Transformation of Aalborg University SmartLab from Reconfigurable Manufacturing Systems to Matrix Production

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Abstract - An analysis of different manufacturing systems was carried - The standard, mass producing dedicated manufacturing system (DMS), the flexible manufacturing system (FMS), the reconfigurable manufacturing system (RMS) and the new matrix production (MP). The goal of the project was to use the case of the AAU SmartLab at Aalborg University to test how to transform an RMS into an MP. Both systems have much higher flexibility than a DMS, but where the matrix production stands out was found to be on the high routing flexibility of such a system. The transformation was conducted in simulation where two models of the SmartLab was created. The current version and a version of matrix production. Based on lead time the current SmartLab performed better both running a single product and a large order of products. Elements were changed to better capitalise on the benefits of MP. New process sequences were introduced. The MP version showed it was quicker at adapting, generally having a lower lead time for a single product. But for a large order of products the current version outperformed. In a following scenario where breakdown of a process was introduced, the matrix production showed better results only if the breakdown would block the rest of the line in the current SmartLab version.
Keywords: Matrix production, AAU SmartLab, Reconfigurable manufacturing system, Discrete event simulation

1 Introduction

The manufacturing system is directly related to the company's production requirements. In the past, volume and variety tend to be inversely proportional. Large companies reduce the average cost of the same product by producing large quantities. However, in today's era, more and more short product life cycle, customers' desire for unique products, and the information explosion brought about by the rapid development of Information Technology force companies to deal with the concept of mass customisation. Therefore, how to balance volume and variety has become a new focus of research. Under the guidance of this demand, the new manufacturing system must meet the three basic conditions of full flexibility, reasonable cost, and high efficiency.

1.1 From DMS to FMS to RMS

Since Ford Motor Company introduced the assembly line into the actual production in 1913 [1], a kind of manufacturing system that only focused on parts had been gradually improved. This kind of manufacturing system is called a Dedicated Manufacturing Systems (DMS). Instead of wasting time and energy on having workers move from station to station, each worker only needed to stand in a fixed position and be responsible for one of the steps of assembling a car. Meanwhile, standardised parts flowed through each workstation by fixed transmission technology (conveyor belts) and were finally fully assembled into vehicles. However, fixed system structure and fixed machine structure sacrifice all flexibility while achieving high efficiency. If the company wants to make a new variety of products, it needs to redesign the entire production line. [2]

In order to solve the problem of production flexibility, new kinds of manufacturing systems are constantly proposed. Flexible Manufacturing Systems (FMS) is one of them. FMS realises part of the flexibility of the system by removing the fixed structure of the system, that is, the machines within the system have to be able to process a variety of products arriving in random order and adapt while sacrificing almost no time or cost. FMS facilitates the manufacturing of a range of products from a predefined part family, where the changeover cost is kept at a minimum. However, low output volume and high initial investment costs limit the development of FMS [3][4]. Traditionally, the flexibility of the FMSs has mainly been contained to one kind of flexibility, product flexibility, However according to [3][4] and [5] there are 10 parameters.

- Machine Flexibility
- Material Handing Flexibility
- Operation Flexibility
- Process Flexibility
- Product Flexibility
- Routing Flexibility
- Volume Flexibility
- Expansion Flexibility
- Control program Flexibility
- Production Flexibility

To realise the potential of some of the other parameters, the reconfigurable manufacturing system (RMS) was created. RMS uses modularization to break through the limitation of fixed machine structure on the basis of FMS. The line consists of modules and modular machines, which can be rearranged before production to fit the design of new production processes, a sign of high process flexibility. This plug-and-play feature also provides a high expansion and volume flexibility. In addition, modularisation also makes RMS have the ability to deal with sudden machine breakdown [3]. If one module malfunctions or the process becomes obsolete, it can simply be removed or replaced with an upgrade without compromising the rest of the system. Table 1 shows the comparison of these three manufacturing systems.

	DMS	FMS	RMS
System structure	Fixed	Flexible	Flexible
Machine structure	Fixed	Fixed	Flexible
Flexibility	No	General	Customised
Productivity	High	Medium	Medium
Dealing with emergencies	No	Medium	High

Table.1. Comparison of different manufacturing system features [6]

1.2 Matrix Production

Although RMS and FMS improve the flexibility of the manufacturing system compared to DMS, the rigid connection by the conveyor belt between machines has not been eliminated. The concept of matrix production is to separate this rigid coupling between the traditional workstations of production lines and reorganise them into different cells, each of which is connected by flexible transportation. Three key components of matrix production are:

- Layout
- Multi-functional cells
- Transportation

The layout of matrix production consists of multiple cells organised as a matrix, which can be seen in Figure 1. Each cell consists of multiple manipulator robots and machines that, ideally, should have the ability to perform a variety of tasks. These products are

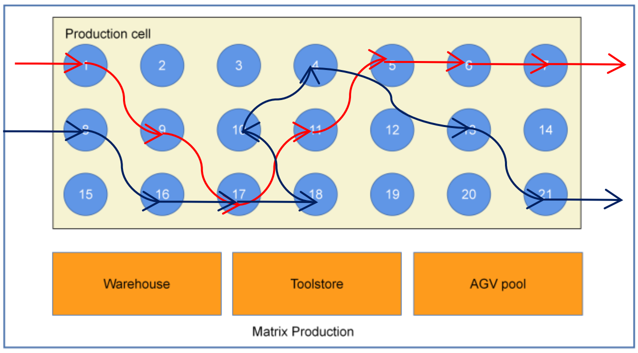

Fig.1. An example of the overview of matrix production

transported around the factory using robotic vehicles instead of the traditional conveyor belts. All of this allows for a higher increase in routing flexibility compared to RMS, due to the numerous routes possible for the products and the number of products that can be manufactured at the same time.

In the system's theory, production can be regarded as the total system, and each cell bears the responsibility of "subsystem". Each element of the whole production system can be classified into different levels, that are connected with each other through material flow, energy flow and information flow [7].

- Station level: the basic unit of matrix production, and the capacity can be adjusted by changing machines or tools
- Cell level: composed of different workstations, which can be changed by adding or deleting

workstations

- System level: represents the total production system and reflects the ability of the system

Each level has the flexibility of adjustment, and each adjustment can produce products with different attributes, which also makes sure the products produced by matrix production have high variance.

At present, the flexible transportation approach is to use automated guided vehicles (AGVs)[8] instead of utilising conveyor belts. The mobile platform is equipped with automatic positioning devices, through robot vision to accept the surrounding environment information, combined with the starting point and endpoint data to create the most effective path. AGVs can also find obstacles in time to avoid and recalculate a new route. Additionally, AGVs can be used not only as a logistics system to assist production but also as a temporary processing platform to share production tasks.

Although matrix production score high in flexibility (especially routing) and production efficiency, there are still limitations. Figure **2** shows the advantages and disadvantages of matrix production. Currently, matrix production is not completely feasible and is still in development, due to mobile robotic transportation is not a fully mature yet.

Matrix Production	
Disadvantages	Advantages
• High initial cost	• Flexible production process
• Low space utilization	• Produce various products at the same time
• Suitable for large scale production	• Satisfy the diverse demand of mass customization
• The technology of transportation robot (AGV) is not fully mature	• Strong ability to deal with risks
• Extra training of workers to learn matrix production	

Fig.2. The disadvantages and advantages of matrix production [8]

2 Method

2.1 AAU SmartLab

In 2015, Aalborg University invested in a module-based reconfigurable manufacturing system (RMS), which called"AAU SmartLab. The key objectives of the SmartLab were to research and demonstrate the concepts, methodologies and technologies involved in Industry 4.0 and investigate how manufacturing industries can benefit from these emerging technologies [9]

The system features various"transportation blocks" which shall be denoted as transport modules. The SmartLab also has various process applications such as drilling and stacking which can be installed on the transport modules. By having the possibility of rearranging the modules and process applications, it is possible to have the SmartLab execute many different tasks/processes. The current setup of the AAU SmartLab can be seen in Figure 3

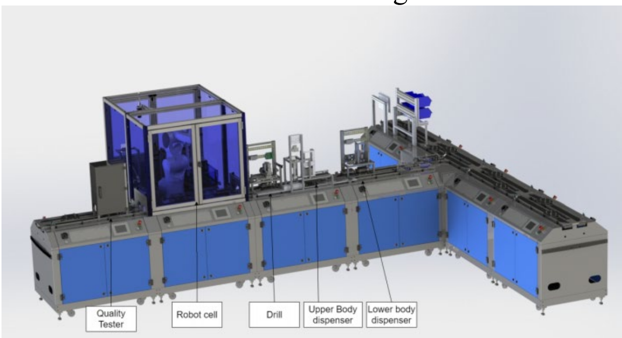

Fig.3. Application modules in the current AAU SmartLab layout [10].

The product being produced at the AAU SmartLab is a "dummy" mobile phone, which consist of:

- 1 bottom cover
- 1 printed circuit board with 2 fuse holders
- 0-2 fuses
- 1 top cover

At the start of the assembly line, an empty pallet carrier is placed on the conveyor belt. When a pallet carrier reaches the lower body dispenser, the lower body of the phone is mounted on the pallet carrier. Afterwards, the drilling application drills holes in the bottom cover. The drilling station has a twin drilling head [11], meaning that it can drill two holes at the same time. The dummy phone can show product variety by having a pair of holes either in one end or in both ends of the phone case [12].

After the holes are drilled, the workpiece is moved to the robot cell. The robot cell is mounted on a buffer module. This allows the robot to operate while other pallet carriers pass the station. In the robot cell, the phone case is first moved for vision inspection, where the placement of the case is checked with vision control. Afterwards, the workpiece is moved to a fixture that holds the workpiece in place. Then the robot performs a tool change to a vacuum tool. The robot then places the print circuit board on the workpiece. Depending on the product requirements, the robot performs another tool change to a fuse gripper tool. The desired amount of fuses are now attached to the PCB. Lastly, the robot changes back to the phone case gripper and places the workpiece on the pallet carrier again. The workpiece moves to the quality inspection workstation. The quality inspection module uses vision to check if the correct amount of fuses are mounted on the phone. If the phone contains the correct amount of fuses, the workpiece will move to the top cover dispenser. Here, the top cover is mounted on the workpiece. If the quality inspection module detects an error, the phone will skip the top cover dispenser and move to a manual inspection station, where the fuses are inspected and mounted [10]. If no errors are detected, the workpiece moves to an unloading area, where the phone can be removed and packed. In Figure 2 the whole processes and sequence are shown in a flowchart.

2.2 Simulation Test

Digital manufacturing reshapes the traditional manufacturing industry from every level of production. The use of digital tools can greatly shorten the Reach & Development time and save a huge amount of company resources. Simulation seeks to describe and analyse the behaviour of a system. From a production perspective, simulation can be used to analyse the current setup, identify flaws and constraints of the setup, investigate new setups, and compare different solutions to a problem. Furthermore, it can be used to visualise layouts and to train staff. With simulation, a company has the possibility of analysing the behaviour of a process over large periods of time instantaneously. In this article simulation will be used as tool to transform the SmartLab into a matrix production. For this Enterprise Dynamics is selected as the digital tool for dynamic simulation analysis of RMS and matrix production. [15]

2.2.1 Simulation Strategy

The simulation strategy for this project covers both a simulation of the current SmartLab layout and a simulation of various matrix-based layouts of the system. Firstly, the current layout and various matrix-based layout models should be conceptualized. The goal of model conceptualization is to obtain an overview of the setup and to understand the working principles. This covers the relationships between processes and the mapping of workpieces through the system. The conceptual model for the SmartLab should be able to describe what happens at all possible (or at least with significant possibility) scenarios. These questions could for example include the handling of different variants, breakdown of one or more processes, failures in assembly, etc. Meanwhile, collecting the data needed for simulation. All simulation data must be verified in the AAU SmartLab before they can be used. Only when the data is absolutely accurate can the output of simulation be meaningful. Table 2 shows the detailed cycle time of each workstation in the SmartLab.

Table.2. Cycle times of the processes in the AAU SmartLab. [10][13][12][14]

Process No.	Process	Cycle Time [s]
1	Bottom Cover Dispenser	6.25
2	Drill	6 / 11
3	Robot Cell	55.8(No fuse)
		74.7(1 Fuse)
		82.9(2 Fuses)
4	Quality Inspection	1.4
5	Top Cover Dispenser	6
6	Packing	4

Based on the conceptual model and data, an As-Is model of the current SmartLab can be created. After the model is generated, the verification and validation steps are performed. The verification step is used to check whether the model meets all the criteria in the conceptual model. If the verification is accepted (meaning that the simulation model covers all the basic features of the conceptual model), the validation step can be performed. This step is used to check whether the simulation is actually executed as a physical system. This means that the cycle time and lead time of the simulation model correspond to the cycle time and lead time of the physical settings.

The new matrix-structured model should also be generated with the use of existing data and workstations. This new model will be compared with the As-Is model to judge whether the current model is beneficial in terms of lead time and utilisation.

2.2.2 As-Is model of AAU SmartLab.

Based on the model conceptualisation of the As-Is model, a simulated model is generated in Enterprise Dynamics. This model accumulates the total transportation distance to be 19.6 metres for this specific layout. The conveyor has been measured to move with a speed of 0.114 m/s. The total transport time is 172 seconds.

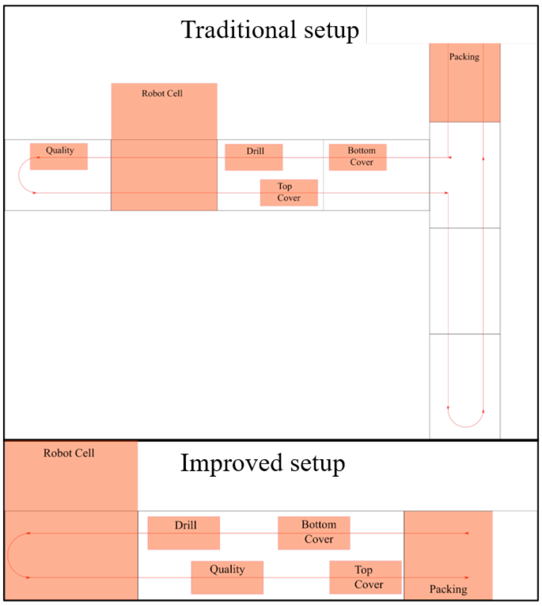

Fig.4. Top view of the layout of the setups of SmartLab proposed.

Since the As-Is model spends a lot of time on the conveyor, an improved version of the As-Is model layout is proposed to cut down on transportation time. The different stations have been moved to a more compact setup and half the modules have been removed. The total conveyor length has been decreased to 9.6 metres. The total transportation time is a bit more than 84 seconds. The layout of the improved model in Enterprise Dynamics is shown in Figure 5.

2.2.1 SmartLab as Matrix Productionl (SLaMP)

Based on the data of the AAU SmartLab, the processes are transformed into a matrix layout where each process is its own cell. The Little Helper robot, which is at the SmartLab facility will be used as the mobile robot for transportation. It is an autonomous mobile robot (AMR) consisting of a MIR robot platform and a UR5 manipulator.[15] The simulation will investigate four feature areas of the SLaMP model. Firstly, how to convert the layout into a matrix production and test the lead time and the utilisation of each workstation and the placement of them. Secondly, adjust the movement strategy of the Little Helper Robot to find the best version. Thirdly, test the loading/unloading parameter of the Little Helper to see its influence in the lead time. And lastly, test the setup with multiple mobile robots to uncover the benefits of them.

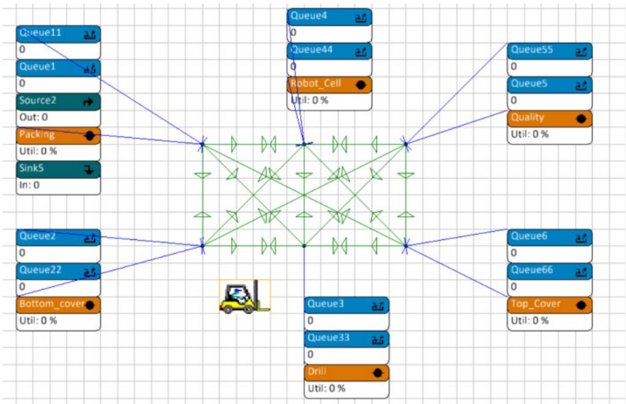

Fig.6. The matrix production layout of AAU SmartLab in the simulation

The placement strategy of the different process workstations is chosen on the basis of the product flow. Since a standard dummy phone follows a set sequence, the workstations need to organised so that the distance between each workstation is minimised.

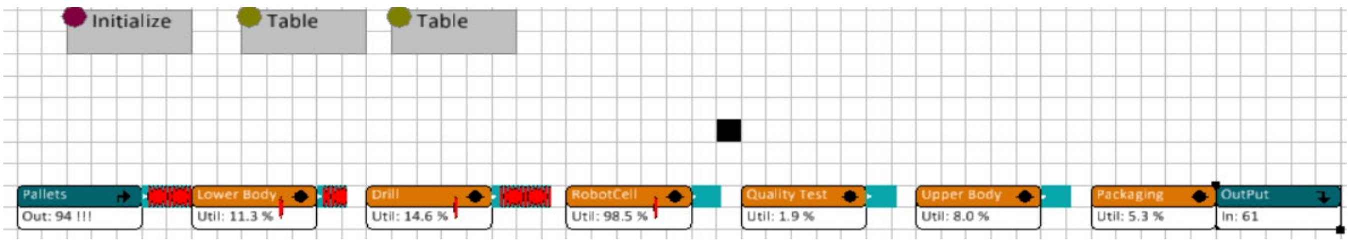

Fig.5. The improved SmartLab As-Is model layout in Enterprise Dynamics (while running)

Since the rigid connection of the manufacturing system has been eliminated, the loading and packaging workstations are placed in neighbour positions to minimise the distance. Moreover, an original layout model should act as the reference. Figure 6 & 7 shows two kinds of matrix production layout of AAU SmartLab.

In order to shorten the lead time, two kinds of movement strategies are developed for the little helper robot. Firstly, First-In-First-Out(FIFO) strategy. As the name states, the strategy here is to sort tasks by registration time. In this case, this means that once the workstation has finished processing the workpiece, it will send a pickup request to the robot. The robot registers the request and places it at the bottom of the task list. The robot traverses the task list from the top to perform tasks registered in chronological order. The workstation are assumed to be able to hold only one workpiece at a time. To avoid violating this in the simulation, the workstation can only request the helper robot when the next station.

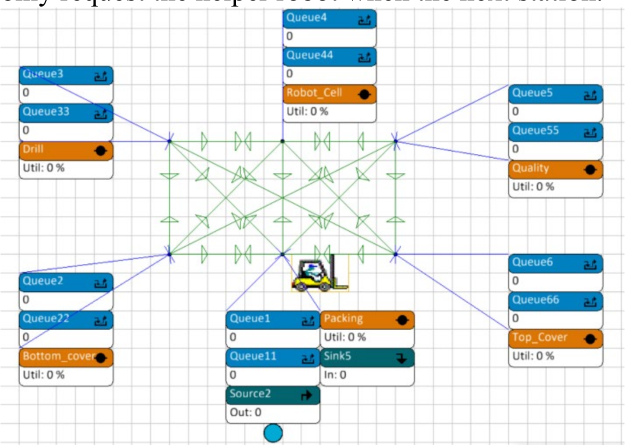

Fig.7. Matrix production model of adjacent workstation with loading / packaging

of the workpiece is available. Secondly, a robot cell prioritization strategy is proposed. This strategy is based on the fact, that the robot cell is the bottleneck with a far greater cycle time than the other processes. Therefore, when a product is sent to a non-robot cell workstation, the robot must wait for the processing to complete instead of following other instructions and going to other workstations.

The duration of loading/unloading time of the æittle helper will directly affect the lead time to complete the order. To test the sensitivity of reducing the load/unload time, the performance of the model were tested with different times. Table 3 lists the results of the comparison. In order to make the matrix production feasible, 5 seconds were selected as the

Loading/Unloading time	Lead time for order list
20s	8h, 25m, 31s
15s	6h, 47m, 21s
10s	5h, 6m, 11s
5s	3h, 28 m, 32s
0s	2h, 39m, 7s

loading/unloading time.

Table.3. Lead time with different load/unload times

To test whether one AMR limits the lead time to complete the order list, a model of two AMRs is introduced as the controlled group. The strategy for the two robots is to have one robot responsible for transportation of workpieces between loading, bottom cover, drilling, and the robot cell workstations, and the second robot responsible for transportation between the remaining workstations.

3 Results Evaluation

3.1 Result of As-Is model VS Improved model

The comparison of the As-Is model and the improved As-Is was tested on lead time based on an order list with the six different product variations. The individual lead times for these variations were also tested.

Table.4. Lead times for the different product variations and a random order list of 100 products

Lead Times	As-Is Model	Improved As-Is Model
Product 1	4min, 11s	2min, 40s
Product 2	4min, 35s	3min, 4s
Product 3	4min, 38s	3min, 7s
Product 4	4min, 16s	2min, 45s
Product 5	4min, 30s	2min, 59s
Product 6	4min, 43s	3min, 12s
Order list	2h, 2min, 8s	2h, 0min, 36s

3.2 Result of Workstations Placement Strategy Test

Table 5 shows the lead time of matrix production using two workstation placement strategies. These two models have the same lead times, which verifies the assumption of an optimal placement of workstations. However, the lead time for both models were much higher than the As-Is model. The utilisation of each workstation was low due to the load and unload time for the Little Helper. Compared with the nearly 100% utilisation of robot cells both in the As-Is model and the improved As-Is model, matrix production can only reach 18.2%. There is still a great gap for improvement in matrix

production in the AAU SmartLab.

Lead Times	Matrix Model 1	Matrix Model 2
Product 1	6min, 11s	6min, 11s
Product 2	6min, 35s	6min, 35s
Product 3	6min, 38s	6min, 38s
Product 4	6min, 16s	6min, 16s
Product 5	6min, 30s	6min, 30s
Product 6	6min, 43s	6min, 43s
Order list	10h, 51min, 40s	10h, 51min, 40s

Table.5. Lead times for the different product variations and a random order list of 100 products for the two matrix production models.

3.2 Result of AMR Strategy Test

By optimising the movement strategy of AMR, two improved matrix models are proposed. The lead time of the improved matrix production model is consistent with the results in Table 5. Changing AMR's movement strategies does not shorten the lead time to complete a single product. The difference is that the utilisations of workstations are improved. Table 6 shows the utilisation of model 1 under two different strategies and original one.

Table.6. A Table of utilisation of matrix style model under three different AMR’s movement strategy.

Utilisation	Original Model	FIFO Strategy	Robot Cell Prioritisation
Bottom cover	1.6%	2.1%	2.0%
Drill	2.2%	2.8%	2.8%
Robot cell	18.2%	23.5%	22.8%
QI station	0.4%	0.5%	0.4%
Top cover	1.5%	2.0%	1.9%
Packaging	1.0%	1.3%	1.3%

Either strategy improves the utilisation of each workstation. Especially FIFO strategy has a greater impact on the results, which reach 23.5% of the robot cell. However, this lead time and utilisation are still not enough for matrix production to replace RMS SmartLab. This led to a lower lead time when processing an order list.

3.2 Result of AMR’s Number Test

An additional AMR was added to this test. By comparing the situation of one AMR to test whether the number of AMR limits the efficiency of matrix production. Table **7** lists the lead time and the utilisation of each workstation when two AMRS were used in both matrix-structured models. From the results, model 2 performs better than model 1. Both models show that increasing the number of AMRS can greatly improve matrix production. However, even though this is significantly lower than the initial lead time of 10 hours and 51 minutes and the utilization of robot cells has more than doubled., the As-Is setup is still performing better due to the high utilisation of the robot cell.

	Matrix Model 1	Matrix Model 2
Bottom cover	5.9%	6.1%
Drill	8.1%	8.3%
Robot cell	67.5%	69.7%
QI station	1.3%	1.4%
Top cover	5.7%	5.9%
Packaging	3.8%	3.9%
Lead Time	2h, 55min, 57s	2h, 50min, 24s

Table.7. Utilisation of workstations and Lead time for the two models with two transport units

4 Introduction of Product Variants

According to the results of previous tests, matrix production does not perform well enough to replace RMS when it is produced according to the setting order sequence. Mass customisation not only means that the company needs mass production capacity but also needs to highly open the optional configuration to consumers. The flexibility of the manufacturing systems is another key characteristic worth testing. Therefore, the following tests will focus on the performance of the two manufacturing systems when the sequence of processes is changed. These sequence changes include a test with drilling and drilling breakdown test. The flexibility of the two manufacturing systems can be tested by comparing the lead times

especially when only a few products are involved. That is because the As-Is model needs four loops to produce such a product, which is a great waste of time.

However, as time goes on, the low utilisation of matrix production's robot cell begins to drag down the whole production. Finally, it was surpassed by the As-Is model.

4.2 Sequence Change Test with Drilling

In order to test the performance of the two models with different product variants, a new process sequence was introduced by adding the potential of an extra drilling process to the product. The three different product variations can be seen in Table 8.

	Bottom Cover Drilling	Top Cover Drilling	Both Cover Drilling
1	Bottom cover dispensing	Bottom cover dispensing	Bottom cover dispensing
2	Drilling	Robot cell	Drilling
3	Robot cell	Quality inspection	Robot cell
4	Quality inspection	Top cover dispensing	Quality inspection
5	Top cover dispensing	Drilling	Top cover dispensing
6	Packaging	Packaging	Drilling
7			Packaging

Table.8. Three different product variation sequences.

4.2.1 Expanded Drilling Process with One Station

Table 9 showcases the lead time results for the three different sequences change with one drilling station. Lead times were tested both for a single product moving through the systems solo, a single product moving through the system as the first order in an order list, and finally an order list of a 100 products with a random sequence of the three different product variations

For the entire order list the As-Is model still has a much better performance.

		Bottom Drilling	Top Drilling	Both Drilling
1Product (Solo)	As-Is	3min,12s	4min,36s	4min,47s
	SLaMP	3min,43s	3min,17s	4min,14s
1Product (Order List)	As-Is	3min,12s	44min,32s	44min,43s
	SLaMP	4min,34s	6min,5s	6min,43s
Order List	As-Is	2 h, 20 min, 11 s		
	SLaMP	3 h, 58 min, 12 s		

Table.9. Lead time results for sequence change test with one drilling station

However, the SLaMP model performs better when dealing with top drilling and both types of drilling for a single product, especially for the product being part of an order list. The As-Is model needs an extra 40 + minutes for the mandatory second loop to have the drilling process applied. Therefore, without changing the structure of the machine, matrix production will show higher flexibility than RMS in a short time, due to its routing flexibility, making it better at adapting. For a large amount of orders, however, the As-Is model performs better.

4.2.2 Expanded Drilling Process with Two Stations

In this test, an extra drilling station is added to both models. The As-Is model will have it added after the top cover dispensing, while for the SLaMP model, it will simply take the form of a new cell capable of performing both types of drilling. The lead times results is showcased in Table 10.

		1Drilling	2 Drilling
1Product (Solo)	As-Is	3min,12s	3min,23s
	SLaMP	3min,24s	3min,44s
1Product (Order List)	As-Is	3min,12s	4min,27s
	SLaMP	3min,23s	4min,44s
Order List	As-Is	2 h, 19 min, 59 s	
	SLaMP	3 h, 56 min, 36 s	

Table.10. Lead time results for sequence change test with two drilling stations

From the results, this new scenario does not require the workpieces to enter the next mandatory loop, so the lead time of the As-Is model is greatly reduced. Under all the requirements, the As-Is model can complete the production ahead of the SLaMP model.

4.3 Drilling Breakdown Test

Breakdown time is inevitable in the actual production. Therefore, this is element has been introduced here, where the models have two drilling stations. A few test prerequisites have been put forward.

- Breakdowns only happen on one of the drilling stations
- The tests are performed on the same order list.

• Breakdowns happen at specified times in both SLaMP and As-Is model.

• Repair duration is the same for both models.

For the As-Is model, two different scenarios were tested. One where the breakdown only affects the drilling process but still allows workpieces to pass the workstation, and one where the path is obstructed by the involved workpiece for the duration of the repair time.

		Test 1	Test 2	Test 3
Breakdown No.		1 & 2	1	2
Total repair time:		1h, 6m, 40s	51min	2h, 23m, 32s
Lead Time	As-Is	2h, 19m, 590s	2h, 18m, 36s	1h, 6m, 40s
	As-Is Obstructed	3h, 8m, 25s	3h, 1m, 33s	4h, 34m, 17s
	SLaMP	4h, 2m, 3s	4h, 0m, 43s	4h, 7m, 55s

Table.11. Results of the breakdown test

Table 11 showcases the results of the breakdown test. The As-Is model performs best in all three tests, when the breakdown does not obstruct the rest of the flow. However in test three, the obstructed As-Is model is outperformed by the SLaMP model. The order list for the SLaMP model has little sensitivity to breakdown compared to the obstructed As-Is model, since the product will just be rerouted to the other drilling cell, showcasing the high routing flexibility of the matrix production. Although two hours seems unrealistically high, the low sensitivity to breakdowns of workstations can be valuable upon expansion of the setup.

5 Conclusion

•FIFO strategy and increasing AMR's number are helpful to speed up the production of slamp;

•In efficiency test, the lead times and utilisation of all SLaMP models are worse than RMS;

• When introducing product variance, MP model shows the an increased flexibility, and in some scenrios lead to a lower lead time for low volume orders. However, when the volume increases, the As-Is model outperformed the MP model.

In general, the test results showed that the lead times of SLaMP are shorter than that of the As-Is modelwhen producing a small batch of products, with an different process sequence. This is in line with thefindings in the analysis, that MP is more flexible than RMS in terms of its routing ability. These benefitswere, however, very circumstantial and with the high throughput of the current system the arguments for converting the are very slim. Based on the above tests, it can be concluded that the current structure of matrix production is not suitable for the current AAU SmartLab and the product it creates. The extra load/unload when imple-menting the Little Helper leads to a lower utilisation of the robot cell and slows down the productionof MP. That being said, matrix production might be well suited in other manufacturing environmentswith more diverse product variants and higher process flexibility.

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