1 Fitness	integer 2 ID	table 3 Chromosomes ->	table 4 Observations
1	Gen 8 Ind 40	12126.50454...	430	Chrom 1	Fitness 430
2	Gen 6 Ind 55	12117.25008...	325	Chrom 1	Fitness 325
3	Gen 14 Ind 13	12068.66648...	763	Chrom 1	Fitness 763
4	Gen 9 Ind 38	12063.17572...	488	Chrom 1	Fitness 488
5	Gen 9 Ind 10	12026.86869...	460	Chrom 1	Fitness 460

Show the best solution. It makes sense, we have the largest buffer before Machine 2, then they get smaller downstream since the machines work progressively faster, as described in the problem statement.

Optimization results

Best Fitness: 12126.5045495884
The parameters of the best solution are set in the model.

Fitness calculation

root.NettProfit with weighting 1

Best parameter of the allocation problems

root.BufferPunch.Capacity: 3
root.BufferLathe.Capacity: 2
root.BufferRiveting.Capacity: 2
root.BufferBending.Capacity: 1

6. My first step was to define experiments. The experiments were made by using the Multi-level Experimental Design tool. This allowed me to run all possible buffer space combinations (If we allow a maximum buffer space of 4 for each buffer).

	Input value	root.bufferpunch.capacity	root.bufferlathe.capacity	root.bufferriveting.capacity	root.bufferbending.capacity
1	Lower level	1	1	1	1
2	Upper level	4	4	4	4
3	Increment	1	1	1	1

Figure 5: Defining Experiments

This gave me 256 experiments, which I then exported to Excel to extract the Pareto frontier.

Experiment	root.bufferpunch.capacity	root.bufferlathe.capacity	root.bufferriveting.capacity	root.bufferbending.capacity	Throughput	WIP	Energy consumed	Nett profit
Exp 001	1	1	1	1	146.20	0.40	826.83	15487.07
Exp 002	1	1	1	2	146.80	0.41	829.01	15252.52
Exp 003	1	1	1	3	147.40	0.42	829.58	15013.96
Exp 004	1	1	1	4	147.65	0.43	830.11	14740.26
Exp 005	1	1	2	1	146.80	0.45	829.09	15252.72
Exp 006	1	1	2	2	147.60	0.46	830.15	15035.36
Exp 007	1	1	2	3	148.55	0.46	831.53	14833.82
Exp 008	1	1	2	4	148.80	0.46	832.46	14561.16
Exp 009	1	1	3	1	149.30	0.48	832.30	15210.74
Exp 010	1	1	3	2	149.10	0.47	832.78	14891.95
Exp 011	1	1	3	3	149.80	0.47	833.83	14664.58
Exp 012	1	1	3	4	150.55	0.48	834.92	14442.30
Exp 013	1	1	4	1	150.60	0.50	834.06	15045.15
Exp 014	1	1	4	2	150.20	0.49	834.97	14707.42
Exp 015	1	1	4	3	150.60	0.49	835.40	14448.51
Exp 016	1	1	4	4	151.00	0.49	835.83	14189.57
Exp 017	1	2	1	1	148.50	0.54	831.89	15429.74
Exp 018	1	2	1	2	151.10	0.54	835.63	15399.07
Exp 019	1	2	1	3	151.95	0.54	837.46	15188.66
Exp 020	1	2	1	4	150.95	0.54	836.02	14785.06
Exp 021	1	2	2	1	151.85	0.56	837.36	15478.41
Exp 022	1	2	2	2	153.60	0.56	839.95	15359.87
Exp 023	1	2	2	3	154.80	0.57	841.42	15183.56
Exp 024	1	2	2	4	154.55	0.57	841.28	14858.20
Exp 025	1	2	3	1	154.65	0.59	840.98	15467.46

Figure 6: Snippet of Experiments

The red squares in Figure 7 represent the Pareto-optimal set.

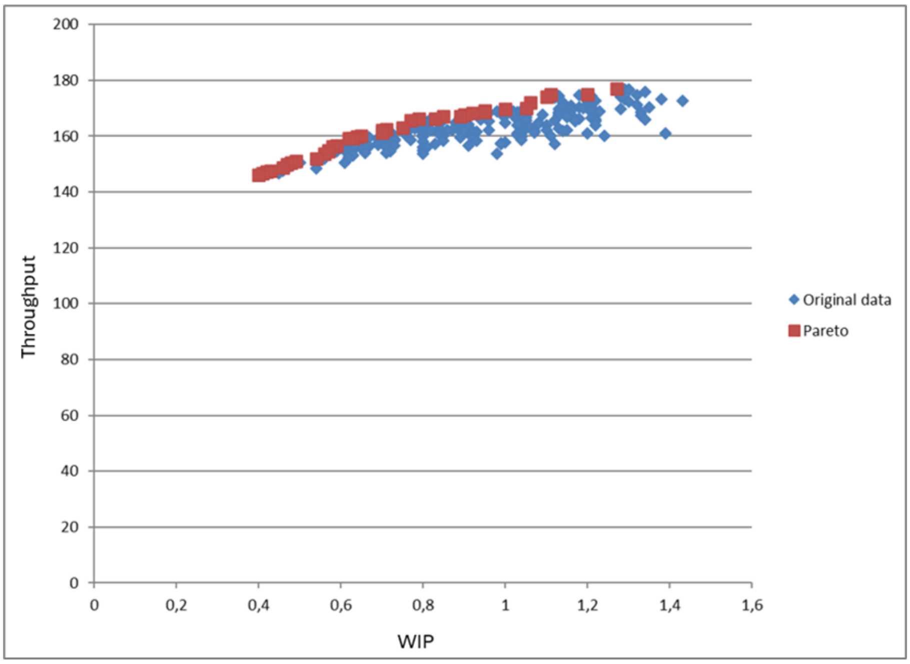


Figure 7: Pareto plot

Total: Cross-check: 91