Vaasan yliopisto
UNIVERSITY OF VAASA

Henrik Skytén

Matrix-structured manufacturing systems

Simulation performance analysis as a successor to dedicated production lines

School of Technology and Innovation
Master’s Thesis in Industrial Management
Master of Science in Economics and
Business Administration

Vaasa 2022

VAASAN YLIOPISTO
Tekniikan ja Innovaatiojohtamisen yksikkö

Tekijä:	Henrik Skytén
Tutkielman nimi:	Matrix-structured manufacturing systems: Simulation performance analysis as a successor to dedicated production lines
Tutkinto:	Kauppatieteiden maisteri
Oppiaine:	Tuotantotalous
Työn ohjaaja:	Rayko Toshev
Vuosi:	2022 **Sivumäärä:** 122

TIIVISTELMÄ:

Kasvava määrä tuotevarianttien kysynnälle johtanut massapersonointiin massatuotannossa. Monet teollisuuden yritykset käyttävät yhä perinteisiä tuotelinjakonfiguraatioita, jotka kuuluvat kiinteisiin työasemiin perustuviin tuotantojärjestelmiin (DMS). Kuitenkaan näiden ei nähdä soveltuvan käynnissä olevaan tuotantotrendiin. Haasteena on löytää valmistusjärjestelmä, jossa korkea tuottavuus yhdistyisi joustavuuteen tuottaa monenlaisia tuotteita. Tätä varten kehitettiin matriisirakenteinen valmistusjärjestelmä (MMS). Lisäksi uudelleen konfiguroitavaa valmistusjärjestelmää (RMS) tutkitaan korvaajaksi perinteiselle tuotantolinjalle. Ongelmana on, että näitä kahta järjestelmää ei ole vertailtu suorituskyvyllisesti. Lisäksi ei ole tutkittu, missä tapauksissa MMS tai RMS olisi parempi vaihtoehto perinteisen tuotelinjan korvaajaksi.
Tämän Pro gradu -tutkielman tavoitteena on vastata kysymykseen, miten MMS ja RMS suoriutuvat verrattuna perinteiseen tuotelinjaan tarkasteltaessa järjestelmän tuottavuutta ja joustavuutta. Lisäksi arvioidaan, missä valmistusskenaarioissa MMS tarjoaa parempaa suorituskykyä kuin RMS ja DMS. Viimeisenä tutkielmassa pyritään vastaamaan mitkä ovat MMS:n edut ja haitat verrattuna RMS:ään ja DMS:ään. Tutkimusaukon täyttämiseksi opinnäytetyö esittää diskreetti tapahtumapohjaisen simulaation. Tutkielma noudattaa kokeellisen tutkimuksen periaatteita deduktiivisella lähestymistavalla, jossa kerätään kvantitatiivista dataa tuotantosimulaatiosta. Teoreettinen katsaus keskittyy valmistusjärjestelmien ominaispiirteisiin sekä taustaan. Tätä tietoa hyödynnetään suunniteltaessa ja rakentaessa simulaatiokoetta. Simuloinnin tuloksia arvioidaan seuraavista suorituskyvyn näkökulmista: hyötysuhde, tehokkuus, toimituskyky ja järjestelmän joustavuus. Nämä perustuvat yleisiin tuotannon kilpailuprioriteetteihin.

Tutkielmassa havaittiin, että MMS tarjoaa korkeimman työaseman käyttöasteen ja tuotantojärjestelmän tehokkuuden. RMS suoriutui parhaiten hyötysuhteen, toimituskyvyn ja joustavuuden näkökulmista. Joustavuutta mitattiin tuotantoskenaarioilla, joissa simuloitiin tuotantohäiriöitä ja muutoksia yhtäaikaisesti valmistettavien tuotteiden määrässä tuotannossa. Tutkielmassa todettiin, että MMS:n tuotantovirta hidastuu merkittävästi, kun valmistettavien tuotteiden määrä järjestelmässä kasvaa korkealle tasolle. DMS suoriutui huonoiten kaikissa skenaarioissa ja suorituskykynäkökulmista. Tämä johtuu joustamattomuudesta vaihtoehtoisille tuotereiteille tekien siitä herkän häiriöille. Molemmat sekä MMS että RMS tarjosivat huomattavasti paremman tuottavuus- ja joustavuuskyvyn kuin DMS. Tutkimuksen tuloksiin perustuen MMS:ää suositellaan tuotantoskenaarioihin, joissa tuotevalikoima ulottuu myös yli tuoteperheen, ja jossa tuotannon kustomointikyky ja korkea työasemien käyttöaste on tärkeää. RMS sopii skenaarioihin, joissa tuotannon toimituskyky ja joustavuus on ratkaisevan tärkeää.

KEYWORDS: Matrix-structures, Production systems, Simulation, Measurement, Manufacturing

UNIVERSITY OF VAASA
School of Technology and Innovation

Author:	Henrik Skytén
Title of the Thesis:	Matrix-structured manufacturing systems: Simulation performance analysis as a successor to dedicated production lines
Degree:	Master of Science in Economics and Business Administration
Programme:	Industrial Management
Supervisor:	Rayko Toshev
Year:	2022 **Pages:** 122

ABSTRACT:

Growing demand for product variations has led to mass personalized production in the manufacturing industry. Many manufacturers still use traditional product line configurations based on a dedicated manufacturing system (DMS). This system is not considered compatible with ongoing manufacturing trend. The challenge is finding a manufacturing system that would combine high productivity with the flexibility to produce multiple types of products. To this end, a matrix-structured manufacturing system (MMS) was developed. In addition, a reconfigurable manufacturing system (RMS) has been researched as a replacement for the DMS. The problem is that these two systems are not compared performance-wise. Moreover, it has not been investigated in which cases MMS or RMS would provide better compatibility to replace the product line.

This Master’s thesis aims to answer how MMS and RMS perform compared to DMS regarding productivity and flexibility. Furthermore, it is evaluated in which manufacturing scenarios MMS provide better performance than RMS and DMS. Finally, thesis seeks to answer what are the benefits and disadvantages of MMS compared to RMS and DMS. To fill this research gap in knowledge, thesis presents a discrete-event simulation experiment. Thesis follows principles of experimental research with deductive approach and collects quantitative data from manufacturing simulation. Theoretical review is conducted focusing on characteristics and background of manufacturing systems. This information is utilized when designing and constructing simulation experiment. Simulation results are evaluated from the following performance perspectives: efficiency, effectiveness, delivery, and operational flexibility. These are based on common manufacturing competitive priorities.

It was discovered that MMS provides highest workstation utilization and overall production effectiveness. RMS performed best in efficiency, delivery, and flexibility perspective. Flexibility was measured with production scenarios which involved simulated production disturbances and changes in number of products in system. It was found that production flow in MMS is declined significantly when number of products in system increases to high level. DMS resulted lowest in every scenario and performance view. The problem is the inflexibility to alternative production routes making it sensitive to production disruptions. Both MMS and RMS provided notably better productivity and flexibility performance than DMS. Based on the results, MMS is recommended for production scenarios where product variety extends over product family with importance in production customization and high station utilization. RMS is suitable for scenarios where delivery performance with flexibility is crucial.

KEYWORDS: Matrix-structures, Production systems, Simulation, Measurement, Manufacturing

Contents

1 Introduction 8

- 1.1 Reasons for research and its uniqueness 9
- 1.2 Research design 10
- 1.3 Objective and limitations of study 11
- 1.4 Research questions 12
- 1.5 Hypothesis 12
- 1.6 Research method 13
- 1.7 Research content 14

2 Literature review 15

- 2.1 Definitions 15
  - 2.1.1 System 15
  - 2.1.2 Manufacturing system 15
  - 2.1.3 Layout 16
  - 2.1.4 Competitive priorities 16
  - 2.1.5 Key performance indicators 16
- 2.2 Manufacturing systems 17
  - 2.2.1 Dedicated manufacturing systems 17
  - 2.2.2 Matrix-Structured manufacturing systems 21
  - 2.2.3 Reconfigurable manufacturing systems 26
  - 2.2.4 Comparison of investigated manufacturing systems 30
- 2.3 Simulation modeling 36
  - 2.3.1 Definition of simulation modeling 36
  - 2.3.2 Simulation modeling and analytical modeling 37
  - 2.3.3 Simulation methods: discrete-event, agent based, system dynamics 38
  - 2.3.4 Manufacturing simulations 39

3 Research Methods 42

- 3.1 Research methodology 42
- 3.2 Research steps 43
- 3.3 Data collection 44

3.4 Data analysis 45

3.5 Research tools 45

3.6 Results validity and reliability 46

4 Simulation model and KPIs 48

4.1 Anylogic simulation tool 48

4.2 Simulation assumptions and manufacturing scenario parameters 50

4.3 Simulation models 54

4.3.1 DMS Model 54

4.3.2 MMS model 54

4.3.3 RMS model 56

4.4 Selection of key performance indicators 57

5 Results 62

5.1 Presentation of simulation models 62

5.1.1 MMS model 65

5.1.2 RMS model 68

5.1.3 DMS line 70

5.2 Data gathering 71

5.3 Simulation results and analysis 73

5.3.1 Simulation results 74

5.3.2 Impact of station failure and repairs. 85

5.3.3 Effect of WIP 94

5.3.4 Scenario ranking 99

5.4 Critical thinking of results 103

6 Conclusions 108

6.1 Summary and findings 108

6.2 Answering research questions 109

6.3 Managerial and research implications 113

6.4 Recommendations for future research 114

References 115

Pictures

Picture 1. Anylogic software: Tools and layout. 48

Picture 2. Anylogic: Simulation run 50

Picture 3. Product agent. 64

Picture 4. MMS simulation model. 65

Picture 5. MMS model process chart. 66

Picture 6. RMS model. 68

Picture 7. RMS process functions. 69

Picture 8. DMS model blocks. 70

Picture 9. DMS process functions blocks. 71

Picture 10. Importing and gathering data from DMS model in scenario 1. 72

Picture 11. Combining results from scenario 1. 73

Figures

Figure 1. Framework of research design 14

Figure 2: Product line. Represents DMS production. 19

Figure 3. MMS layout. Adapted from Schönemann et al. (2015) 24

Figure 4. RMS system with crossovers. Adapted from Koren et al. (2018). 28

Figure 6. DMS process flow chart. 54

Figure 7. MMS process flow chart. 55

Figure 8. RMS process flow chart. 56

Figure 9. Simulation visualization blocks. 62

Figure 10. Process Library blocks. 63

Tables

Table 1. System comparison table. Adapted from Koren and Shpitalni (2010). 31

Table 2. Simulation inputs 1. N symbolize normal distribution. 52

Table 3. Simulation inputs 2. Processing times. 53

Table 4. Setup times for MMS. RMS and DMS do not have setup time. 53

Table 5. Overall statistics table. Describes overall result of system in specific scenario.58

Table 6. Productivity performance indicators. Efficiency and effectiveness. 60

Table 7. Delivery performance indicators 61

Table 8. Scenario 1 results. 78

Table 9. Scenario 2 results. 81

Table 10. Scenario 3 results part 1. 84

Table 11. Flexibility scenario inputs. Other inputs are same as in scenario 1. 86

Table 12. Failure scenario results. Part 1. 91

Table 13. Failure scenario results. Part 2. 92

Table 14. Percentage change to Scenario 1. Failure scenarios. 93

Table 15. Buffer 5 and Buffer 10 results. 97

Table 16. Buffer 5 and Buffer 10 percentage change to Scenario 1. 98

Table 17. Example of calculating performance ranking in Scenario 1. 100

Table 18. Example for calculating percentage change score. 101

Table 19. Scenario ranking results. 102

1 Introduction

Manufacturing has changed radically throughout the history. Koren and Shpitalni (2010) presents that due to the globalisation, manufacturing has shifted from mass production in 1955 and mass customization in 1980s to the present personalized production. For manufacturers the change has corresponded as shift from high-volume, low-variety production to lower volume and increase of product variety and fluctuation of demand (Koren & Shpitalni, 2010). Continuously changing business trends such as global competition, growing customer demands, climate change and stricter regulations force manufacturing companies constantly develop their production systems.
Crucial part of improving manufacturing operations is designing appropriate manufacturing system. Because this requires substantial amount of investments and time, manufacturers try to implement system which is suitable for their production strategy and withstand ever-changing customer demands and competition.

Manufacturer's competitive production priorities aim to accomplish one or more of the following goals: improving product quality, reducing total costs by increasing productivity, adding flexibility to increase product variety, and improving delivery performance by increasing delivery speed and reliability (Awwad, Khattab, & Anchor, 2013). Here productivity can be divided into efficiency and effectiveness. The experts in the field have developed multiple manufacturing systems to accomplish these goals. According to Koren and Shpitalni (2010), the ideal manufacturing system would be adaptable to market demand, cost-efficient, flexible to new product variants and include short lead time. Old manufacturing systems cannot manage these simultaneously. Finding optimal layout becomes more difficult when manufactured products include different steps and processing times.

Product line configuration representing dedicated manufacturing system (DMS) is currently favoured by manufacturers by its productivity, simplicity, and cost-efficiency. However, it does not provide flexibility to produce multiple types of products which is crucial for answering changing customer demand. Promising state-of-the-art production system solving this problem is called matrix-structured manufacturing system (MMS) presented by Greschke, Schönemann, Thiede and Herrmann (2014). Schönemann, Herrmann, Greschke and Thiede (2015) shows that MMS leads to substantial workstation utilization rate and flexibility increase while providing possibility to produce multiple types of products compared to DMS. Still, MMS has not been compared to any other modern production configuration in recent studies meaning difficulty to evaluate other options. Moreover, there is no extensive performance analysis of MMS considering multiple performance perspectives. This makes evaluation of MMS compatibility as successor for DMS more challenging. To conclude, there is a gap in knowledge when evaluating MMS performance from multiple performance perspective and lack of comparisons to other modern manufacturing system configurations.

1.1 Reasons for research and its uniqueness

The purpose of the thesis is to evaluate MMS suitability to replace DMS with production performance analysis. The challenge is that there are relatively few studies focusing on MMS compared to other manufacturing system theories. Only few years ago, MMS has acquired more popularity in manufacturing field. Moreover, studies concerning MMS compatibility to different production competitive priorities are missing. Hofmann, Brekemeier, Krahe, Stricker and Lanza (2019) have evaluated MMS to DMS with simulation test measuring flexibility and production disruption sensitivity. Still, other production competitive priorities such as delivery has not been investigated. In addition, most simulation studies have only included basic performance indicators measuring MMS, thus collection of indicators to measure specific performance view is still missing.

Studies regarding MMS show promising results replacing DMS line, but comparison to other modern manufacturing system is missing. To evaluate options for replacing DMS with other system, another potential manufacturing system is presented. Koren and Shpitalni (2010) present reconfigurable manufacturing system (RMS) which framework is a parallel product line where crossover connections is added between stages. Layout resembles product line, but with usually more than one station per stage. Two main benefits stated are capability to change production capacity or functionality when needed which enables responds quickly to unknown market demands (Koren & Shpitalni, 2010). This makes RMS crossover line interesting to compare with matrix structured line as they share similar characteristics.

The thesis goal is to present new insight regarding selected manufacturing systems focusing on performance measurement from different performance perspectives. These perspectives are based on production competitive priorities such as flexibility or delivery. With help of the thesis, businesses in manufacturing field can evaluate MMS compatibility to their own production scenario and potentially further improve production performance. Because studies have investigated MMS only in perspective of productivity and flexibility, thesis will also evaluate MMS from other production performance perspectives. Thesis will also present multiple performance indicators measuring specific competitive priority thus reflecting results from different views of exact production priority.

1.2 Research design

This thesis aims to fill research gap in knowledge by presenting an experimental computer simulation study of MMS. Simulation experiment was selected because case studies regarding MMS was not found and only few simulation comparisons with other manufacturing systems are published. In simulation, different production scenarios are implemented into simulation model where each model represent one of investigated system. Traditional product line (DMS) and parallel line with crossovers (RMS) presented by Koren and Shpitalni (2010) are added to compare results with MMS. Here, DMS presents the most popular production configuration among manufacturers whereas RMS presents another modern production line alongside MMS to replace DMS. Both MMS and RMS try to solve similar problem: combining flexible and high-volume production which are essential for mass customization production. From simulation, following performance perspectives are measured: efficiency, effectiveness, delivery, and flexibility. One of the competitive priorities, production quality, is not measured. Measuring quality in simulation study is extremely challenging and requires a lot of planning. Also, thesis has limited time schedule which is why it was neglected. Key performance indicators for each investigated competitive priority are selected based on ISO 22400 standard. Simulation part of study can be summarized as follow. Manufacturing scenarios is simulated multiple times on each system model. All raw simulation data is saved which is further processed into performance indicators measuring selected performance views. Finally, indicators are used to compare simulation results between systems in specific production scenario.

1.3 Objective and limitations of study

The objective of thesis is to compare manufacturing systems using performance related indicators. Simulation results are used to determine in which production scenarios MMS is suitable for replacing DMS or similar system and thus which manufacturers can potentially benefit from MMS configuration. Therefore, thesis focus performance comparison and does not consider financial, practicality and sustainability perspectives for example.

Production scenarios are designed to reflect common activities and occurrences in production. Thus, simulation scenarios do not try to reflect specific manufacturing field operations or characteristics. Simulated operations and activities are limited and for example logistical processes and product transitions between workstation are not simulated. Other limitations of simulation are discussed in chapter 4.3 Simulation models.

1.4 Research questions

With this thesis, the aim is to answer the following research questions:

I) How MMS and RMS perform compared to DMS regarding productivity and operational flexibility when considering production time and WIP?

II) In which production scenarios MMS is more suitable than DMS or RMS according to the simulation results?

III) What are the benefits and disadvantages of MMS when compared to RMS and DMS?

The first questions try to answer whether MMS and RMS are suitable for replacing DMS line in future where customer demand requires high productivity production and manufacturing multiple types of products. Second question seeks to find in which production scenarios MMS can provide better results than other selected systems. Final question gathers advantages and drawbacks of MMS according to simulation results and literature review.

1.5 Hypothesis

Based on the literature on the field, the following hypotheses are presented:

- H1: MMS leads to highest efficiency when workstation utilization is considered.
- H2: DMS provides fastest throughput rate in failure free production scenarios
- H3: RMS leads to shorter production time than DMS in production scenarios where workstation failures occur.

First hypothesis is based on Schönemann et al. (2015) and Greschke et al. (2014) statement that MMS focus on providing high station utilization leading to increased production efficiency. This is expected to happen because of increased number of stations able to produce specific production stage and with ability to produce multiple process stages in one station (Schönemann et al., 2015; Greschke et al., 2014). The second hypothesis is based on simulation test in Hofmann et al. (2019) and statements in Koren and Shpitalni (2010). According to Hofmann et al. (2019) simulation results, DMS delivers noticeably higher product throughput than MMS. In Koren and Shpitalni (2010) research regarding RMS they note that DMS productivity is higher than RMS if workstations are highly robust against failures. This also means that DMS productivity is higher when failures do not occur in production. If station is prone to failures RMS provides better productivity (Koren & Shpitalni, 2010). This argument forms the third hypothesis.

1.6 Research method

Thesis is based on descriptive approach to identify and describe characteristics of investigated manufacturing systems. Thus, it focuses on answering *what* simulation results indicates. It does not try to deeply analyse, why particular system is not suitable for exact production conditions or why system has certain characteristics. To evaluate manufacturing systems, an experimental simulation will be constructed where different production scenarios are implemented. The experiment is conducted as simulation observation and performance data analysis. Scenarios include different inputs where for example production volume, buffer size and failure occurrence changes. These represent independent variables. Dependent variables are the outputs of simulation which are production results and implemented simulation indicators. Simulation results are used to form relationships between performance of manufacturing system and manufacturing scenarios. Every manufacturing system is simulated in each scenario with same initial production inputs. Manufacturing systems are tested by within-subject design investigated by Charness, Gneezy and Kuhn (2012). This means every manufacturing system design is tested on every production scenario separately.

Data sources includes primary data gathered from simulation experiment and secondary data collected from related literature and previous studies. Both quantitative data based on performance measurement and qualitative data regarding system characteristics and design are utilized. In literature review, qualitative information is collected from secondary sources regarding the framework of MMS, DMS, and RMS production line. Information is used to building simulation models and reflecting each system characteristics. From Kang, Zhao, Li, and Horst (2016) research based on ISO 22400 standard, key performance indicators for each production performance perspective are gathered and selected. For experimental 2-D simulation tool, Anylogic simulation modeling software is used. Anylogic version is 8.7.0 personal learning edition. For collecting data from simulation, multiple production performance measuring parameters are implemented together with simulation database recordings which are imported into Microsoft Excel to calculate overall statistics and key performance indicators.

1.7 Research content

Literature review in chapter 2 focuses on MMS, DMS and RMS characteristics and background. Chapter also presents simulation modeling and differences between different simulation methods. Chapter 3 Research methods describe methodology, approach, techniques, and tools used. Chapter 4 Simulation model and KPIs present simulation tool, limitations, model framework, and selection process of KPIs (key performance indicators). Chapter 5 Results illustrate constructed simulation models and process of data gathering from simulation. In addition, simulation results are presented which are analysed and compared between manufacturing systems. Finally, systems are ranked according to scenario and the results collected are analysed. Chapter 6 Conclusions summarise the findings and answer to research questions and hypothesis. Figure 1 summarizes thesis steps.

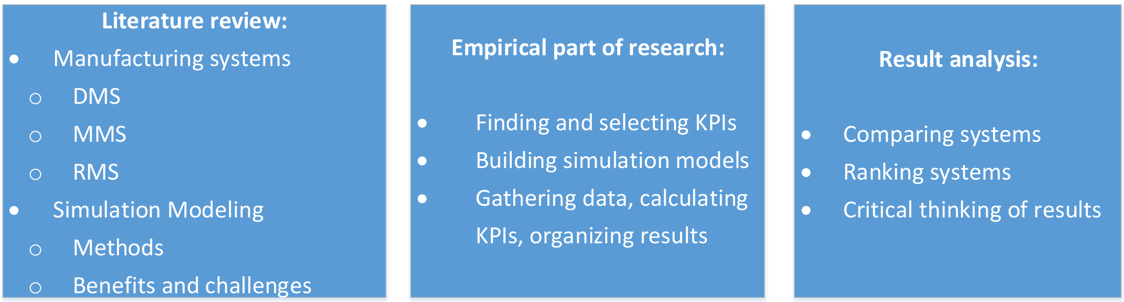


Figure 1. Framework of research design

2 Literature review

This chapter presents the literature review part of the thesis. First, the manufacturing systems that are the focus of the research are presented. Each system is defined and characterized by acknowledged benefits and disadvantages. Moreover, the production line layout of each system is illustrated. Then, simulation modeling is defined, different simulation methods presented and finally manufacturing simulation is described.

2.1 Definitions

In below some fundamental topics are described related to this research. The definitions belong to fields of manufacturing, computer simulation, business strategy and statistical measurement.

2.1.1 System

In manufacturing perspective, system is combination of people, equipment, products, and processes to form capacity for needed objectives (Alexopoulos, Efthymiou & Chryssolouris, 2014). In this study, system refers to one of the selected manufacturing systems.

2.1.2 Manufacturing system

Caggiano (2014) defines manufacturing system as a collection of resources with shared information and physical flows in the production facility. Manufacturing system can indicate whole facility or department, part of it or one production station (Caggiano, 2014). In this research, manufacturing system is used for referencing all operational components of production system needed for producing required products. In other words, it is used to reference whole simulation model of specific system.

2.1.3 Layout

Layout is defined as organizing physical resources (e.g., workstations, equipment, workers, machines, and stages) into the production facility. Even existing facility layout changes in the course of time due to changes required in production. (Stephens, 2019, p. 2-3). Layout has crucial effect to production performance and thus is one of the key parts investigated in this research.

2.1.4 Competitive priorities

According to Krajewski, Malhotra and Ritzman (2018, p.36) “Competitive priorities are the critical operational dimensions a process or supply chain must possess to satisfy internal or external customers, both now and in the future”. Management selects the ones which are important to maintain other processes successful and keep or grow the market share (Krajewski, Malhotra, & Ritzman, 2018, p. 36). Competitive priority is not same as competitive advantage. Competitive priorities investigated are productivity, flexibility, and delivery. Productivity can be divided into efficiency and effectiveness.

2.1.5 Key performance indicators

According to ISO (2014), International Organization for Standardization, key performance indicators, in short KPIs, “are defined as quantifiable and strategic measurements that reflect an enterprise's critical success factors”. In production, KPIs are utilized finding unnecessary processes and accomplishing set objectives. (ISO, 2014.) In this research, KPIs are used to measure the level of production performance from specific competitive priority view.

2.2 Manufacturing systems

Manufacturing systems combine equipment, workers, material, and information flow together to produce a product. It starts from product design and ends in delivering the finished product. Manufacturing activities consist of product design, production planning, production control, production equipment and production processes. Decisions related to manufacturing are ultimately connected to decision attributes such as flexibility, time, and cost. These are measurable performance requirements driving the change in manufacturing. Manufacturers aim to focus on few specific attributes which they are going to improve to reach business objectives. (Chryssolouris, 2006; Gola & Świć 2012.) Thus, manufacturing systems are built to respond desired manufacturing attributes, also called competitive priorities.

Next, three selected manufacturing systems for this study are presented. All these systems are designed for high volume production but have different system layout and principles.

2.2.1 Dedicated manufacturing systems

Dedicated manufacturing system is a production system in which work platforms and machines are placed in fixed positions according to the work steps of the product to be manufactured. It is designed to produce one or couple variants of products. (Esmaeilian, Behdad & Wang, 2016; ElMaraghy H., Monostori, Schuh & ElMaraghy W., 2021.)

Dedicated manufacturing systems were born from Henry Ford’s invention of mass production configuration on Model-T car factory in 1908. The invention emphasized highly standardized production steps and conveyor belts to move product parts more rapidly. With this invention, it was possible to move from craft production into more productive mass manufacturing. The principle of dedicated lines is economies of scale strategy where focus lies increasing product output to minimize cost per product. (ElMaraghy et al., 2021.)

Dedicated manufacturing systems can be divided into continuous manufacturing systems and intermittent manufacturing systems. Continuous systems are based on made-to-stock model where market forecast plays critical role for optimizing inventory level. Production is carried out by low variety of standardised products with pre-determined order sequence executed in large volumes. These types of production systems are mass production and process production. Intermittent manufacturing systems are made-to-order and can produce more variety of products in lower volumes. Products here commonly requires continuous adjustments to product itself and operations. Systems like batch production, job shop and project manufacturing represent intermittent manufacturing. (Gola & Świć, 2012.) In this study we focus on continuous manufacturing system, product line, which belongs to group of mass production systems.

Product line is most common configuration of DMS. Product lines produce one or couple similar products in high quantity. Workstation which utilizes automation are placed in fixed positions and connected with transfer lines. (Koren, 2006.)
In this layout, workstations are placed according to the sequence of manufactured product (Koren & Shpitalni, 2010). Thus, product flow is unidirectional where product start from other end of line and go through same repetitive processing stages. The objective of dedicated line is high-volume and highly standardised production while minimising cost and processing time in workstations, buffer space and material transport. (Kiran, 2019; Koren, 2006.) From now on, we refer product line as DMS which is chosen to represent dedicated manufacturing systems due to its popularity by manufacturers.

DMS has relatively low cost per product as it focuses on one or few products. For new products or increasing substantially the volume, new product line must be placed. (Koren 2006.) Thus, configuration is inflexible for new product types and larger changes in production. Balancing the process times in workstations and reducing the distance of stations is seen crucial, which dramatically effect to the total production time and utilization of stations (Hoffman, Brakemeier, Krahe, Stricker & Lanza, 2019). Workstations must be placed according to sequence of product's processing phases. Production control, material handling and quality control is straightforward as production flow is parallel with repetitive standardised tasks. Failures or maintenance halt whole production line as for each production step is designated to only one workstation. Production is based on made-to-stock model where critical role lies in demand forecasting. (Kiran, 2019.)

As mentioned earlier, DMS consists of sequentially placed workstations fitted as closely as possible to each other. Production starts from other end of line where product flow go through same production steps and final step is processed at end of the line. DMS uses small buffers and straightforward material handling. Each workstation has its own resources needed for processing the exact step. Commonly automated machines and workers process the products in workstations. The workstation can only process one step and usually only one product type. Material handling focuses on moving processed product from workstation to next station which is commonly accomplished by conveyors. Product line is demonstrated in figure 2.

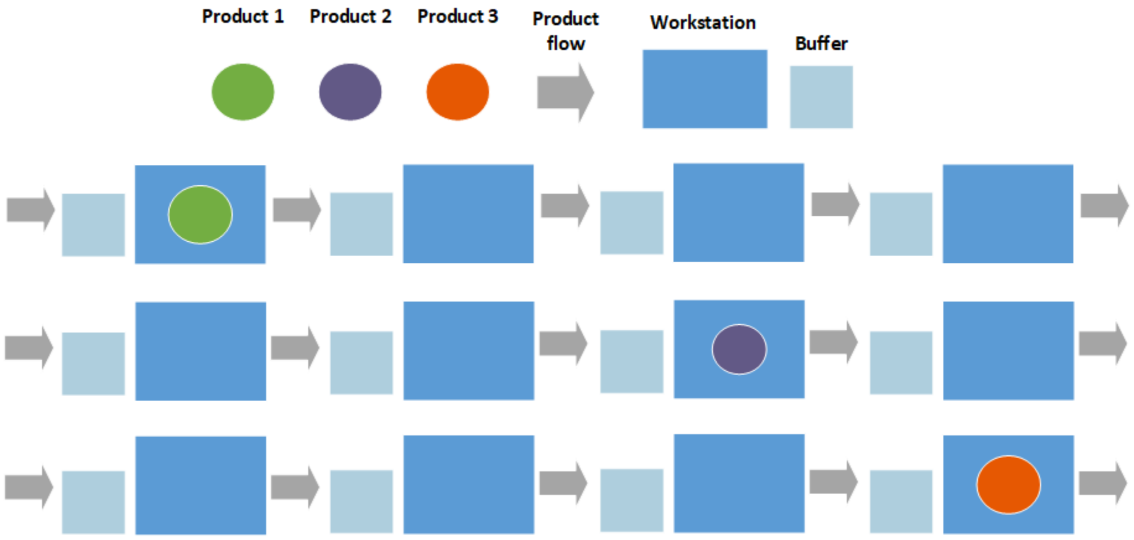


Figure 2: Product line. Represents DMS production.

With standardised and repetitive stages, DMS reduces tasks in one workstation and simplifies both production control and material handling. When production tasks are evenly balanced between workstations, the total production time is reduced while utilization of stations is increased. Because workstations are placed tightly together, the configuration saves space needed for transportation systems and reduce transporting time. (Kiran, 2019.)

However, the main disadvantage of layout is inflexibility for product variations. For every future product the new line must be placed. Moreover, every station needs its own tools and other resources as sharing them with other stations can be complex. This also requires more space in workstation thus increasing total requirement of needed production space. As layout is constructed for high volume production, the fluctuation of demand or decrease of volume raise production costs. If production tasks cannot be divided evenly for workstations, problems of blocking and starving arises. Supervision is needed to ensure smooth flow of products between stages. However, this increases pressure towards workers. Predictive and preventive actions for production failures and required maintenances is required as workstation’s incapability for work stops whole production line. (Kiran, 2019.)

Product layout is one of the traditional manufacturing layout designs and most used in manufacturing industry. Product layout will be analysed more deeper on this research and compared to other modern manufacturing systems as being still popular layout in most manufacturing cases. Moreover, the product line is most suitable for comparing with MMS and RMS described later as high-volume production system. Other traditional layout approaches are:

- Process layout
- Cellular layout
- Fixed-position layout. (Kiran, 2019; Sule, 2007.)

Process layout is based on grouping workstations according to their operational capabilities. They are placed separated department also called job shops. Here workstation can process multiple types of products. (Kiran, 2019; Sule, 2007.) Process layout is used on low-volume production where variability of product can be high. Cellular layout is arranged according to product flow where workstations are located in same department which are usually called cells. The cell can produce any products in product family. Cellular layout aims to reduce setup time and manufacturing costs. This is accomplished by experienced workers which can operate multiple workstations and usually fewer workforces are needed than number of workstations.

Fixed position layout is implemented on large-scale products which are difficult or impossible to move and manufactured usually by project-type occasions (e.g., constructing ships or plants). Products are placed on fixed position where all needed resources are gathered. The layout is implemented on very low volume manufacturing, but product can be completely customized by customer. (Kiran, 2019.)

The problem that traditional layout options have is they are unable to efficiently manufacture both multiple different products and with high volumes (Schönemann, 2015). Promising two manufacturing systems to solve this problem are matrix-structured manufacturing systems and reconfigurable manufacturing systems.

2.2.2 Matrix-Structured manufacturing systems

Matrix structured manufacturing system is a combination of intelligent and agile manufacturing system. MMS is described as flexible and scalable matrix formed workstation configuration utilizing cyber physical system (CPS) and adaptable material control system where each workstation act as autonomous, cooperative manner. To accomplish this, machines and equipment are built with sensors and microcomputers where each station is connected to production network. (ElMaraghy, 2021; Schönemann et al., 2015.) Accordin to Greschke et al. (2014) MMS aims to elimination of constant cycle time "by a specific allocation of several operation steps onto specifically arranged workstations" and decentralized material flow control system. Here, the distribution of products to workstations is not assigned in advance (Schönemann et al., 2015). Differently from DMS, MMS is divided from central system into independent sub-systems presented by modular workstations (Trierweiler, Foith-Förster & Bauernhans 2020).

MMS is designed to handle high-volume and multiple product manufacturing simultaneously respond to volume fluctuation and new product variations. Furthermore, the configuration can be rearranged or modified according to process changes. MMS promises high utilization of workstations with high flexibility and efficiency. (Greschke et al., 2014; Schönemann et al., 2015.)

Matrix structured production concept was introduced by Greschke et al. (2014) as a solution for high volume and flexible manufacturing system for automotive industry. Later, Schönemann et al. (2015) developed a framework for simulation implementation for MMS and compare it to traditional product line. Now, studies have focused on the following areas of MMS: overall framework by Greschke et al. (2014) and Schönemann et al. (2015), changeable elements in MMS system by Trierweiler et al. (2020), MMS resource availability evaluation by Klos and Patalas-Maliszewska (2019), material handling systems for MMS by Filz, Herrmann and Thiede (2019) and logistical solutions for MMS by Fries, Wiendahl and Assadi (2019). Kuka Systems (2016) shows practical example of MMS production features and principles.

Matrix-structured manufacturing configuration presents one of the latest approaches for flexible manufacturing system and differs significantly from traditional manufacturing fundamentals. The main goal of MMS is to eliminate constant cycle by presenting individual cycle times for workstations. Consistent cycle time leads to increase in waiting time and propose individual cycle time for each workstation. The goal is ensuring average cycle time of each station matching average process time. (Greschke et al., 2014.)

Other objective for MMS is forming a workstation which can produce multiple process steps and providing several compatible workstations for each process step. To reduce blockings in production and increase robustness against disruptions, several workstations even at the end of the line can process same work packages (WP). To reduce starving and increase utilization of stations, each workstation can process multiple WPs. These additions require dynamic product routing system with bidirectional transport

routes where every station is connected to each other. (Greschke et al., 2014; Schönemann et al., 2015.)
Product flow control strategy is based on decentralized decision on workstations, which occurs when product is processed and must select optimal next station according to control strategy. In real case scenarios, the next station decision is possible to be processed by microcomputers in workstation handling unit. The information about current situation of available stations can be accomplished by centralized manner with production network server which collects and shares information or decentralized matter via RFID-technology. Decentralized information system is favoured because it enables the independent product specific control strategies (i.e., individual product route can be controlled with different strategies). When implemented optimally, product control ensures high utilization rate and robustness against disruptions. (Greschke et al., 2014; Schönemann et al., 2015.)

Workstations in MMS are usually arranged in matrix form into manufacturing facility. Still, stations can be arranged by the restrictions of the facility or with goal to reduce traveling distance for example. Components in MMS consist of workstation, their buffers, process steps, products, and material routes. It is important to note that material flow must be designed so that transporters can move freely to any workstation (i.e., transporter can move from station 1 to station 2 or station 9 and the other way). Each workstation is capable of processing multiple products and process steps. The allocation of steps to workstations be accomplished by multiple ways, however considering the balancing workload between stations should be desired. Moreover, it should be favoured that each step can be processed in multiple station, minimum requirement being at least once. (Greschke et al., 2014; Schönemann et al., 2015.)

Each workstation can process one product at the time and equipped with limited buffer. In DMS production line if next station is full, product must wait workstation to be available blocking the current one. However, workstations in MMS can produce multiple process steps meaning product can choose other compatible workstation or wait the station which is available first. Furthermore, if more than one station is available the decision can be based on product flow control strategy such as shortest time till processing, minimization of distance travelled or even longest idle time between workstations. If every station is full but some compatible stations have space in buffer the decision can be based on again strategy of product flow control. (Schönemann et al., 2015.) Illustrative layout of MMS is in figure 3.

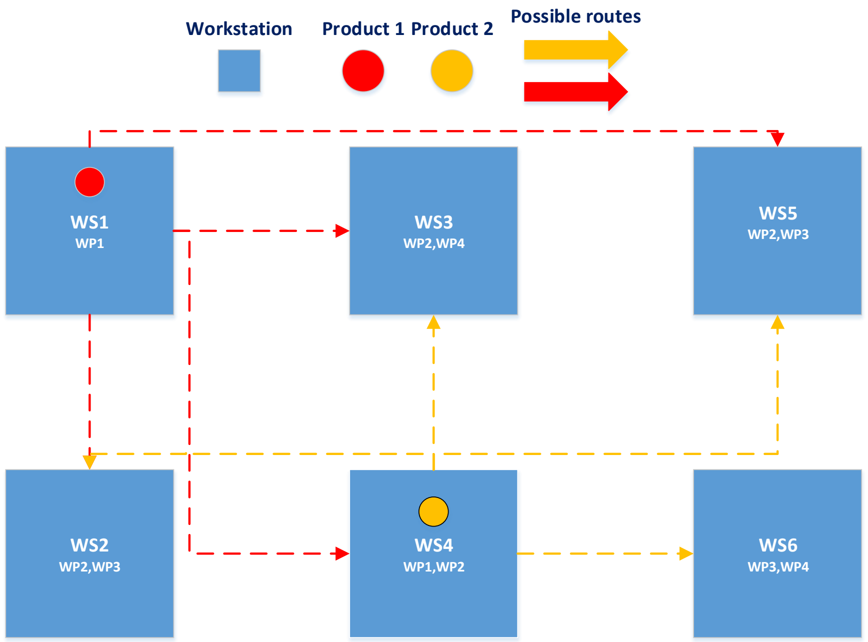


Figure 3. MMS layout. Adapted from Schönemann et al. (2015)

There are some discussion and evaluation about benefits and disadvantages of MMS system. Still, many of these are on discussion level thus not practically proven. Many of benefits are gathered from the results of computer simulation test. MMS workstations with multiple product and process step processing capability is noted to increase utilization of workstations and potential to use lower performing machines and handicapped workers on workstations due to individual cycle time on stations (Schönemann et al., 2015). Dynamical product flow control increase resistance against disruptions (e.g., machine failure and maintenance) and improve thus production quality. Autonomous independent workstations enable adding or removing stations without effecting other stations making system more scalable and efficient. Worker benefits included are reduced stress by removing station sequence dependency on process steps. (Schönemann et al., 2015; Greschke et al., 2014.)

Discussed disadvantages include implementation of modern flexible and adaptive material transportation system which require large investments, modern transport solutions such as AGV (automated guided vehicles) and integrating them to the material control network. This is seen one of the greatest challenges of implementing MMS due to its complexity. (Schmidtke, Rettmann & Behrendt, 2021; Schönemann et al. 2015.) Quality supervision and assurance can be challenging when multiple stations are able to process same process steps. Matrix production performance highly depends on design of allocations of process steps, buffers and product types to station and layout (Klos et al., 2019; Greschke et al., 2014). Other drawback is high investment cost to implement system with modern technology such as implementing micro-computers and sensors and building the network. MMS configuration requires more space in facility which can cause need for new facility. Larger scale process implementation or production testing still requires halting current production which can change ultimately whole layout and allocation design. (Schönemann et al., 2015; Greschke et al., 2014.) This means testing on manufacturing simulation on the proposed layout is highly recommend. MMS is seen beneficial in manufacturing cases where station cycle time changes notably between stations (Schönemann et al., 2015). Positive impacts of implementing MMS to production scheme where cycle times of stations have been balanced is still missing.

Due to lack of knowledge in research field, there are only few controversies presented. Still, Hoffman et al. (2019) showed that increased flexibility in MMS does not necessary lead to better productivity. In their study, production line resulted in faster throughput time and increased production output rate. In MMS, order tardiness was notably higher than in DMS although MMS performed better in rush orders. They explained that too low production routing flexibility in MMS configuration leaded to decreased performance compared to DMS. Finally, they concluded that production scenarios are suitable for MMS, where either naturally longer production interruptions occur, or the timely delivery of rush orders is important. (Hoffman et al., 2019.) It can be argued that DMS performed better because optimal order sequence for DMS was calculated whereas in case of MMS was not. In other study, presented by Schönemann et al. (2015) system optimizations were not done which resulted better overall performance in MMS.

2.2.3 Reconfigurable manufacturing systems

RMS was developed to combine productivity of DMS and flexibility of flexible manufacturing system (FMS) (Koren & Shpitalni, 2010). Koren et al. (1999 p. 529) defines RMS as *"... is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements. "* . In this context, reconfigurability means ability rearrange or change the parts in manufacturing system cost-effectively (Setchi & Lagos, 2004).

The RMS system can be divided into design of architecture, configuration, and control (Bi, Lang, Shen & Wang, 2008). RMS is constructed with flexibility extending to product family where changes to production can be made with low alternation requirements. This leads to increased scalability and flexibility in production and market demand responsiveness inside product family. (Koren & Shpitalni, 2010.)

Koren, Gu and Guo (2018) present six fundamental characteristics for RMS system and its components. These are essential as they make reconfiguration process quicker and cost-efficient while increasing system responsiveness. The fundamental characteristics are the following:

- Scalability: ability to add, remove or change system parts
- Convertibility: changing functions in system to meet new requirements
- Diagnosability: monitoring product quality and quickly recognise the causes of defects

- Customization: flexible multi-type production inside product family
- Modularity: Separating production functions into autonomous units
- Integrability: easy integration of new modules into system using hardware and software interfaces. (Koren et al., 2018.)

RMS principles are based on fundamental characteristics above. To acquire system scalability, RMS should be designed so that cost-efficient changes can be made for future market demand. Convertibility is achieved when production can be altered effectively to make new products. Adding inspection stations right stages ensure responsive diagnosability against quality problems. Customization is accomplished when system can be configured effectively in the range of product family. Modular units in stages should be capable of reconfiguration of machines and reallocation of tasks to stages where goal is balancing the operational times thus maximising productivity. When integrating new stations in time of reconfiguration, the maintenance policies should be considered. (Koren et al., 2018.) Implementing all principles is challenging task and requires changing whole production structure but should not be excluded. These principles are necessary for optimal RMS system and gathering all benefits with it.

In RMS layout, workstations with same tasks are placed side by side. In every process stage, there are usually more than 1 workstation that can process the exact phase. Stations have crossover connections in every stage meaning the next work package can be processed in any workstation on next stage. Thus, operations and machines are identical in every stage. When considering material handling system, for example gantries can move objects to right station on stage. When process is ready, gantry can pick object and drop it to conveyor where it moves to next station. It is also possible to use only conveyors to handle whole material handling. Currently, the AGVs are studied for suitable solution. (Koren & Shpitalni, 2010; Koren et al., 2018.) The drawback of AGVs is that they make handling process more complex and have higher investment costs.

For production configuration (e.g., how many stations on each stage) and product flow control (e.g., selection of next station) it advised to use mathematical modelling and optimal solution algorithm. Here should be noted that these models should be made adaptable to future reconfigurations. (Andersen, Brunoe, Nielsen & Rösiö, 2017.) Reconfiguration control system need to be fused with open RMS structure with ability to coordinate and control machines (Koren & Shpitalni, 2010). This requires that new reconfiguration objective is divided into individual objectives where decentralized system controller sends commands to autonomous workstations are equipped with own controllers (Bi et al., 2008). The illustrative example of RMS configuration is illustrated below in figure 4.

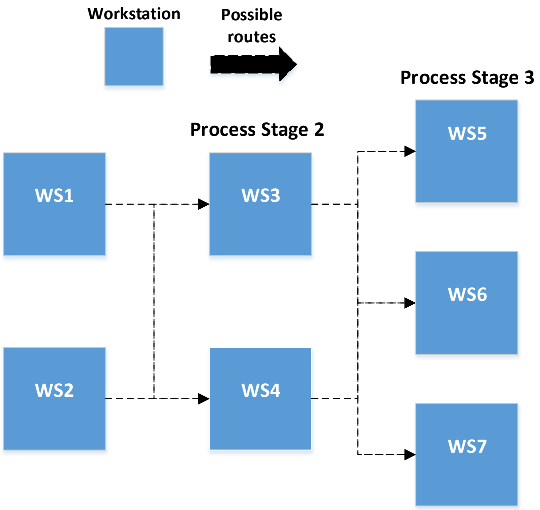


Figure 4. RMS system with crossovers. Adapted from Koren et al. (2018).

The key advantage of RMS is that it combines DMS and FMS benefits meaning high throughput with flexibility to product family. In addition, RMS has ability to quickly response to customer demand changes. Moreover, RMS production capacity and functions can be adjusted, which is not commonly possible for DMS or FMS. RMS provides crossover connections between stages meaning selecting fastest route for product is possible and during station failure, the production does not stop completely. These increases the productivity and reliability of system. (Koren & Shpitalni, 2010.)

The drawback of RMS system is restriction of flexibility to product family. Thus, adding completely new type of product into current configuration is not possible. In addition, if current or new manufacturing system is does not possess RMS six fundamental characteristics, the reconfiguration becomes significantly more challenging. The quality issues can be challenging to track in large multitype production which is why the inspection stations need to be placed on critical stages. (Koren et al., 2018.) Even though RMS has been developed in last century, only in recent years the RMS has received more popularity by manufacturing companies. Because of this, lack of practical guideline for developing and implementing RMS system is still missing. (Andersen et al., 2017.) Still, Koren et al. (2018) notes that RMS and its core features have been successfully implemented by a U.S. automotive manufacturer.

According to Bortolini, Galizia and Mora (2018) extended literature review from 1999 to 2017, majority of published studies related to RMS try to implement characteristics of RMS to current manufacturing system. Research focus on following perspectives of RMS: design of RMS (Bi et al., 2008; Rösiö & Säfsten, 2013; Andersen et al., 2017), fundamental elements (Singh, Gupta S., Mohammad & Gupta P., 2017), flexibility in RMS (ElMaraghy, 2006) and artificial intelligence for RMS (Renzi, Leali, Cavazzuti & Andrisano, 2014; Bortolini et al., 2018). Many studies create guidelines for measuring RMS characteristics such as reconfigurability (Gumasta, Gupta, Benyoucef & Tiwari, 2011), customization (Kombaya, Hamani & Kermad, 2021), convertibility (Maler-Speredelozzi, Koren & Hu, 2003) and adaptability of RMS (Huettemann, Gaffry & Schmitt, 2016). Finally, other fields investigated are optimal reconfiguration points (Huang, Wang, Shang & Yan, 2018) and transition towards sustainability (Khezri, Benderbal & Benyoucef, 2021).

Bortolini, Galizia & Mora (2018) points that research trends in RMS literature can be divided into evaluation of reconfigurability level, analysis of RMS characteristics, performance evaluation, suitable fields for implementation and integration to Industry 4.0. Many studies neglect methods for best practises for designing modern RMS and ways to encourage transition from old system to new RMS system specifically for smaller manufacturers. Computer simulation and experimental testbeds are seen to key encouragements in this matter. Systematic ways to include RMS information to system network are anticipated. (Bortolini et al., 2018.)

Simulation comparisons between RMS and DMS or RMS and MMS were not found. As mentioned earlier, Koren and Shpitalni (2010) states if production is interruption free, DMS would provide better productivity. Based on numeric equations, Freiheit, Shpitalni, Hu and Koren (2003) present that RMS has improved productivity and less throughput variance than DMS where variance depends highly on amount of station failures. Kuzgunkaya and ElMaragphy (2007) concludes based on experimental manufacturing scenario with mathematical model that RMS can sustain high utilization rates throughout the production. RMS was also compared to flexible manufacturing system (FMS) where RMS performed better in view of utilization and justified financial investment (Kuzgunkaya & ElMaragphy, 2007). Controversial studies regarding RMS improvements over DMS were not found.

2.2.4 Comparison of investigated manufacturing systems

Table 1 presents main differences between manufacturing systems according to literature review. In below system differences are compared.

Table 1. System comparison table. Adapted from Koren and Shpitalni (2010).

SYSTEM FEATURES	DMS	RMS	MMS
Main principle	Fixed product line	Reconfiguration	Elimination of cycle time
System structure	Fixed	Changeable	Changeable
Station structure	Fixed	Changeable	Changeable
System focus	Product	Product family	Co-production
Number of stations per process stage	One	One or multiple	Multiple
Production material flow	Unidirectional	Unidirectional with crossovers	Multidirectional
Work packages per station	One	One	Multiple
Production control System	Centralized	Decentralized	Decentralized
Layout	Serial line	Parallel with crossovers	Matrix design
Performance features			
Productivity	Very high	High	High
Scalability	No	Possible	Possible
Product variety flexibility	No	Product family	Co-production
Product system utilization	High -very high	High	High
Robustness against Failures	Low	High	Very high
Characteristics			
Diagnosability	Straightforward	Manageable	Not investigated
Convertibility	Low	Possible	Possible
System modularity	No	Yes	Yes
System integrability	No	Yes	Yes
Costs & implementation			
Cost per part	Low	Medium	Not investigated
Initial investment cost	Reasonable	High	Very high
Implementation difficulty	Simple	Challenging	Very challenging
Technology requirements	Low	Advanced	Very advanced

First, each mentioned manufacturing system has its own focus. DMS aims to cost effective mass production with fixed autonomous product lines. RMS is based on its six reconfigurations principles providing high productivity with necessary responsiveness and flexibility to fluctuating demand. MMS focuses on eliminating constant cycle time with independent station times with dynamic production flow control. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Shpitalni, 2010.)

Today, changeable system and station structure is needed for adjusting production capacity and functions to changing customer demand (Koren et al., 2018). MMS and RMS possess this, however DMS does not. This emphasises careful analysis of market and careful design of DMS structure. Moreover, DMS is not capable of rearranging, adding, or removing workstations, contrary to RMS and MMS where station structure and its functions is possible to change. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Shpitalni, 2010; Koren et al., 2018.)

DMS based product line focuses producing one or few products efficiently with high volumes. RMS can change the production focus between one or family of products increasing responsiveness to market demand. MMS goes even further where is it possible to produce one or multiple variants of products belonging to product family or even completely new type of product. Product line can only have one workstation per stage as adding capacity to production requires building new line. This means that smaller capacity changes are not possible for DMS. RMS can have one or multiple stations per stage meaning flexible capacity adjustments. Also, not only MMS include more than one workstation that can process the exact task and product type, but stations can be placed any location in layout, not necessarily next to each other as in RMS. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Shpitalni, 2010; Koren et al., 2018.)

Production material flow of DMS is one-way where products always proceed into next station. This simplifies the material flow planning and side by side stations enable fast transportation. However, in RMS the product can be transferred to any of the stations on next process step which are placed as group in parallel. Thus, the design of transportation system case can be challenging although combination of spine gantries with cell gantries is seen promising solutions in transportation. The MMS makes design of transportation system even more complex as is it necessary that product can be delivered any of the stations in production system. This means transportation connections between every station bidirectionally. Here, AGVs has been seen only compatible solution for transportation now. The other unique feature of MMS is ability to process multiple process steps and different product types at same station unlike RMS and DMS both limited to one work package. This increases available stations and thus decreasing blockings. Still, RMS station can process any type of products inside product family, unlike product line where separate line for any new product is required. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Shpitalni, 2010; Koren et al., 2018.)

Production control system in RMS and MMS are based on decentralized control policy as opposed to DMS centralized control policy. Decentralized control is based on hardware located usually in workstations with open-architecture and easily configured control interface making even quick production modifications possible. Still, designing and constructing the decentralized control system needs careful design and experienced workers. The layout also differs on each manufacturing system, DMS is based on serial product line layout, RMS utilizes product line with parallel crossovers and MMS used its own unique matrix shaped design. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Shpitalni, 2010; Koren et al., 2018.)

The differences between performance features among the manufacturing systems can be found. DMS line has been known for its high productivity capability. It is presented that RMS productivity can be even higher than DMS if the reliability of stations (e.g., station failures) is low. If high, the DMS is presented to have higher productivity. (Koren & Shpitalni, 2010.) According to Hoffmann et al. (2019) simulation test, the productivity of traditional line is also higher than MMS. Moreover, if WIP level of production increases it can significantly decrease the productivity of MMS. Scalability of production capacity is a challenge for DMS as removing stations from old line is usually impossible and adding resources requires whole new line. Both RMS and MMS handles capacity changes without problems because both production system structure and station structure are changeable as mentioned earlier. Moreover, both provide needed flexibility to process product varieties unlike DMS, although RMS is restricted into product family. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Sphitalni, 2010; Koren et al., 2018; Hoffmann et al., 2019.)

RMS is presented to have consistent high station utilization according to Kuzgunkaya and ElMaraghy (2007) numeric model where RMS performance were analysed. In case of DMS utilization rate, the results are divided from high to very high. The difference depends on the fact that if there is possibility to balance production tasks evenly. Hoffman et al. (2019) presented very high utilization rate for balanced DMS at 96% and Schönemann et al. (2015) showed mediocre results at 57% at unbalanced line. The authors also got mixed results for MMS as Hoffman et al. (2019) stated at average 66% and Schönemann et al. (2015) 86%. Here, the main differences seem to be caused by capability to change product operations order and number of machines that able to process exact task.

When considering the robustness of production, station ability to handle failures, DMS line is most vulnerable because breakdown of station or transporting line stops production where the incident has happened (Koren & Shpitalni 2010). Klos et al. (2019) notes MMS to be resistant to breakdowns as it provides stations which can process multiple tasks and product variants. RMS is also capable of providing multiple stations with same tasks, but in case where the transportation system (e.g., spine gantry) breaks, there is challenge to transport product into next processing stage because all capable stations for specific tasks are grouped on same location. The damage is smaller on MMS system where multiple AVGs are utilized and capable of transporting products to any station. (Koren & Sphitalni 2010; Schönemann et al. 2015.)

A comparison can also be made using other characteristics of the production such as diagnosability, modularity and integrability which were defined earlier. RMS aim to bring all these characteristics into production as they are part of six fundamental characteristics to build reconfigurable system. Some of these have less recognition in DMS and MMS. Still, integrating diagnosability policy into DMS should be rather uncomplex due to separate unidirectional product lines. In literature, there are no investigation about production diagnosis in case of MMS. However, it can be noted that detecting product quality problems afterwards and tracking can be challenging because of complex product routing system. In convertibility perspective, it is possible to change machine or station functions in RMS and MMS, but again in DMS not possible. This means adapting to new product requirements requires redesigning the line. Both MMS and RMS are modularly structured meaning altering them according to production schemes is achievable while DMS provides only fixed structure. In addition, the integration of new components into the system is smoother on decentralized control system possessed by RMS and MMS than centralized one in DMS although the designing and implementation of the system may prove difficult. (Grescke et al. 2014; Koren & Shpitalni 2010; Schönemann et al. 2015.)

When considering the financial and implementation aspects, DMS provides the easiest and most cost-efficient solution. Cost-per-part is low on DMS when production capacity is fully utilized, whereas in RMS case it is presented to be in acceptable level if later variable demand and future products variants is considered. This is not investigated in MMS. However, co-production ability in MMS can justify increased costs. (May, Schmidt, Kuhnle, Stricker & Lanza, 2021; Koren & Shpitalni, 2010.) Initial investment cost in DMS is reasonable, RMS requires high investments and MMS very high because of AGV transportations system and high-level of automation. MMS is also noted to require state-of-art manufacturing technology including cyber physical systems, autonomous industrial robots and AGVs to fully utilize its potential. (Koren and Shpitalni, 2010; Schönemann et al., 2015.)

2.3 Simulation modeling

Simulation modeling has become very popular design and analysis tool in recent years in various industries. According to multiple reports, simulation software market has grown substantially in recent years, and it is forecasted to grow also in upcoming years. In USA, IndustryARC (2021) has forecasted simulation software market size growing to 20 billion dollars by 2026 and compound annual growth rate (GAGR) of 17%. Currently, global simulation software market size is 7.8 billion US dollars. In the beginning, simulation was used to examine and adjust current processes in manufacturing operations but now have extended to utilizing in testing new processes and predicting possible future problems in production. (Mordor Intelligence, 2021.) Automotive, aerospace, defence, electrical and electronics industries has been predicted to grow fastest in simulation software market (Allied Market Research, 2018). Thus, simulation is becoming an important tool for manufacturing companies for analysing production processes. This research also utilizes simulation modeling for comparing and evaluating manufacturing systems performance. In below, simulation modeling is defined and compared to analytical modelling. Finally current methods for simulation modelling are presented.

2.3.1 Definition of simulation modeling

Academic dictionary has defined *modeling* as “The devising or use of abstract or mathematical models to assist calculations and predictions” (MOT Oxford Dictionary of English). Modeling aims to build simplified copy from real-world system into computer model where system and its components can be experiment freely without a risk damaging the original one. Because of limited computer memory, processing capacity and time, every modeling designer must choose which system components should be modeled. (Borshchev, 2013.) On same dictionary, *simulation* is described by “Imitation of a situation or process” (MOT Oxford Dictionary of English 2021). Winsber (2019) presents computer simulation as “a program that is run on a computer and that uses step-by-step methods to explore the approximate behavior of a mathematical model.” Computer simulation model is thus executable model where system’s dynamic functions are executed according to model rules. These rules that let system proceed into next stage can depend on for example system's flow chart, conditions on system environment or time-based system function schedules. Computer simulations include usually visual presentation of model with graphical and textual elements. (Borshchev, 2013.)

Simulation modeling is building virtual model from object of study and imitating it with the modeling rules to analyse its dynamic behaviour. With simulation model it is easier to understand the structure of the system and its relationship with components. Moreover, it possible to test system in different environmental scenarios and progress on timeline. (Borshchev, 2013.)

As mentioned earlier, the greatest for benefit for virtual simulation models is ability to test and modify real-world systems or completely new systems without ruining the real system. In perspective of manufacturing, this means making a virtual copy of examined production system and analysing its operations and functions in simulation. Moreover, performance data of model can be stored to further analyse the system and its performance.

2.3.2 Simulation modeling and analytical modeling

Modern simulation modeling provides many advantages when compared to traditional analytical modeling which has been used in for decades. These advantages have been important factor from moving from analytical modeling to simulation modeling particularly in cases where model have had dynamical properties. Spreadsheet modeling is most used method for analytical modelling. Spreadsheet modelling is particularly used in Microsoft Excel software. In spreadsheet modeling, inputs of model are implemented on "cells" and results are presented on other cells. Cells include formulas and other functions which form information to model. (Borshchev, 2013.) For example, one group of cells can include production times while other cells can form this into production rate with production performance formulas which can finally be illustrated on visual graph.

The problem for analytic based models and its formula-based functions is modeling dynamic systems. Dynamic models include non-linear functions, time-based events, causal relationships between inputs, and combination of all these in growing numbers. (Borshchev, 2013.) Best way to describe this is considering modelling a production line. Production line includes various moving objects with cause-and-effect relationships in different times and locations. The decision for moving product to available workstation in particular time depends on other events occurred before and require analysing the events' sequence. The example shows that modelling this on Excel spreadsheet is impossible or at least extremely difficult and time consuming. Simulation modeling provides necessary functions to accomplish this. In conclusion, analytical modeling is preferred when illustrating static relationships between data and simulation modelling is desirable when examining dynamic behaviour of object or system (Borshchev, 2013).

2.3.3 Simulation methods: discrete-event, agent based, system dynamics

Simulation modeling can be conducted using one or more simulation methods. Currently, there are three types of simulation method. These are discrete-event, agent-based and system dynamics simulation. Discrete-event simulation means simulating real-world system dynamics based on sequence of events in time (Babulak & Wang, 2010). The key is that activities in simulation are placed in sequence which occur in chronological order. Moreover, variables in simulation change only on specific time points. Here, model is constructed from objects, its features, simulation actions and actions duration times. (Banks, Carson, Nelson & Nicol, 2010.) Discrete-event simulation is most used simulation method currently in various industries. Babulak and Wang (2010) notes that discrete event simulation is most capable decision support tool in manufacturing globally now and in future. Discrete event method is commonly used for modeling operational level or micro level of system with high detail (Borshchev, 2013).

Agent-based simulation is the newest method from the three developed in early 2000s. While discrete-event and system dynamics focus on top-down modelling viewpoint, agent-based start building model from model's objects describing their characteristics and activities. This is preferable when it is difficult to understand system model in big picture or relationships between objects. Agents, the entities of agent-based model, include numerous parameters or other form of information to describe its characteristics and state charts or similar tools to illustrate agent's behaviour. Agents can be placed (and usually used) in dynamical environment built by using discrete-event or system dynamics methods. In environment, agents can interact with each other forming cause-and-effect relationships and dependencies finally building whole system behaviour. Agent-based simulation is particularly used for building the behaviour of entities in system from microlevel objects to larger whole entities of multiple components. (Borshchev, 2013.)

System Dynamics (i.e., continuous simulation) method was invented in 1950s and it is based on modelling structural factors of studied system. Moreover, it emphasises the causal relationships between elements in which connections between elements express dependencies. It is a closed system that itself determines its own behaviour. The logic behind system dynamics view is to think system activities and decisions as general phenomena which then have possible effect to other phenomena. System dynamics generally describes systems in strategic level such as social systems, ecosystems, or economics. (Borshchev, 2013.) System dynamic is practical tool when describing dynamic relationships between elements where one element presents larger system e.g., operating time of product when building a product life cycle.

2.3.4 Manufacturing simulations

In manufacturing industry, simulation has become very capable design and analysis tool. Use cases include simulating material flow, production layout, manufacturing processes, and even worker ergonomics of manufacturing system (Mourtzis, 2020). Simulation can be used in many sections of manufacturing for:

- Testing new operations, equipment, facilities, strategies, and policies.
- Improving current system or its components by tracing current or potential problems, finding opportunities for development and configuring the old system using performance metrics.
- Measuring the state of real system and benchmarking.
- Finding most effective solutions for implemented equipment or policies.
- As computer-aided tool for assisting in on specific tasks e.g., production planning. (Mourtzis, 2020; Babulak & Wang, 2010.)

As simulation possibilities extend widely in organisation, management in many levels can utilize it (Babulak & Wang, 2010). Benefits and reasons for utilizing simulation contains:

- Low cost and quick way to test and analyse current or future system when compared to real-world methods. Moreover, it provides risk free experimentation for possible investments. Even very accurate simulations are possible reflecting real system more realistically. However, this requires more time and simulation experience.
- Easier to perceive system as a whole and pinpoint dependencies and relationships between system resources. (Mourtzis, 2020; Mourtzis, Doukas & Bernidaki, 2014.)

Challenges of manufacturing simulation contains:

- More complex and extensive simulation models require more computational power thus meaning more expensive and newer CPUs and GPUs.

- Commonly simulation software provides limited object library and tools. In addition, they are usually focused on specific resources and functions.
- Each simulation software is built based on its own data type and domain thus combining models or sharing data between them is difficult.
- In manufacturers point of view, collecting continuously data from real factory requires management and supervision. This is expensive, requires expertise and is hard to implement. (Mourtzis et al., 2014.)

3 Research Methods

This chapter explains the research methodology, research steps, data gathering, research tools and results validity analysis. The thesis utilizes research onion guideline presented by Saunders, Lewis and Thornhill (2007) to form appropriate framework for research and its goals.

3.1 Research methodology

Research onion describe the steps to needed to formulate appropriate research method. It includes research philosophy, research approach, research strategy, time horizon, and data collection methods. Research philosophy tells what objectives research have and type of knowledge searched. Philosophies can be divided between positivism and constructionism. Main difference is that positivism believes phenomena exists identical between research subjects whereas constructionism consider phenomena is affected by the subject group. (UKEssays 2018.) This research believes in positivism where results of this research are observable and generalizable principles when comparing differences between manufacturing systems. Still, the research's simulation model has multiple parameters and functions which affect the results, but these will be further analysed in critical thinking of results section.

Research approach describes how research theory is constructed and corresponds to what the results are based on. One of two main approaches is deductive where hypothesis is constructed from existing theory and research constructed then try to confirm it. Other one, inductive approach, aim to develop theory from results obtained in research. (Saunders et al., 2007,117-119; UKEssays, 2018.) As this research focuses on gathering information from simulation models of manufacturing systems and comparing results with hypothesis based on literature review, the deductive approach is selected.

Research strategy describe the means of how research is conducted. There are multiple ways to execute the research including experiment, case study or literature review. Strategy can also include more than one approach (UKEssays, 2018; Saunders et al., 2007, p. 135-136.) The experimental research is chosen because research examines selected manufacturing systems in controlled simulation environment and analyse them against existing expectations about manufacturing performance.

The strategy also includes choices about using mono-, multi- or mixed methods for collecting data and analysing it. Data used can be quantitative (numerical) or qualitative (non-numerical) or both. (Saunders et al., 2007, p. 145-146.) This research collects only quantitative data from the simulation experiment and analyse data with statistics and performance indicators thus belonging to mono method strategy.

When concerning the time horizon for research completion, the choices are either cross-sectional horizon or longitudinal horizon. In cross-sectional horizon, the research is interested in examining phenomena in particular time whereas longitudinal gathers data from different time intervals. (Saunders et al., 2007, p. 148.) The research data will be gathered in cross-sectional time horizon because the study will be simulation based where results does not change due to time.

3.2 Research steps

This research presents experimental simulation study of the following manufacturing systems: MMS, RMS and DMS. The goal of the research is to measure each system performance in changing manufacturing scenarios. Measurement of performance is accomplished with performance indicators calculated from raw simulation data which measure one of the following selected performance perspectives: efficiency, effectiveness, delivery, and flexibility. With performance indicators the systems are compared and evaluated to answer research questions. Research can be divided into following five steps:

1. Conducting literature review from manufacturing systems characteristics and framework.
2. Finding and selecting appropriate key performance indicators for measuring different performance perspectives.
3. Building simulation model for each manufacturing system and designing manufacturing scenarios.
4. Observing systems during simulation and importing simulation data into MS Excel spreadsheets. Here data is filtered and organized to calculate KPIs and presenting them in scenario data tables.
5. Analysing results, comparing simulation results with existing research, and answering the research questions and hypothesis.

3.3 Data collection

Through the research, multiple type of data was gathered. Data collected can divided into primary data and secondary data. Primary data is information that is gathered and analysed by researcher whereas secondary data is information collected and processed by someone else (Sachdeva, 2008, p. 109-113). Type of primary data collected in this study are numerical data from manufacturing simulation including manufacturing scenario results, statistics, and performance indicators. Secondary data in this study consists of literature review section where data gathering focuses on investigated manufacturing systems' layout, characteristics and manufacturing performance tests and comparisons. This data is collected from multiple research articles from manufacturing focused journals and research articles. The aim for article timeline is from 2010 to 2021. Still, some articles before 2010 that was seen crucial for gaining knowledge from manufacturing systems was selected.

In addition, "snowballing" method was utilized particularly in case of finding knowledge from MMS systems. This means finding new sources of information from key research articles (Breda University 2022).

3.4 Data analysis

For analysis, simulation data and key performance indicators are utilized. The viewpoints of simulation meters are whole production system, workstations, and products. For example, research does not measure the performance of transportation operations. The unit of analysis is manufacturing line which will be compared with other production lines. Data analysis focuses on interpreting calculated KPIs comparing results between systems and scenarios. Moreover, results are reflected to simulation comparisons found in literature review.

3.5 Research tools

Because this research focus heavily on simulation experiment, the selection of appropriate simulation software is important. Particularly modeling MMS requires specific functions from software to reflect all its characteristics. At the start of the research requirements of simulation software were listed. First, 2D-simulation model was found to be sufficient instead of 3D-simulation for simulating systems at moderate level. This enables faster simulation process due to saved computing power and memory which is important because research simulate longer time scales multiple times. Second, to simulate more complex MMS system both discrete-event and agent-based simulation methods are needed. Third, to ensure needed operational functions for constructing manufacturing models, ability to program simulation commands is required. Here, the programming language preferred is Java. Three investigated simulation software with student or free access were AnyLogic, Visual Components, and Tecnomatix Plant Simulation. When considering first requirement Visual is limited to 3D simulation. Moreover, the software requires substantial amount of computing power and memory (Visual Components 2022). Tecnomatix software offers both 3D and 2D modelling possibility but uses SimTalk programming language (Tecnomatix Plant Simulation 2018). Anylogic was favoured as it does not require substantial amount of computing power or memory and provides both 3D and 2D -simulation with Java programming for custom simulation commands (Anylogic 2022). Fulfilling requirements, Anylogic was seen most appropriate simulation software for simulating investigated manufacturing systems. Anylogic can also extract raw data to Microsoft Excel for further data processing.

Thus, selected computer softwares to conduct this research are Anylogic simulation software and Microsoft Excel. All production simulation were accomplished using 2D simulation presented on next chapter. With Anylogic, different manufacturing systems were constructed into virtual models which was then observed to produce specific number of products. Moreover, some graphs and parameters were implemented to measure manufacturing performance. Microsoft Excel was primary used to convert simulation data into KPIs and scenario summary tables to observe and compare performance results between manufacturing systems.

3.6 Results validity and reliability

Reliability and validity analysis of conducted research are ways to analyse research trustworthiness and result correctness. Reliability measures the consistency of results when experiments are reproduced in same environment with same participants. Validity on the contrary measures the accuracy of research results. (Adams et al., 2014). The considerations of these two are crucial for measuring correctly and rightfully.

Virtual simulation of manufacturing system brings its benefits and drawbacks when concerning reliability and validity. In case of reliability, simulation experiments are easily reproducible and testing conditions does not change. In addition, other researchers can replicate the model to test it independently. Simulation enables changing values of model variables to measure result consistency. For example, processing time of product or production volume can be changed to measure effect to production performance.

The most significant challenge to research reliability in simulation study is that real-world implementation results are most likely different even if they are built with same conditions. The reason for this is the affecting factors to measurement that cannot be modeled or there is no knowledge of them influencing the results.

When evaluating validity, it is crucial to know how to measure exact concept. This implies to relevant and existing theory in the field. Because this study measures performance of different production systems, the study implements KPIs which are based on ISO 22400 standard. This ensures right measurement basis for measuring investigated competitive priorities. The research also compares results to existing knowledge in literature and simulation experiments to evaluate correctness.

The threat to result validity is defining realistic production scenario inputs and their variation. For example, defining required time for fixing breakdown in workstation. Research solves this partially by simulation inputs which are relatively close to other simulation experiments. However, the greater validity threat in this study is manufacturing functions and operations which are not modeled in simulation. As mentioned, this study does not simulate transportation system in production, but which will have notable effect on performance measurement results. For example, transportation times in MMS is most likely higher than RMS or DMS due to longer distance between stations and increased amount of transportation need for producing product.

In perspective of internal validity, implemented simulation functions, inputs and scenarios affect substantially to results. This means that same logic, inputs and objectives behind operations and parameters must be placed in all test subjects, in this case manufacturing systems. For example, product routing strategy must be same in all systems. In this case, this research calculates minimum time till processing based on products in buffer and station. In perspective of external validity, results can substantially vary from real-world system because of environmental factors, restrictions, and correct implementation level.

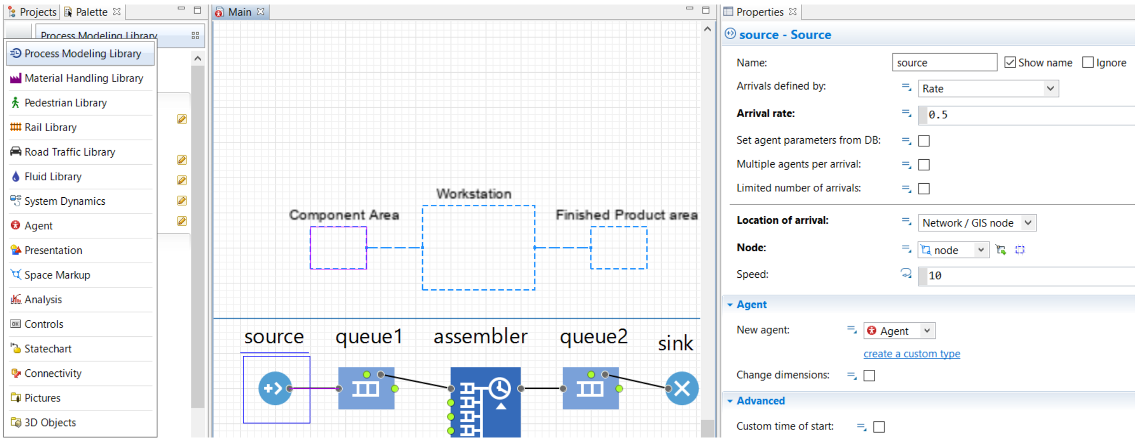
4 Simulation model and KPIs

4.1 Anylogic simulation tool

Anylogic is modern multimethod computer simulation software. This means Anylogic is capable of using more than one simulation methods simultaneously. As mentioned earlier, three simulation methods were discrete-event, agent-based and system dynamics. Anylogic provides also different modeling methods such as flowcharts and state charts. With Anylogic, it is possible to build models and simulate various industry fields including manufacturing, transportation, and supply chain. (Anylogic 2021a; Anylogic 2021b.)

In research's model, discrete-event simulation will be utilized modeling required production operations. Moreover, agent-based objects including multiple parameters is used to implement information into simulation model objects. System-dynamics method will not be used in this research as aforementioned methods is seen sufficient.

Next, the fundamental functions of simulation software are briefly introduced. Functions can be divided into three software windows where all modifications to model are done. The three function windows are palette window, model window and properties window.



source - Source

Name: source ☑ Show name ☐ Ignore
Arrivals defined by: Rate
Arrival rate: 0.5
Set agent parameters from DB: ☐
Multiple agents per arrival: ☐
Limited number of arrivals: ☐
Location of arrival: Network / GIS node
Node: node
Speed: 10

Agent

New agent: Agent
create a custom type
Change dimensions: ☐

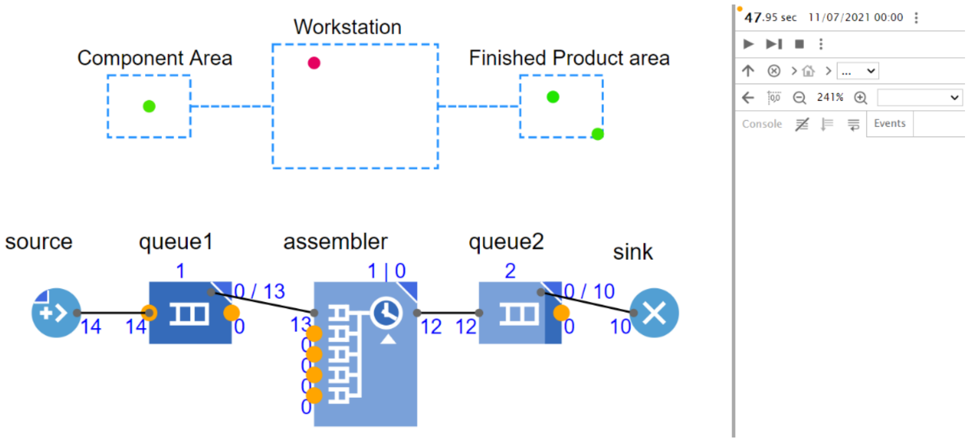
Advanced

Custom time of start: ☐

Picture 1. Anylogic software: Tools and layout.

Picture 1 illustrates the Anylogic software layout. The window on left is called palette. Palette include of all necessary tools and functions to build a simulation model. It includes different libraries e.g., process modeling, material handling and so forth. Here, the process modeling, agent, and analysis libraries were used most. Libraries are divided by their use purpose and functionality. For example, process modeling library include all operation modeling blocks. These utilize agents (i.e., entities with implemented parameters) which act as objects and resources on model (e.g., products and transporters). Above process blocks, there are space markup tools which execute different action mainly focused on agents' location. For example, creating agents on desired area on model and marking paths that resources take are some operations. These function blocks are rectangular nodes and path arrows. (AnyLogic Help, 2021a.) Creating agents with specific attributes, building process flow chart with process library blocks, and marking each object and resource location and flow with space markups are fundamentals tools which combined can be build the virtual model and simulation operations.

The right window of simulation software is called properties which can be used to configure model objects, resources, process blocks, and model layout. This can also be called settings window as all changes to current model can be altered here. (AnyLogic Help 2021b.) On the centre of Anylogic software window is model and simulation layout which show the process flow chart and simulation visualisation. Before mentioned library blocks are dragged from model library into this to take effect. When required function blocks and simulation objects are placed, the main layout show their operations and animations on simulation presentation area in simulation run. Simulation run is illustrated on picture 2 below.



Picture 2. Anylogic: Simulation run

4.2 Simulation assumptions and manufacturing scenario parameters

Simulation models constructed in this research include predetermined simulation input parameters. Moreover, some simulation limitations must be made to meet research time schedule. Assumptions are linked to functions of manufacturing model and production method principles. First, all manufacturing models work in continuous production system flow around the clock. Second, minor production stops such as breaks or shift changes are not simulated. Third, simulation model does not include transportation system, logistics functions or employer behaviour as model focus on performance in wider whole production system view and effectiveness of manufacturing system layout. The order of production tasks is always same meaning there are no interchangeability between production tasks. For example, production step three cannot be executed on a product until product has gone through process step two. All production orders have same priority; thus, rush orders are not included. When product has opportunity to choose its next workstation, same selection strategy will be used in all systems. This means that MMS and RMS use same selection criteria. DMS does not include opportunity for workstation selection because in every stage there is only one station. The criteria will be based on shortest waiting time till processing which include calculating time needed to process all products on workstation buffer and on station itself. In each simulation manufacturing scenario, the produced product volume will be predetermined based on scenario inputs. These and other simulation input parameters is presented in table 2.

Simulation consists of production of two product types: product 1 and product 2. Both products will be manufactured evenly. Product 1 include 5 process steps and product 2 consists of 4 steps. Manufacturing scenarios are simulated 10 or 3 times depending on scenario to gather more accurate performance information. The reason why more simulation runs are not executed because Anylogic Personal Learning Edition has limited functions and requires executing every simulation run manually in order to store simulation raw data into Excel. Models include random number generator which will be used to demonstrate fluctuating demand and unexpected station failures for example. Production volume differentiate by each scenario to simulate longer and shorter time scales. Maximum workstation buffer size is ten and minimum of 1 depending on scenario. The amount of work packages (i.e., process steps) and number of workstations remain the same in all scenarios.

Simulation includes unexpected failures or maintenances which will occur on all workstations. Time between failures is defined as mean time between failures (MTBF) whereas time to repair the problem as mean time to repair (MTTR). Workstation maintenance schedule is presented mean time between maintenance (MTBM) and time needed for maintenance as maintenance time (MT). These simulate production stops which are used to measure breakdown resistance and flexibility of system. MTBF and MTBM is calculated using truncated normal distribution where minimum and maximum values are specified so that failure does not occur too early on production or at all. Mean illustrate the most potential time failure to occur and standard deviation the spread of failure times. MTTR and MT is calculated using uniform normal distribution reflecting both shorter and longer station downtimes evenly. Product order interarrival time reflects the fluctuation of demand where truncated normal distribution is used. However, order arrival time does not change in scenarios. Reason is to demonstrate high-volume production where the manufacturing systems is utilized at full capacity.

Table 2. Simulation inputs 1. N symbolize normal distribution.

Production Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**
Number of product types	2	2	2
Product type distribution	Even	Even	Even
Production Volume (units)	1000	5000	1000
Buffer Size (units)	1	5	1
Number of work packages (WP)	5	5	5
Number of workstations (WS)	10	10	10
Failure MTTF (minutes) Truncated N (min,max,mean,standard deviation)	-	N (5000,15000, 10000,1000)	N (100,600, 300,50)
Repair MTTR (minutes) Uniform N (min,max)	-	N (10,120)	N (5,30)
Maintenance MTTM Truncated N (min,max,mean,standard deviation)	-	-	N (4000,8000, 6000,300)
Maintenance Time Uniform N (min,max)	-	-	N (30,60)
Interarrival time (minutes) Truncated N (min,max,mean,standard deviation)	N (1,50,20,5)	N (1,50,20,5)	N (1,50,20,5)
Simulation runs	10	10	10

Table 3 illustrates processing times for each production tasks. Manufacturing of product one contains additional process step when compared to product two. Processing times differ on process stage and between product type. Varying process times aim to reflect unbalanced cycle times between stations common in real systems. Processing times is calculated using normal distribution to bring realistic variation between every processing time. Processing time input values does not change according to scenario. This is meant to highlight differences between scenario results when simulation inputs are changed.

Table 3. Simulation inputs 2. Processing times.

Processing times for work packages (minutes) Normally Distributed N (time,1min)	**Product1**	**Product2**
WP 1	28	32
WP 2	24	36
WP 3	35	29
WP 4	33	38
WP 5	30	-
Total Processing time	150	135

Station setup times presented in table 4 concerns only MMS because RMS and DMS process only one type of work package per station. During setup time, workstation adjust and change necessary tools each time when work package differs from previous one. If it is same as previous, there is no need for changes and thus no setup time required. The setup time is intentionally slightly higher than actual one to make it easier to see its effect on MMS output. Setup time is approximately 16% from average processing time.

Table 4. Setup times for MMS. RMS and DMS do not have setup time.

Conditions for set-up time in workstation	**Time (min)**
If same process task as previous one	0
If other process task than previous one	5

4.3 Simulation models

4.3.1 DMS Model

Dedicated manufacturing system model is based on product line principles. In model workstations are placed according to sequence of product processing stages. System can produce two different products. Model includes two product lines where both types of products can be produced in both lines. Each station contains necessary tools to perform the specified work step. Production flow is unidirectional. Workstation includes buffer, station, and output buffer. When order arrives, product identification code (ID) is created, and product instance moved to waiting area. When first station is free or buffer has space, product is moved to first station. When product is processed, it moves to output buffer. When station 2 is available product is moved to process stage 2. Finally, when product has been processed in all process stages, it is transported to finished product area.

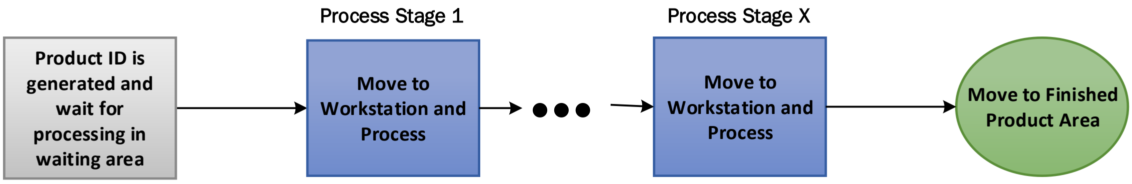


Figure 5. DMS process flow chart.

4.3.2 MMS model

Matrix-structured layout is the most complex one of investigated manufacturing systems. MMS requires unique product routing and workstation placement. As mentioned in literature chapter, the production starts from finding suitable workstation meaning possessing capability to process needed work package. If multiple suitable stations are available, selection depends on product routing strategy. In the model, the shortest time till processing is used. Workstations are placed into matrix shape layout. Because product routing is not predetermined, every station is arranged so that it is possible to transport product into any of the stations.

In model, process flow chart follows Schöneman et al. (2015) and Grescke et al. (2014) proposed models with some modifications. This is because discrete-event type simulation method which was selected to simulate all manufacturing systems in research. Schönemann et al. (2015) used agent-based modelling which is seen more appropriate for simulating MMS. However, agent-based modelling requires more experience and skills from simulation modeling and advanced Java-programming.

Manufacturing process flow logic is described in figure 8. Here, production starts from creating identification number (ID) for product instance which waits processing in specified waiting area. Products must wait in waiting area until suitable workstation with needed tools for processing is available. When workstation is available, simulation model verify which compatible workstations are available and which station has minimum time till processing (MTTP). When optimal workstation is found, the product is transported to selected workstation either for processing or to wait in buffer. Afterwards, when station processed the product, model checks if next required work package can be processed in same workstation (WS). Otherwise, product is placed to output buffer waiting for the model to find next available station. This differs from Schönemann et al. (2015) model which prioritise finding next station first. Processing next process phase in same station (if possible) reduces transportation capacity load. When station has processed the final work package on product and product has been moved to output buffer, model checks if product is ready. If this is the case, product is transported to finished product area.

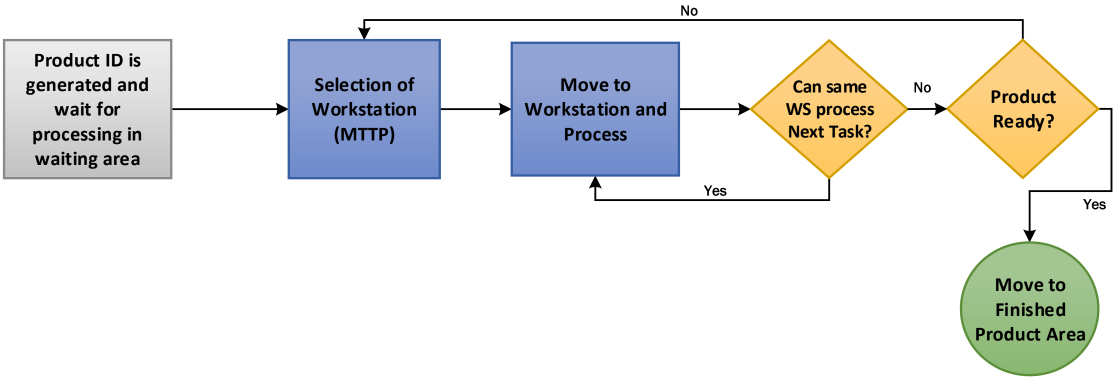


Figure 6. MMS process flow chart.

4.3.3 RMS model

Reconfigurable manufacturing system layout resembles DMS. The difference is each process stage can include multiple stations in RMS. Stations in one process stage is placed in parallel where executed tasks are the same. Moreover, they are arranged according to the process steps of the product to be manufactured.

Production starts from waiting for available station in waiting area. If multiple stations are available in first process stage, the decision is based on minimum time till processing (MTTP). Otherwise, product selects first available station if other stations are busy. Product then moves first to workstation buffer and then for processing. When processing is finished, product is moved to output buffer where selection of station for next process stage is made. Finally, when product is finished, it is transported to finished product area. As mentioned, each process stage can contain multiple stations and number of stations can differ between stages. In research simulation model, the number of stations in each work stage is based on which formation provides best average utilization of workstations according to simulation run analysis.

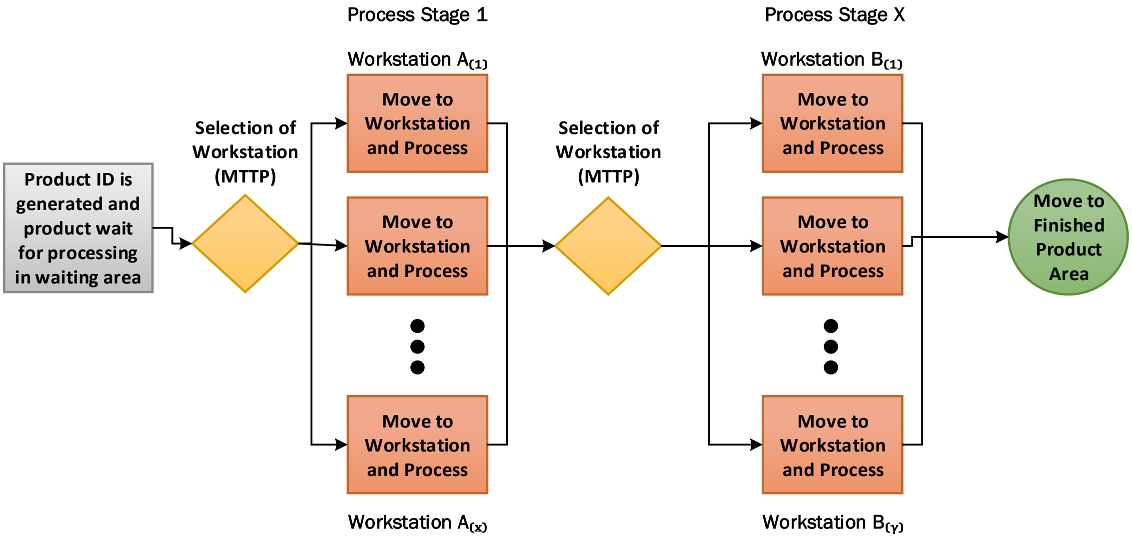


Figure 7. RMS process flow chart.

4.4 Selection of key performance indicators

For performance evaluation and comparison between manufacturing systems, key performance indicators (KPIs) are needed. In research, these measure production in both station and whole production level. The goal is to find suitable metrics to assess the level of performance from different performance perspectives selected to this research. These were production efficiency, effectiveness, delivery, and flexibility. Efficiency measures how well resources are utilized in production and effectiveness evaluate resource level to successfully perform production tasks (Oxford Reference, 2022). These combined measures productivity. Delivery measures the speed and consistency of production with time-based indicators. Lastly, production flexibility in this study measure robustness and adaptiveness of system. This means how system withstands various disturbances, capacity, and workload changes. Flexibility can also mean ability to handle other changes in production, but research has limited it before mentioned areas.

Majority of selected indicators are based on international ISO 22400 standard which define and describe performance indicators used in manufacturing operations globally in multiple industrial fields. The standard presents performance indicators with their formula, included sub elements and suitable manufacturing fields. (ISO, 2014.) Indicators selected are mostly presented by Kang et al. (2016) who gathered all KPIs created by ISO organization and then divided them into comprehensive, basic, and supporting KPIs. Comprehensive indicators are formed from basic indicators and focus commonly for evaluating whole production system. Basic KPIs can be categorized into productivity, quality, and maintenance sections. Supporting KPIs include time and quality sections. KPIs presented measures productivity from both efficiency and effectiveness point of view. Time related indicators measures both production and maintenance field. (Kang et al., 2016.) ISO standard does not provide indicators for measuring manufacturing flexibility. Flexibility is harder to measure because of its extensive viewpoint considering multiple factors. Still, for example Hoffman et al. (2019) analyses and measures flexibility via operational and routing flexibility. Operational flexibility requires interchangeability in production task order which is not investigated in this research. Routing flexibility however can be measured investigating the effect of production failures and repair times. Moreover, they use WIP (work-in-process) as one flexibility indicator. (Hoffman et al., 2019.) Schönemann et al. (2015) and Klos et al. (2019) evaluate MMS robustness simulating machine breakdowns. Thus, failure occurrence with repair times and WIP will be used in this research to measure flexibility in view of robustness of system and routing flexibility. Flexibility will be measured by implementing appropriate scenarios to measure this rather than using key performance indicators where comprehensive indicators are not available. WIP is exception as it will be used also measuring production effectiveness.

Indicators selected are based on basic level KPIs and supporting KPIs. To quickly see overall results of system in each scenario, the overall statistics presented in table 5 was implemented. This includes production output, total time, buffer capacity, total downtime, average station utilization, average throughput time and total setup time. These can be seen in table below.

Table 5. Overall statistics table. Describes overall result of system in specific scenario.

Overall statistics
Production output
Total time (min)
Buffer capacity
Total downtime (min)
Average station utilization
Average Throughput Time (min)
Total setup time per product (min)

Next, key performance indicators used in this research will be introduced. The following productivity, delivery, and flexibility indicators are gathered from Kang et al. (2016) based on ISO 22400 standard, Klos et al. (2019), Schönemann et al. (2015) and Hoffman et al. (2019). Indicators which measure productivity were categorized into production efficiency and effectiveness sections, time related indicators into manufacturing delivery section, and indicators related to testing system robustness and adaptiveness into production flexibility section. Tables 6 and 7 shows the indicators selected.

Selected indicators for measuring efficiency are:

- Availability: measures ratio between actual usage time for work resource and total manufacturing time. This indicates how much time workstation uses for processing tasks versus setup-time, station delays and station downtime.
- Allocation efficiency: actual work time compared to planned time. This determine are enough of products routed to workstation.
- Technical efficiency: indicates how large portion of time station failures consume compared to actual station processing time.
- Utilization efficiency: measures the actual productive time of work resource. Low utilization rate may be caused by either low work allocation to station or increased non-productive activities on station or both.
- Allocation ratio: illustrate time that production order uses for queueing to workstations and transportation.
- Production process ratio: Similar as allocation ratio but also include setup time and other delays on station and compares it to actual order execution time. (Kang et al., 2016.)

When considering effectiveness view of production, the following indicators were selected:

- Effectiveness: measures how productive machine or workstation is during worktime. It compares planned cycle time to resulted cycle time.
- Throughput rate: is comprehensive performance indicator which measure how many products can be manufactured in desired time.
- Blockage ratio: time consumed when products cannot advance from workstation.
- Starvation ratio: time consumed when there are no products to be processed on workstation.
- Work in process (WIP): presents total number of incomplete products in production system. (Kang et.al., 2016.)

Table 6. Productivity performance indicators. Efficiency and effectiveness.

Efficiency
Availability
Allocation efficiency
Technical efficiency
Utilization efficiency
Allocation ratio
Production process ratio
Effectiveness
Throughput rate (per hour)
Setup-ratio
Blockage ratio
Starvation ratio
WIP

Time related indicators which were selected for measuring delivery speed includes:

- Throughput time: time from starting order production to order is manufactured.
- Queueing time: time product is waiting to be processed. Does not include time during transportation. (Kang et.al., 2016.)

Here should be reminded that transportation is not simulated meaning transportation times are close to zero and thus not measured. The three last indicators for delivery were implemented during simulation testing, which was seen beneficial for analysing delivery consistency.

- Minimum order time: the shortest time product goes through production.
- Maximum order time: the longest time product goes through production.
- Standard deviation (SD) of throughput time: measures how far throughput times have spread from the average value.

Table 7. Delivery performance indicators

Delivery (units in minutes)
Average throughput time per product
Average queueing time per product
Minimum order time
Maximum order time
Standard Deviation of throughout time

Manufacturing system flexibility is harder to measure as there are no standardized measurement guideline for them. Still, Hoffmann et al. (2019) presented some indicators for flexibility:

- Effect of failure and station repair time: analysing changing failure occurrence and repair time to whole production performance.
- Effect of WIP: how number of products in system affects the overall performance. Commonly excessive WIP level means slower production flow leading to longer waiting times and increase in station blockings. The indicator can be used to evaluate the speed of production flow and how well system routes the products. In this research WIP level modification is achieved by changing the station buffer capacity. (Hoffmann et al., 2019.)

Described flexibility indicators will be measured by adding additional simulation scenarios where failure and WIP effect is evaluated separately. The effect of these will be analysed by evaluating scenario performance results with other mentioned performance indicators.

5 Results

5.1 Presentation of simulation models

Before presenting the models, key components of simulation model are introduced. For visualization of manufacturing systems, model uses three space markups blocks: rectangular node, path, point node. Oval shapes presents products. In figure 10, visualization blocks are illustrated.

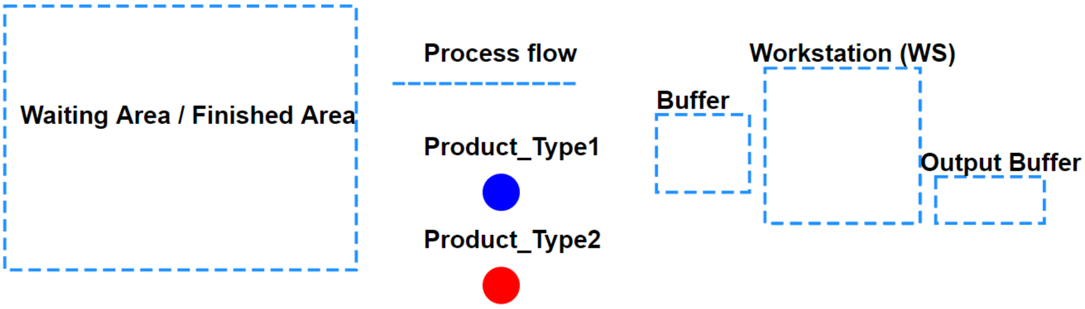


Figure 8. Simulation visualization blocks.

The following process blocks from Anylogic Process Modeling Library were used (see figure 11):

- Source block creates agent instances into model. In model, used for generating products needed to be processed.
- Sink block removes agent from model. This is used at the end of the process flow chart. In model used for removing all finished products when production simulation is finished.
- Queue block stores agents until next process block is available. In model act as station buffer.
- Wait block stores agents in block until product is manually released. It holds products in station’s output buffer until suitable workstation is available.
- Delay block stores products for certain time. It is utilized for keeping finished products in finished product area until all products are processed.

- Assembler block can be used for merging agents into one new agent. It visualizes processing tasks in workstation and stores new information into product instance e.g., processed work packages.
- SelectOutput and SelectOutput5 block route agents to correct output port according to criteria given. It is used for routing products to right workstation.
- In SelectOuputIn and SelectOuputOut blocks, product enters from in-port where it can be moved either specified out-port or according to probability. In model acts as transportation tool for moving products. Transportation time is zero.
- Hold block prevents product from accessing to next process block until it is unblocked manually. This is used between buffers and stations so that products do not proceed to station before it is available.
- TimeMeasureStart and TimeMeasureEnd measure throughput time in production. (Anylogic Help 2021b.)

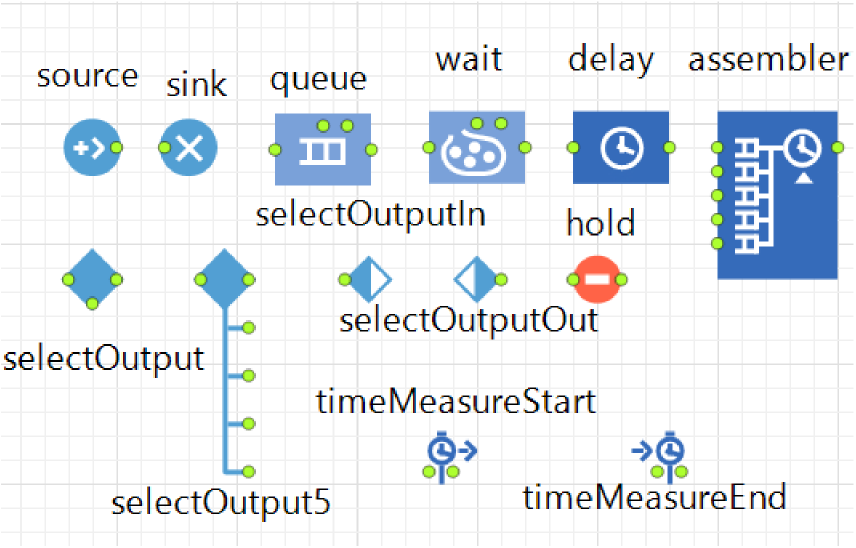
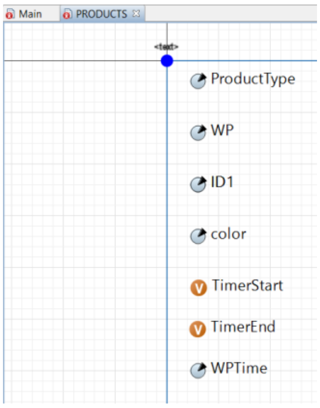


Figure 9. Process Library blocks.

In addition, the following Agent type tools from Anylogic agent library were utilized:

- Parameter is used for store various model information. Here, it is used for storing initial manufacturing scenario values and saving workstation processing and waiting time data.
- Event can produce multiple different types of actions in model on predetermined time. It is utilized for finding available workstations and calculating total waiting time and processing time in stations.
- Variable is single variable that store static or dynamical data. Here, variables are used for storing information. For example, what work stages each station can process and which process stages product has passed.
- Collection consists of multiple variables. In model it is used for storing required total station time in each station (i.e., estimated waiting time on buffer with needed processing time) and sorting this information. Moreover, it is utilized for presenting available workstation with capability to process defined work package. (Anylogic Help 2021c.)

In order to modify values of product instances, for example marking processed work packages, agent-type object was created. This stores all information of single product agent such as product type, identification number and time in system (see picture 3).

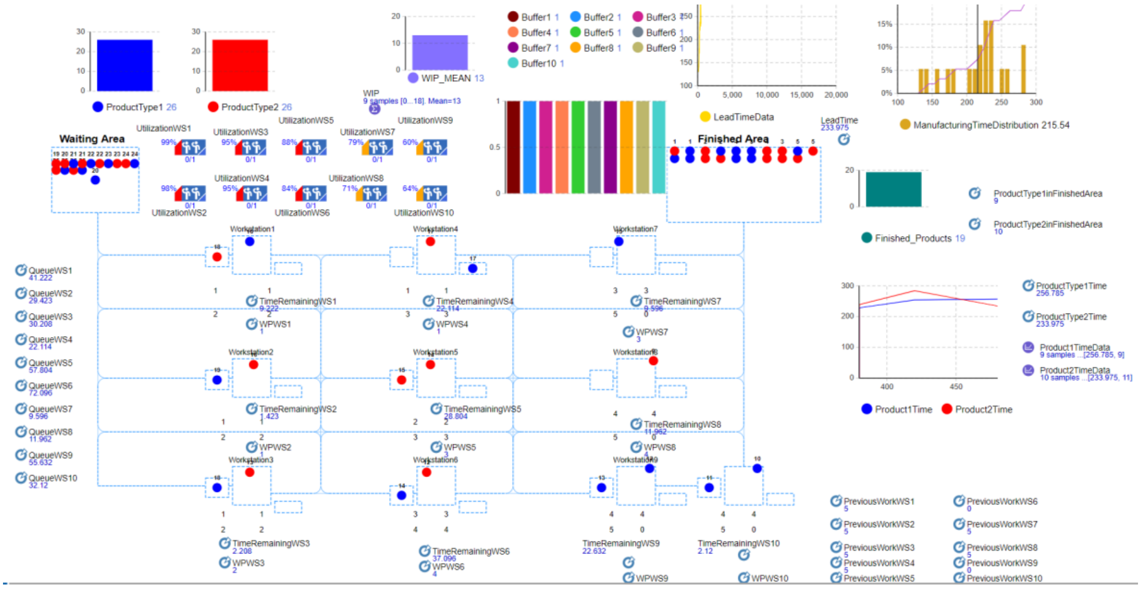


Picture 3. Product agent.

For model analysis during simulation run, the following items from Anylogic analysis library were used:

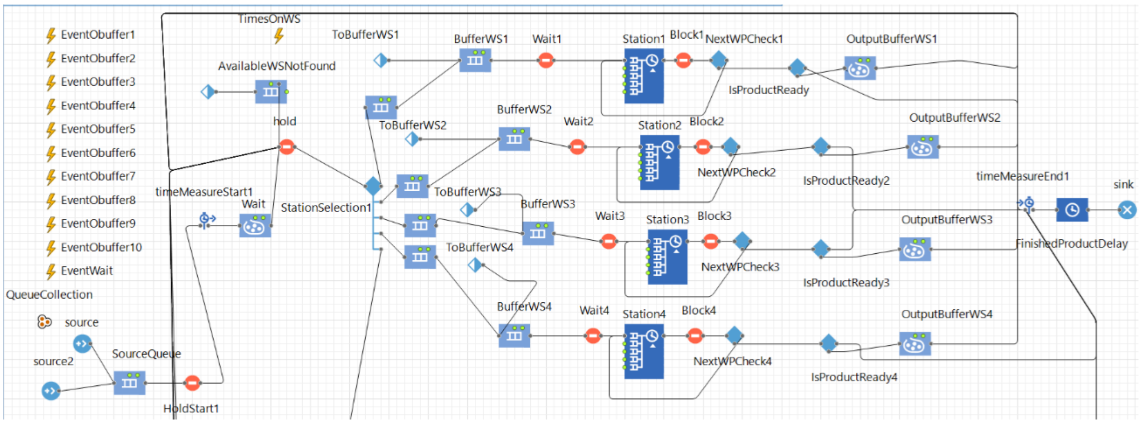
- Statistics calculate different statistical data from data samples. In simulation used for e.g., calculating average WIP during simulation run.
- Data set collects and store data samples. Here, it utilized e.g., storing lead time for every product.
- Graphical tools such as bar chart, time plot, histogram. These presents average buffer size, lead time and its distribution. (Anylogic Help 2021d.)

5.1.1 MMS model



Picture 4. MMS simulation model.

MMS model consists of 10 workstations where all stations are connected to each other enabling transportation between any station. In model seen in picture 4, every station presents remaining processing time and work package being processed. *QueueWS* parameters show station total time including processing all products in station and its buffer. Moreover, it is utilized to route product to station which has shortest waiting time. Model includes various statistical parameters and graphs to visualize overall performance as seen in picture above. Differently from other investigated manufacturing models, setup time of workstations is calculated and stored in *PreviousWorkWS* parameters. Model produces evenly both product 1 and 2 according to selected initial simulation scenario inputs. Operations and functions in simulation model are explained below. When all products are processed according to production scenario requirements, the simulation will stop. Model calculates multiple statistical indicators during simulation run i.e., number of finished products and total production time. Anylogic stores these and other simulation data which can be examined after simulation has ended. Later, data can be exported to Microsoft Excel for calculating KPIs.



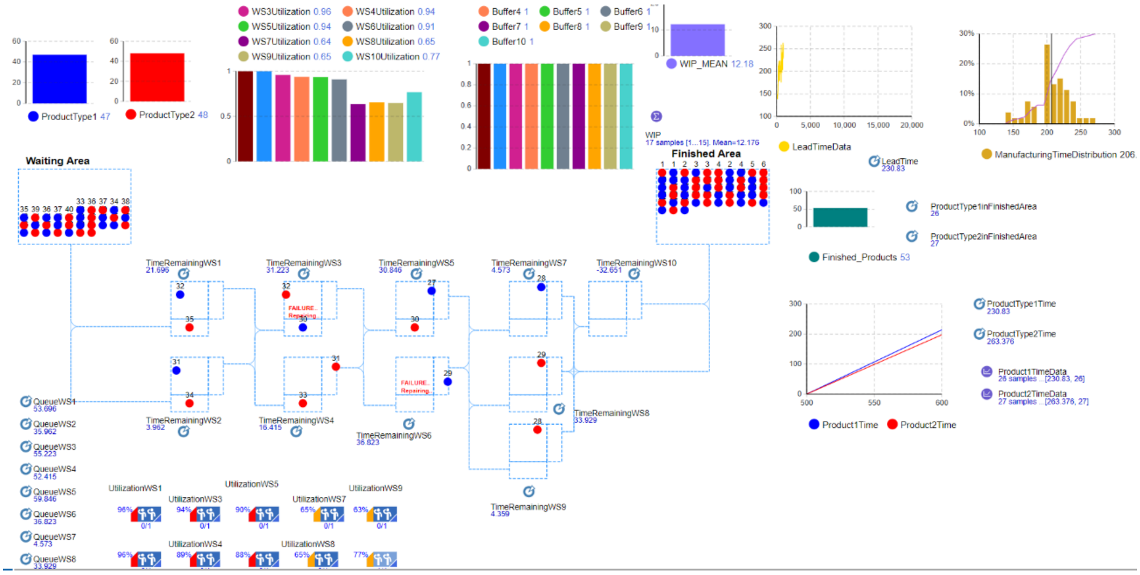
Picture 5. MMS model process chart.

Picture 5 illustrates the process blocks and stages in MMS model. Picture above only shows process blocks used from station 1 to station 4. Still, other stations include same blocks. Production starts from generating product type 1 and 2 in *Source* blocks. Product instances are then placed into *SourceQueue* buffer. One of the generated products proceeds to *Wait* block and other generated products remain in waiting area. Wait block is linked to *EventWait* block which checks if there are one or more stations available which can process first work package. When at least one suitable station is found, the product will be moved to *StationSelection* block. In this block, the model tests which stations can process the first process stage, and which of these stations has shortest waiting time. When station is found, the product will be moved to this station's *BufferWS* block. If there are no other products at the station, product moves to *Station* block. Station will process the product by specified task time. During the process, it possible that station failure or maintenance occurs which pauses the production in that station. In this case, model will add estimated repair time into station's remaining process time which is presented by *TimeRemainingWS* parameter. When station has processed the product, product enters *NextWPCheck* block where it is tested if same station can process next process stage. If yes, product moves into same station for processing. If not, *IsProductReady* block checks whether product is finished. If this is the case, product will be moved to *FinishedProductDelay* block located in *Finished Area* during simulation. This block keeps products in storage until required product amount according to manufacturing scenario is fulfilled. If product is not ready, product will move to *OutputBufferWS* block. This block is linked to *EventOBuffer* event function which will search for next available station suitable for processing next work package. *QueueCollection* stores waiting times of all station in real time during simulation. In addition, it is linked to EventOBuffer block which uses this information for releasing the product which has waited longest time on station's output buffer. When at least one available workstation is confirmed, the product will be released from OutputBufferWS block and moved back to StationSelection block. TimeOnWS event block calculates estimated processing times and waiting times on each station. In MMS model, stations process the following process stages:

- Stations from 1 to 3 handles work packages 1 and 2.
- Station 4 process stages 1 and 3.
- Station 5 manages 2 and 3.
- Station 6 process 3 and 4.
- Station 7 manages 3 and 5.
- Stations from 8 to 10 process work packages 4 and 5.

This combination was seen most beneficial during simulation testing and provides better performance results when compared layout where work packages would have been implemented to stations evenly.

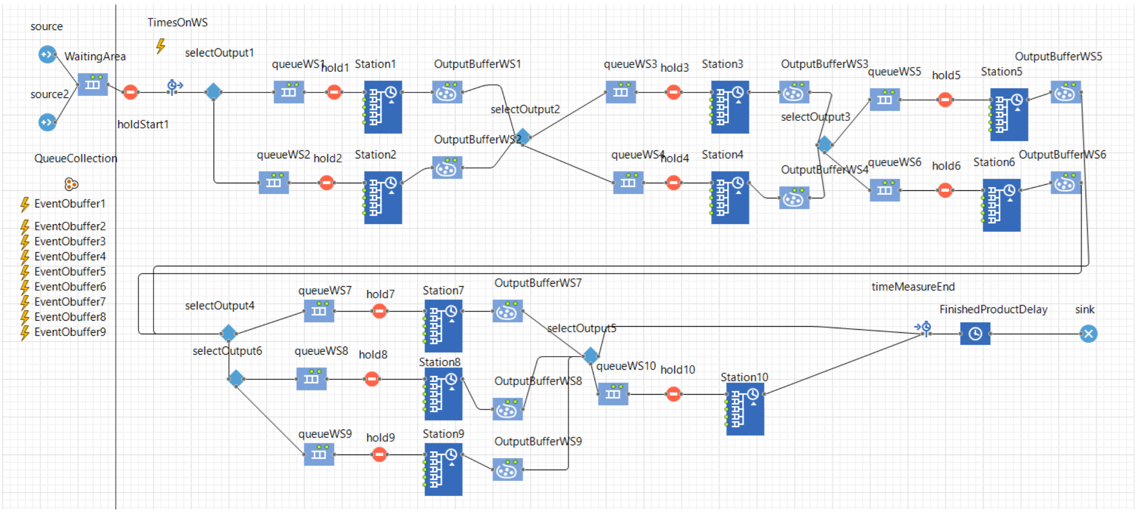
5.1.2 RMS model



Picture 6. RMS model.

RMS model include 10 workstations placed in two parallel lines with crossover connections after every process stage. Stations with same tasks are placed next to each other vertically and it is possible to add more stations on process stages later. Stations can handle both product types, but only one process stage. Station 1 and 2 process WP1 (work package 1), station 3 and 4 WP2, station 5 and 6 WP3, station 7, 8 and 9 WP4, and only station 10 process WP5. Here can be seen that stage four has three stations where other stages two. Because product type 2 has only four process stages, station 9 is assigned to process production stage 4. Model includes same initial parameter inputs and functions as MMS to calculate waiting time on station, remaining process time and so on. However, model does not include calculation of set up time because the process task in station does not change. As seen in picture 7, the model includes same visual statistical indicators as MMS model.

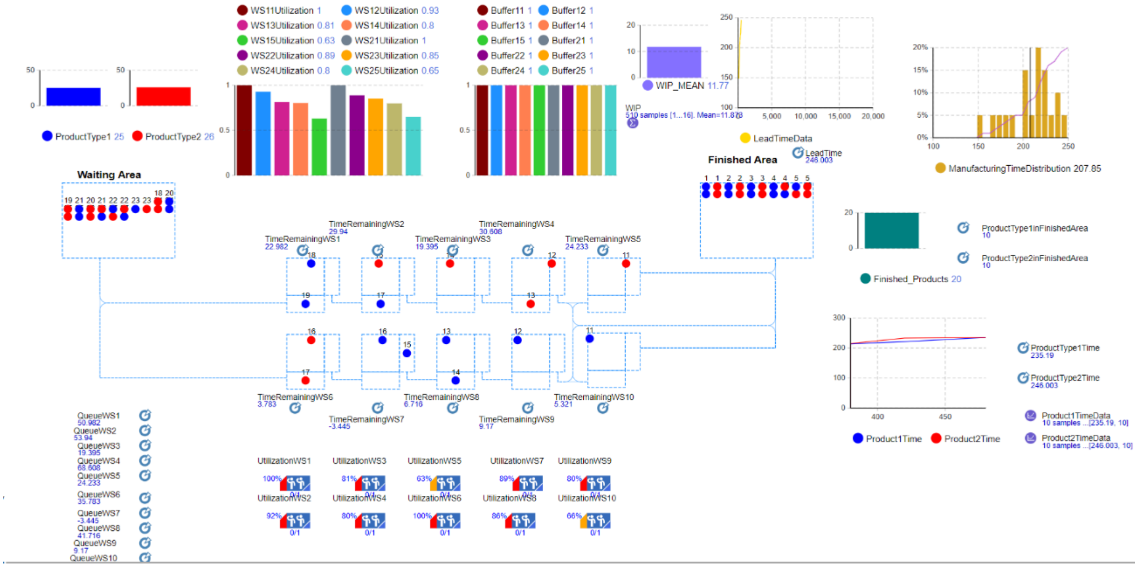
Model shows RMS unique ability to remove stations on stages where additional stations are not needed and add stations to other phases where they are needed. In RMS simulation model it was diagnosed that adding station 9 to phase 4 provided better overall manufacturing performance and increased overall station utilization than in model where each phase has equal number of stations.



Picture 7. RMS process functions.

Picture 7 presents the model function blocks of RMS model. Manufacturing starts from product generation in *source* and *source 2*. Generated products wait in *WaitingArea* until either buffer of *queueWS1* or *queueWS2* has space available. *SelectOutput1* function block checks if *Station1* have smaller buffer and shorter waiting time than *Station2*. If yes, product proceeds to Station 1 buffer and if no, product proceeds to Station2 buffer. Again, when station is ready to process, product moves from buffer to station. After processing, product is moved to output buffer waiting for transportation to available station on next phase. *EventObuffer* blocks act as function to find available WS and send signal to output buffer for transportation. This process is repeated until product is on process stage 4 where *selectOutput5* examine if product type is 2. If so, product is moved to finished working area since the product type has only four process stages. Otherwise, product type 1 is moved to *Station10* or its buffer for final processing. *TimeOnWS* block again calculates the waiting times on all stations.

5.1.3 DMS line

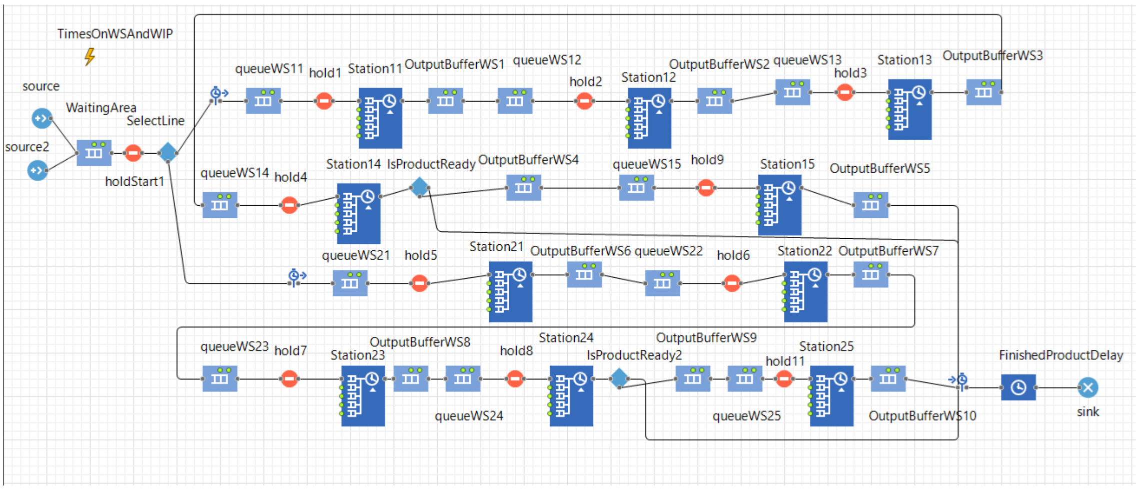


Picture 8. DMS model blocks.

DMS simulation model (see picture 8) consists of two lines with 5 stations each where each station process one production stage. Both lines can manufacture both product types 1 and 2. Product line 1 include workstations from 1 to 5 and product line 2 use stations from 6 to 10. Production stages is arranged horizontally where station 1 and 6 handle work packages 1, station 2 and 7 process WP2 and so on. Product must be processed from start to finish at one line meaning there are no crossover connections as in RMS. Because product type 2 has only four process stages, after WS4 (i.e., workstation 4) and WS9 is added additional transportation route where product type 2 products are transported into finished product area. Product type 1 continues normally to either WS5 or WS10 for processing final work package. Simulation model calculates same visual performance statistics as previous models.

Other option for DMS line configuration would have been set two separate production lines where each line product one product type. This was tested where product line 1 produced product type 1 and line 2 produced type 2 products. Results indicated substantial increase of total production time and lower station utilization which is why it was dismissed.

DMS model starts from generating products orders into waiting area (see picture 9). When either buffer *queueWS11* (i.e., line 1 and station 1) or *queueWS21* is available, product is moved to one of the stations depending which station is free or has shorter time for waiting to be processed. When first work package has been completed, product is moved to station output buffer where it waits until next station's buffer has space. Production continues until product has reached process stage four (i.e., Station14 or Station24). After this stage, *IsProductReady* function block checks whether product type is 2 and if so, product is moved to finished product area represent by FinishedProductDelay block. However, if product type is one product is moved to final processing phase and after moved to finished product area. *TimeOnWSAndWip* block calculates all stations estimated waiting time on buffer and needed processing time on station during simulation. Moreover, it calculates both line's WIP through simulation run.

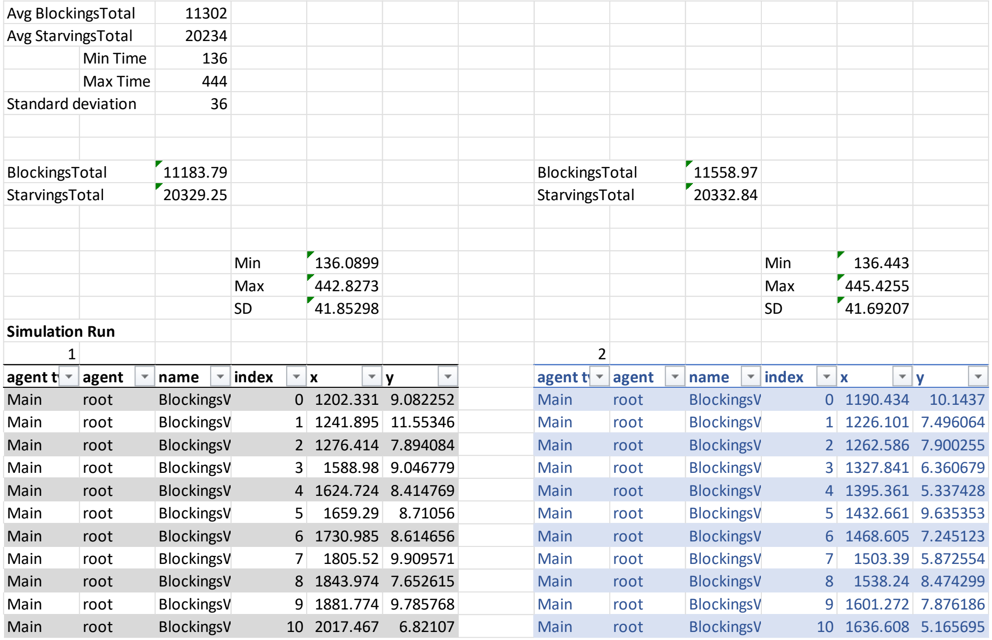


Picture 9. DMS process functions blocks.

5.2 Data gathering

Data gathering process, data filtering and calculation method for key performance indicators is briefly introduced below. Total of 45 simulation runs were executed. Simulation scenarios 1,2 and 3 involved total of 30 simulation runs, 10 per manufacturing system. Moreover, research included scenarios measuring manufacturing flexibility via failure occurrence and WIP level changes. These consists of total 15 simulation runs meaning 3 simulation runs per scenario. Simulation runs were seen sufficient as results did not change dramatically.

All simulation raw data was imported into Microsoft Excel where it was organized according to scenario, manufacturing system and data type. In addition, data types were divided according to manufacturing system and one data type sheet included all simulation runs in specific scenario. For calculating performance indicators, the average result from simulation runs were used. This will balance the results of abnormal simulation runs. However, as scenario 1 overall results in picture 11 suggests, total production time and other indicators in all systems only changed slightly during simulation runs. When each simulation run was finished, screenshot was taken and stored. From picture, total production time (TPT), actual order execution time (AOET) and work in process (WIP) data were collected which were presented by simulation visual graphs. Finally, calculated performance indicators, tables and other crucial data from simulation runs were combined into one Excel sheet which was categorized by scenario, manufacturing system, and performance perspective with its indicators. Pictures 10 and 11 illustrate the process of data importing, gathering and organizing.



Avg BlockingsTotal	11302
Avg StarvingsTotal	20234
Min Time	136
Max Time	444
Standard deviation	36

BlockingsTotal	11183.79	BlockingsTotal	11558.97
StarvingsTotal	20329.25	StarvingsTotal	20332.84
Min	136.0899	Min	136.443
Max	442.8273	Max	445.4255
SD	41.85298	SD	41.69207

Simulation Run

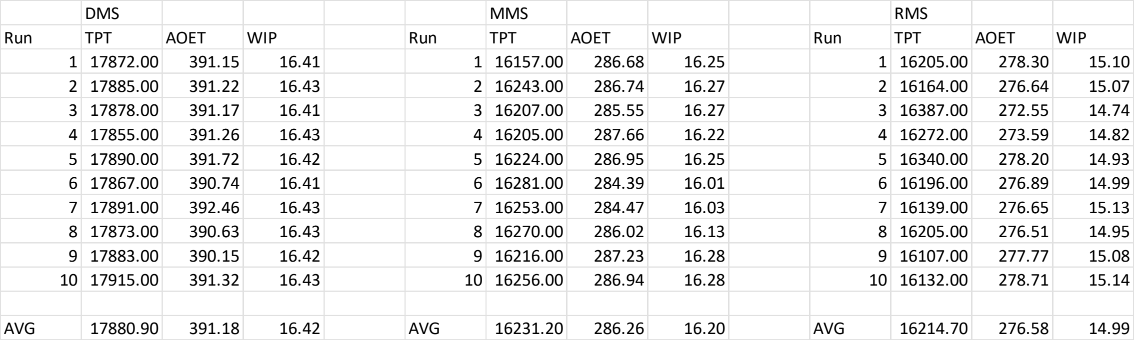
1

agent t	agent	name	index	x	y
Main	root	BlockingsV	0	1202.331	9.082252
Main	root	BlockingsV	1	1241.895	11.55346
Main	root	BlockingsV	2	1276.414	7.894084
Main	root	BlockingsV	3	1588.98	9.046779
Main	root	BlockingsV	4	1624.724	8.414769
Main	root	BlockingsV	5	1659.29	8.71056
Main	root	BlockingsV	6	1730.985	8.614656
Main	root	BlockingsV	7	1805.52	9.909571
Main	root	BlockingsV	8	1843.974	7.652615
Main	root	BlockingsV	9	1881.774	9.785768
Main	root	BlockingsV	10	2017.467	6.82107

2

agent t	agent	name	index	x	y
Main	root	BlockingsV	0	1190.434	10.1437
Main	root	BlockingsV	1	1226.101	7.496064
Main	root	BlockingsV	2	1262.586	7.900255
Main	root	BlockingsV	3	1327.841	6.360679
Main	root	BlockingsV	4	1395.361	5.337428
Main	root	BlockingsV	5	1432.661	9.635353
Main	root	BlockingsV	6	1468.605	7.245123
Main	root	BlockingsV	7	1503.39	5.872554
Main	root	BlockingsV	8	1538.24	8.474299
Main	root	BlockingsV	9	1601.272	7.876186
Main	root	BlockingsV	10	1636.608	5.165695

Picture 10. Importing and gathering data from DMS model in scenario 1.



	DMS					MMS					RMS		
Run	TPT	AOET	WIP		Run	TPT	AOET	WIP		Run	TPT	AOET	WIP
1	17872.00	391.15	16.41		1	16157.00	286.68	16.25		1	16205.00	278.30	15.10
2	17885.00	391.22	16.43		2	16243.00	286.74	16.27		2	16164.00	276.64	15.07
3	17878.00	391.17	16.41		3	16207.00	285.55	16.27		3	16387.00	272.55	14.74
4	17855.00	391.26	16.43		4	16205.00	287.66	16.22		4	16272.00	273.59	14.82
5	17890.00	391.72	16.42		5	16224.00	286.95	16.25		5	16340.00	278.20	14.93
6	17867.00	390.74	16.41		6	16281.00	284.39	16.01		6	16196.00	276.89	14.99
7	17891.00	392.46	16.43		7	16253.00	284.47	16.03		7	16139.00	276.65	15.13
8	17873.00	390.63	16.43		8	16270.00	286.02	16.13		8	16205.00	276.51	14.95
9	17883.00	390.15	16.42		9	16216.00	287.23	16.28		9	16107.00	277.77	15.08
10	17915.00	391.32	16.43		10	16256.00	286.94	16.28		10	16132.00	278.71	15.14
AVG	17880.90	391.18	16.42		AVG	16231.20	286.26	16.20		AVG	16214.70	276.58	14.99

Picture 11. Combining results from scenario 1.

5.3 Simulation results and analysis

Before analysis and comparison between manufacturing systems, some restrictions and limitations regarding simulation models and analysis method are noted. For simulation models, any of the manufacturing models were not fully optimized. Simulation model optimization requires advanced simulation software tools not included in free version of Anylogic. Moreover, each manufacturing systems weaknesses are easier to see when operations are not optimized. Still, some improvements were made during simulation testing related to division of tasks between the workstations. With MMS, the improvement focused on changing production stages processed on workstations. In RMS, this involved changing number of workstations on each phase. With DMS it was tested if two separate lines for each product type was more efficient than line were both product types were made. The latter was chosen as it produced better results.

One restriction of simulation model is product stages are not interchangeable (i.e., changing the order of process stages). Furthermore, workstation tasks cannot be merged (i.e., balancing workstation process times by combining activities or subprocesses). Thus, optimization procedures regarding these cannot be made as in Hoffman et al. (2019) simulation test which included interchangeability between process stages and optimization of DMS line with predetermined sequence of orders.

When considering selected performance indicators, it can be stated that all production performance viewpoints and indicators are not covered. Thus, results may vary when more accurate and wider range of performance indicators are implemented. Tested manufacturing scenarios and its inputs have crucial effect of performance results and larger category of scenarios with changing input values would produce more precise results. However as mentioned, this research aims to give overall performance results according to selected performance perspectives to form guideline, in which tested manufacturing scenarios or similar scenarios specific manufacturing system would be better choice compared to others.

Many scenario results will give exceptionally high results especially in scenario 1 because it does not include any production interruptions and setup time for DMS and RMS. Moreover, all scenarios neglect worker shifts and other production delays which would normally reduce performance results. On other hand, this makes also clearer to see what simulated production functions and events will most likely have impact to specific indicator and system. On the contrary, it cannot be seen how neglected activities could affect to specific production system.

The effect of increasing production volume to ten thousand units was tested in all scenarios to see if results change. Here, outcome was that overall results remained very close to scenarios results and indicating same level of performance.

5.3.1 Simulation results

Overall results of scenario 1 and production efficiency statistics can be seen in table 8. To summarize scenario 1 inputs, scenario involves producing one thousand units with workstation buffer capacity of 1. Scenario does not include station failures or other interruptions. Here, focus is to evaluate how manufacturing systems operate without any production interruptions reflecting best-case scenario.

In overall statistics, RMS acquires fastest production time although only marginally shorter than MMS whereas DMS have clearly slowest time. Here, should be reminded that MMS include station setup time of 5 minutes for every product when previous product stage differs to current one on station. Setup time illustrate the time needed to change suitable tools on station. MMS has total setup time of 15,219 minutes or about 15 minutes per produced product. This means notable total production time increase. It can be noted that if there were no setup time in MMS system or relatively low, MMS would most likely have fastest production time. Still, commonly workstations with ability to produce multiple process phases involve noteworthy setup time. DMS dramatically longer manufacturing time points to problems on productivity effectiveness. Average station utilization is clearly highest in MMS by 97,3% comparison to RMS 90,4% and DMS 87,3%. In case of RMS, the lower utilization origins from product stage four workstations where one additional WS was placed. In this phase, the average utilization rates were approx. 74% for three stations which lowers overall station utilization. In case of DMS, the last production phase lowered the total utilization rate as product type 2 did not include this phase meaning only type 1 products were routed to last workstation leading to utilization rate of 43% in WS5 and 41% in WS10. MMS result indicates high product routing efficiency and multiple stage processing capability meaning more routing options. Interestingly, RMS system managed to provide shortest average throughput time. This will be more discussed in delivery section below.

After overall statistics, efficiency related indicators are listed. Availability measures workstations efficiency related to used time for processing versus setup-time, blockings, and idle time in case of scenario 1 (Kang et al., 2016). RMS has clearly highest station availability ratio. Setup-time lowers availability rate in case of MMS and might be the cause for being the lowest. DMS performs only slightly better, where it seems the station blockings reduce the results. Allocation efficiency is similar to availability, but it considers also setup time and downtime as productive time (Kang et al., 2016). This leads to highest result for MMS whereas RMS and DMS results remain same. Technical efficiency measures the ratio of delays caused by failures to total processing time (Kang et al., 2016). This is removed from scenario 1 indicators as this scenario does not include any station failures. Utilization efficiency differs from before mentioned station utilization as it compares station processing time to time used for processing, setting up, and downtime (Kang et al., 2016). Because there are no setup-time for RMS or DMS and no downtime in scenario 1, RMS and DMS receives perfect score 100%. While MMS got 90,7% it can also be concluded that setup time has 9.3% effect on MMS utilization efficiency. Allocation ratio indicates the time product uses for queueing and in blockings in this scenario (Kang et al., 2016). This is because scenario has no downtime and simulation model does not include transportation time which is basically zero. MMS gets highest allocation rating of 55.1% while RMS results 51.5%. Here can be seen that MMS benefits its unique product routing system with multiple routing options. As RMS provides two routing options on each process stage, RMS acquires remarkably better allocation ratio than DMS with 36.4%. Next, Production process ratio, is similar to allocation ratio but do not consider setup-time and down time into processing time (Kang et al., 2016). This means that RMS and DMS results remain to same as allocation ratio, whereas MMS process ratio decreases to 49.7%. When considering the efficiency view in overall, MMS and RMS seem to perform very closely in this scenario whereas DMS results lowest in almost every indicator.

From effectiveness perspective, throughput rate shows that MMS and RMS have same rate with 3,7 products per hour while DMS has 3,4 per hour. Setup-ratio for MMS shows that changing tools for producing other work packages on station has significant of 9.7% impact to effectiveness decreasing productivity. High blockage ratio of 7.2% and starvation ratio 13% indicates unbalanced cycle times in DMS model, increasing queueing time due to incapability to product routing. Higher starvation can be partially explained the fact last workstation in DMS and RMS produces only type 1 products raising starvation time. MMS accomplish avoiding almost all production blockages with low starvation ratio due to flexible routing and multiple work package processing ability. When considering WIP, lower levels is seen more beneficial as it helps keeping production flow steady while decreasing station queueing time and blockings thus leading to faster throughput time (Hemalatha, Sankaranarayanasamy & Durairaaj, 2021; Hoffman et al., 2019). RMS provides the lowest WIP level with average of 15 during production whereas MMS and DMS 16.2 and 16.4 respectively with same production inputs (i.e., equal order intervals and buffer capacity of 1). There were no WIP limit implemented to simulation models meaning orders were routed to stations immediately when station buffers were available. In overall, MMS presents more effective system because of minimal starvation and blockings ratio although slight WIP difference to RMS.

From delivery view, RMS provides fastest product throughput time with 277 minutes comparison to MMS with 286 minutes. DMS resulted substantially higher time with 391 minutes. Thus, DMS queueing time is two times longer than MMS. The longer throughput of DMS seem to occur from longer waiting time. Moreover, previously mentioned high blockage ratio further increases time to produce a product. Interestingly, MMS had lower waiting time whereas RMS provided faster throughput. Reason seems to point again to setup time in case of MMS. Minimum and maximum order time presents extremums of product throughput time where fastest time for product type 2 can be 135 minutes and for type 1 150 minutes without any delays on system. Furthest extremums are in RMS model which indicates largest spread of order times however not notably. Standard deviation describes how far order times are from the average. As expected, largest deviation happens in RMS but surprisingly lowest in DMS with 36. This means that 68% of order times in case of DMS are within plus or minus 36 minutes from average value of 391. Overall delivery results are best in MMS however RMS have fastest throughput.

To summarize results in scenario 1, RMS seems to provide best overall scenario results with fastest production time and highest efficiency. MMS strengths relies on workstation utilization and overall effectiveness thanks to flexible product routing and multi product stage processing ability. DMS have some issues in efficiency, effectiveness, and delivery when station times are not balanced although it manages to keep order times consistent.

Table 8. Scenario 1 results.

	Scenario 1		
Overal statistics	**MMS**	**RMS**	**DMS**
Production output	1,000	1,000	1,000
Total time (min)	16,231	16,215	17,881
Buffer capacity	1	1	1
Total downtime	-	-	-
Average station utilization	97.3%	90.4%	87.3%
Average Throughput Time (min)	286	277	391
Total setup time per product (min)	15.3	-	-
Efficiency	**MMS**	**RMS**	**DMS**
Availability	90.2%	97.3%	91.3%
Allocation efficiency	99.9%	97.3%	91.3%
Technical efficiency	-	-	-
Utilization efficiency	90.3%	100.0%	100.0%
Allocation ratio	55.1%	51.5%	36.4%
Production process ratio	49.7%	51.5%	36.4%
Effectiveness	**MMS**	**RMS**	**DMS**
Throughput rate (per hour)	3.7	3.7	3.4
Setup-ratio	9.7%	-	-
Blockage ratio	0.1%	2.5%	7.2%
Starvation ratio	2.2%	9.1%	13.0%
WIP (Work in Process)	16.2	15.0	16.4
Delivery	**MMS**	**RMS**	**DMS**
Average throughput time (per product)	286	277	391
Average queueing time (per product)	113	130	235
Minimum order time	137	135	136
Maximum order time	438	467	444
Standard Deviation of throughput time	40	41	36

In Scenario 2 systems produced 5000 products with buffer capacity of 5. Furthermore, workstations failures were added. Failures on each station was set after 10,000 minutes on average or approximately 7 days of work. Repair times were uniformly distributed meaning short (10 minutes) and longer (120 minutes) repair times evenly. This represents longer production time scale where infrequent productions interruptions occur with quick and longer repair times. In overall statistics (see table 9) MMS finished the production in fastest time even 13 hours earlier than RMS. There is remarkable 14.2 days gap in DMS to MMS production time. Part of DMS overtime can be explained by total station downtime of 89 hours comparing to MMS and RMS with 78 hours and 73 hours respectively. Comparing to scenario 1, MMS manage to improve station utilization resulting 98.7% while RMS and DMS maintains same rate with 90.6% and 86.1%. Despite this, RMS provides fastest throughput time of 650 minutes while MMS 749 minutes and DMS remarkably slower with 1043 min. MMS result is again somewhat decreased due to setup time.

When comparing efficiency indicators to scenario 1 results, station availability in MMS and RMS remains same level where as DMS case it is lowered by 6%. The reason seems to be downtime increase but when simulation data in scenario 2 was analysed further it was found that the reason is substantial increase of idle time on stations. This effect can also be seen in allocation efficiency where MMS and RMS result remain same as scenario 1 but DMS result decreased 5,4%. Technical efficiency indicates that failures have minimal effect to processing time in all systems. Likewise, utilization efficiency of workstation is lowered only marginally. Allocation ratio is halved in all systems compared to scenario 1 because of longer waiting times due to increased buffer size. The same occurs in production ratio. The effect seems to be lowest in RMS case which performs best regarding efficiency in overall.

Some changes to effectiveness can be seen in table 9 compared to scenario 1. MMS product throughput rate is fastest at 3.8 per hour, RMS 3.7 per hour and slowest in DMS with 3 per hour. Setup ratio for MMS is lowered to 9.5% still indicating notable impact. Blockage ratio of MMS and RMS remains unchanged to scenario 1, but DMS ratio is increased by 5.4%. For starvation, MMS manage to drop ratio down to 0.5%

from 2.2% in scenario 1. For RMS the result remains the same and DMS inclined 1.5% compared to scenario 1. Thus, station failures have no crucial effect to effectiveness indicators in MMS and RMS but affects DMS by adding blockings and starvation. The increase of WIP in all systems is mainly due to increased buffer capacity. Where MMS and DMS the level of WIP is 45 or above, the RMS manage lowering it to roundly 39. Considering all the effectiveness indicators, MMS performed best.

According to delivery indicators, RMS resulted highest in all indicators with noticeable degree. Average product lead time is almost 100 minutes faster than MMS and 390 minutes faster compared to DMS. In RMS system, products must wait to stations 72 minutes less than in MMS and 366 minutes less than in DMS. The lower WIP level in RMS case can have partial effect to this as there are fewer products in system. Maximum order time is increased as expect when buffer capacity is increased. However, maximum lead time in case of DMS is way higher than in MMS and RMS. It was also verified that there were over 343 product times that exceeded the 1500 minutes mark. One explanation for this is orderly occurred workstation failures in all stations with long repair times which dramatically increase the waiting time after every process stage when station buffers include multiple products. Failures and repairs in workstations are programmed to occur with same probabilities in all systems. Because MMS and RMS provide at least one additional station in same process phase, additional station have most likely helped avoid very long throughput times. Deviation between order times is lowest in RMS system where there is noticeable difference even to MMS. Deviation in DMS is exponentially higher due to station failures especially where repair time is high.

Summarizing scenario 2 results, MMS had lowest total manufacturing time and utilize workstations most. RMS seem to have slightly better on overall efficiency, whereas MMS had higher production effectiveness. On other hand, RMS delivery performance is notably better. DMS is affected highly by increased buffer capacity and system failures which increase its production time. Because there is no flexibility regarding product routing, waiting times are increased. Moreover, combination of long waiting lines and station failures dramatically increase throughput time as delays are reflected to products waiting to be processed.

Table 9. Scenario 2 results.

	Scenario 2		
Overal statistics	**MMS**	**RMS**	**DMS**
Production output	5,000	5,000	5,000
Total time (min)	79,934	80,730	100,452
Buffer capacity	5	5	5
Total station downtime (min)	4,677	4,388	5,348
Average station utilization	98.70%	90.60%	86.10%
Average Throughput Time (min)	749	650	1043
Total setup time per product (min)	15.0	-	-
Efficiency	**MMS**	**RMS**	**DMS**
Availability	89.80%	96.80%	85.20%
Allocation efficiency	99.90%	97.40%	85.90%
Technical efficiency	99.30%	99.40%	99.30%
Utilization efficiency	89.90%	99.40%	99.30%
Allocation ratio	21.20%	22.00%	14.30%
Production process ratio	19.00%	21.90%	14.20%
Effectiveness	**MMS**	**RMS**	**DMS**
Throughput rate (per hour)	3.8	3.7	3
Setup-ratio	9.50%	-	-
Blockage ratio	0.10%	2.40%	12.60%
Starvation ratio	0.50%	9.00%	14.50%
WIP (Work in Process)	45.5	38.6	46.8
Delivery	**MMS**	**RMS**	**DMS**
Average throughput time (per product)	749	650	1,043
Average queueing time (per product)	575	503	869
Minimum order time	138	135	135
Maximum order time	1,239	935	5,308
Standard Deviation of throughput time	123	74	515

For scenario 3, 1000 products will be produced with buffer capacity of 1. Now, workstation failures are changed occur more frequently, but with short to medium repair times. Failures occurs on average after five work hours. Minimum repair time is 5 minutes and maximum 30 with uniform distribution. These illustrate small frequent interruptions in production system. Moreover, scheduled maintenances were added which occurs after around 100 working hours in station. The maintenance time is uniformly distributed with minimum of 30 minutes and maximum 60 minutes. The overall statistics in table 10 shows RMS has shortest total production time of 17,206 minutes. In MMS the time is only a fraction longer. Again, DMS needed considerably more time meaning difference of 9.8% to MMS and 10.7% to RMS. However, total downtime of DMS is 11.2% longer than in MMS and significant 19.9% compared to RMS. If total production time is longer, the amount of station failures rises. Same as other scenarios, station utilization is highest in MMS but interestingly DMS improve its utilization to 89.6 % outperforming RMS with 85.6%. Improvement in DMS case is linked to utilization increase in workstation 5 and 10 which jumped from average of 42% into 76%. Lower utilization of RMS points to process stage 4 where additional station was added. Here, the average utilization rate of three stations were 71%. RMS throughput time is fastest with 296 minutes per product which is remarkable 42% shorter time than in DMS. For MMS, time per product was 305 minutes and total needed setup time per product was approx. 15 minutes. This means MMS could perform even faster if setup time were minimized. When comparing results to scenario 1, small frequent failures and scheduled maintenances has 6.8% effect to total production time for MMS whereas in RMS the effect was 6.1% and for DMS 6.5%. Effect of failures will be further tested on flexibility performance evaluation chapter.

Regarding efficiency performance, RMS performs best when considering all indicators. Notable difference can be seen in availability of stations which favour RMS. MMS excels at allocation efficiency because of low idle time in stations which is multiple times lower than in RMS and DMS. Technical efficiency is highest in RMS due to lower total downtime. Utilization efficiency also favour RMS, however DMS with same downtime would result higher. MMS performs best in allocation ratio notably. However, production process ratio is highest in RMS meaning faster production flow in system. This is considerably slower in DMS. When analysing effectiveness performance, MMS results best in overall. The throughput rate of MMS and RMS are the same whereas in DMS is slower. MMS setup ratio has still notable effect to production effectiveness. MMS blockage ratio is extremely low which is only a fraction of RMS and DMS results. MMS avoid blockings as there is more options where products can be routed thus less time is spend blocking the station. Moreover, MMS transportation system prioritise waiting products on output buffers regarding waiting time thus transporting first the ones which have waited the longest. This reduces notably blockings on stations. RMS is provided with same transportation logic, but DMS does not as there is only one station per process stage per line. MMS provides also good results on starvation ratio due to routing ability and capability to process multiple process stages on one station. As mentioned earlier, the high starvation ratio for RMS origins from stage 4 as there are three stations processing same task whereas earlier stages have only 2. Interestingly, DMS provides surprisingly low starvation ratio, which partly originate from increased station repair times which keeps stations busy. Moreover, as there is only one station per stage, more products are waiting to be processed. RMS provides again lowest WIP level. RMS always moves products to next station after processing unlike in MMS product can be processed twice if current station is able process also next work package. This may slow production flow in system. In DMS products spend more time on system because lack of additional stations on process stage. Thus, they must wait longer in buffer.

Delivery is fastest on RMS. In overall, MMS resulted closely to RMS, but DMS needed considerably more time. Queueing time is lowest in MMS closely followed by RMS. Meanwhile, products in DMS line must wait almost double the time. Changes to extremum values of throughput time is smallest on RMS meaning no notable peaks on production time. MMS performed similarly, whereas in DMS some peaks were found. All systems had similar deviation between throughput times with only small difference.

Summarising scenario 3 results, failures and maintenances have clearly most effect on DMS slowing production flow notably. Interruptions had same but not as large effect to MMS and RMS. These performed similarly although RMS provided faster total time and throughput. Meanwhile, MMS can utilize all stations better than RMS. The impact of MMS setup time to performance can be argued.

Table 10. Scenario 3 results part 1.

	Scenario 3		
Overal statistics	**MMS**	**RMS**	**DMS**
Production output	1,000	1,000	1,000
Total time (minutes)	17,342	17,206	19,049
Buffer capacity	1	1	1
Total stations downtime (min)	10,132	9,396	11,274
Average station utilization	91.0%	85.6%	89.6%
Average Throughput Time (min)	305	296	420
Total setup time per product (min)	15.2	-	-
Efficiency	**MMS**	**RMS**	**DMS**
Availability	84.7%	90.7%	85.7%
Allocation efficiency	99.8%	96.7%	91.9%
Technical efficiency	93.4%	93.8%	93.3%
Utilization efficiency	84.9%	93.8%	93.3%
Allocation ratio	55.0%	51.2%	39.9%
Production process ratio	46.7%	48.0%	37.2%
Effectiveness	MMS	RMS	DMS
Throughput rate (per hour)	3.5	3.5	3.1
Setup-ratio	9.1%	-	-
Blockage ratio	0.1%	2.7%	6.3%
Starvation ratio	2.5%	8.8%	3.2%
WIP (Work in Process)	16.2	15.1	17.3
Delivery	**MMS**	**RMS**	**DMS**
Average throughput time (per product)	305	296	420
Average queueing time (per product)	120	139	238
Minimum order time	138	135	151
Maximum order time	488	478	523
Standard Deviation of throughput time	47	47	45

5.3.2 Impact of station failure and repairs.

For measuring flexibility performance, additional simulation tests were executed based on scenario 1 inputs. Utilizing flexibility measurement methods in Hoffman et al. (2019) and Schönemann et al. (2015), scenarios measure the effect of failure, repair time, and WIP. Total of five flexibility scenarios were added. Additional scenarios are illustrated on table 11.

First three scenarios measure the effect of length of failure and repair time to performance. Here, scenario one measures how short mean time to failure (MTTF) with short mean time to repair (MTTR) affect to system performance. Second scenario evaluate effect of long MTTF with long MTTR. Third one presents worst-case scenario where short MTTF and long MTTR are implemented. These three scenarios measure the robustness of systems against breakdowns and product routing capability. In last two scenarios, failures and repairs are removed focusing to the level of WIP. WIP level is investigated by first increasing station buffer size to five and then ten. Increasing WIP show manufacturing system's ability to handle larger production load and maintain consistent performance. Each scenario was simulated three times to balance abnormal simulation results. Table 11 summarize inputs changed in each scenario. Results regarding effect of failures and repair times are presented in table 12, 13 and 14. Performance is by default compared to scenario 1 results.

Table 11. Flexibility scenario inputs. Other inputs are same as in scenario 1.

Production parameters	**Short MTTF & Short MTTR**	**Long MTTF & Long MTTR**	**Short MTTF & Long MTTR**
Production volume (units)	1000	1000	1000
Buffer size (units)	1	1	1
Failure MTTF (minutes) Truncated n (min, max, Mean, standard deviation)	N (200,400, 300,20)	N (800,1000, 900,30)	N (200,400, 300,20)
Repair MTTR (minutes) Uniform N (min, max)	N (5,15)	N (30,60)	N (30,60)
Simulation runs	3	3	3
Production parameters	**WIP Medium**	**WIP High**	
Production volume (units)	1000	1000	
Buffer size (units)	5	10	
Failure MTTF (minutes) Truncated n (min, max, Mean, standard deviation)	-	-	
Repair MTTR (minutes) uniform N (min,max)	-	-	
Simulation runs	3	3	

The first scenario shows that short frequent disruptions with short repairs have small effect to production systems performance according to overall statistics in table 14. The total production time increased similarly with average of +3.2% in all systems where the growth was smallest in RMS. MMS and RMS station utilization was dropped by -3.1% and -2.7% respectively whereas DMS increased by +5.2%. This happened as last stations in DMS were busier with repairing task causing utilization jump from 42% to 81%. Short disruptions increased throughput time for DMS by 25 minutes meanwhile dropped in MMS by 11 and RMS by 6. Negative performance change to overall statistics was lowest in RMS.

Efficiency indicators declined in every model only slightly. If percentage change to scenario 1 is considered, the DMS is the least affected by short interruptions. However, it resulted in lowest overall score. Availability drops in all systems on average of -3% where most on RMS by -3.2% caused by failures. Allocation efficiency marginally increased for DMS, for others remained same. Technical and utilization efficiency is declined almost equally on all systems. Allocation ratio is remained unchanged on MMS and RMS whereas in DMS is increased by +2.6% because repair times are included to stations busy time. Production process ratio rose by +1,2% in DMS on contrary to other systems where it declines marginally when repair time is not included anymore. Overall efficiency results show highest performance in RMS as seen in table 12.

Regarding effectiveness, results slightly declined due to interruptions. Comparing to scenario 1, throughput rate has decelerated on average of 3% where in DMS most. Blockings and starvations remained somewhat same in MMS and RMS while in DMS dropped by -0,8% and prominent -9,8% correspondingly because of repairing tasks. WIP increased only by +5,1% in DMS, for other remained same level. MMS had clearly lowest blockings and starvation ratio whereas RMS smallest WIP level. Highest variation in results were in MMS and lowest in RMS when compared to scenario 1. All indicators considered MMS resulted top (see table 13).

In delivery, lead time per product increased most in DMS by +6% whereas in MMS +4% and RMS +3%. Queueing time change was highest in MMS by +4% and lowest in RMS by +1,4%. Fastest average throughput time were in RMS, meanwhile MMS had shortest queueing time on station. Rise of minimum and maximum order time were highest in DMS. Standard deviation of throughput time rose in MMS by +6,9% and especially for DMS by +12,7% while in RMS remained same. RMS provided best overall delivery results where failures and repairs affected delivery the least.

In conclusion, short and frequent interruptions seem to have slight effect to MMS and RMS whereas more notable in DMS. RMS performed best in overall. This is surprising as MMS offers more product routing options and can process two different process stages in stations. Still, the gap between the two was small. DMS performs worst from the systems, where repairs keep particularly last stations busier but increase products in system resulting in slower production flow. This can be seen notably longer total production time and order time. Percentage change to scenario 1 were lowest in RMS whereas highest in MMS.

Next, the results of more infrequent failures with longer repair times (i.e., long MTTF and long MTTR) are examined. If comparing overall statistics to previous scenario, intermittent station disturbances with longer repairs have larger negative impact to production performance than frequent shorter production failures. Moreover, total downtime increased +48,5% on average from previous failure scenario. When compared to Scenario 1, total time increase was lowest in RMS with +4.6% whereas in MMS by +5.4% and in DMS by +5%. Again, RMS produced fastest total time. Station utilization was lowered most with -4.9% in MMS although provided highest ratio. This is to be expected after a particularly high level of utilization in Scenario 1, which is more affected by longer repair times. Same occurs also for RMS in throughput time with increase by +6.3%. Nevertheless, RMS resulted marginally faster than MMS. Smallest change to results were in DMS although its performance was lowest.

Overall efficiency performance seems to decrease most in RMS and the least in DMS. Still, RMS provided best overall results. Availability, allocation ratio and production process ratio were declined most in RMS by -6.1%, -1.9% and -4.3% respectively. For DMS, these indicators showed -4.2%, +3.3% and +1.3% and for MMS -4.2%, -0.7%, and -2.9%. Indicators point stations are less available as they must use more time for repairs increasing total production time. All efficiency indicators declined by average of -2.9% in MMS, -3.9% in RMS and -1.6% in DMS. For effectiveness of system, the longer repairs notably reduced throughput rate and increased unfinished products in system. Comparing to scenario 1, throughput rate dropped by -0.2 products per hour meaning average of -4.8% reduction in all systems. WIP increased +5.7% for DMS and +2.7% in RMS decelerating flow speed in production. For MMS WIP level remained almost same with +0.6% increase. Largest change in blocking were in RMS by +1% and starvation on DMS

-9.8%. Starvation in DMS is explained by increased repair activities. Negative performance percentage change was again lowest in DMS and highest in MMS although performed best in overall.

Delivery indicators inclined notably in all systems particularly in RMS where percentage change was largest. Now, MMS had almost same throughput time meanwhile providing clearly shorter queueing time. All systems order time deviation was dramatically increased and most in DMS and lowest in MMS. This time MMS delivery performance resulted top. To summarize, occasional failures with longer repair times affected most RMS although it still provided marginally better manufacturing time and order time than MMS. Even though efficiency performance reduction was highest in RMS, indicator results remained top. MMS provided best results regarding effectiveness and delivery while providing closely same total time and order time. Greatest change in DMS was increased lead time and its deviation. RMS provided slightly better overall results than MMS, meanwhile DMS performance reduction was lowest.

Last failure simulated scenario combines frequent production failures with longer repair times (i.e., short MTTF and long MTTR). The scenario illustrates worst case scenario. Even though this is not realistic in longer time scale, it helps to understand how combination of these two impact system performance and indicators. Overall statistics shows that total time is increased average of +15.7% compared to previous scenario +5%. Now, total downtime is tripled to previous scenario. It is expected that substantial amount of production time is needed to handle breakdowns on stations. This was confirmed as overall statistics shows significant station utilization decrease by -13.5% in MMS and -11.2% in RMS. However, DMS utilization is only reduced by -4.2%. Reason seems to be linked to MMS and RMS additional station on each process stage which cannot be utilized fully due to longer repairs happening frequently. Here, MMS maintains highest overall utilization rate of 83.8% which is only marginally higher now than in DMS while in RMS 79.2%. Order throughput time has also significantly increased by +14.5% on average. RMS provides smallest change to order time in addition to fastest throughput and lowest total time. Performance decrease is lowest again in DMS while highest in MMS.

From efficiency perspective, RMS indicators are lowered the most and the least in DMS similarly as in previous scenario. Average percentual change to scenario 1 indicators were -8%. From long frequent disruptions, availability, technical and utilization efficiency, and production process ratio suffered the most. Availability rate drops for all systems due to increased amount of time used for fixing stations. Average result of technical and utilization efficiency show productive time is lost in MMS by -13%, -13.7% in RMS and -14.2% in DMS. Same as in previous scenario, time-consuming interruptions slows production flow and thus production process ratio declines. Because blockings and starvation decrease significantly compared to Scenario 1 due to increased repair tasks, allocation ratio increases in DMS thus no realistic performance improvement.
From effectiveness view, throughput rate decreases significantly in MMS and RMS by -0.5 products equal to -14% and -13,8%. Other indicators remain close to same as in scenario 1, however starvation in DMS is lowered by -9.4% and WIP increased by one. Most likely stations are busy either repairing stations or processing increased number of piled orders. MMS has notably better blockage and starvations ratio compared to other two, but RMS manage to keep WIP level the lowest due to faster product flow.

Delivery indicators point that all indicators rise dramatically along with increased disruptions. In RMS system, products are finished the fastest whereas queueing time is smallest on MMS. This time, DMS has lowest standard deviation of production time. Moreover, increase of queueing time is minimal in DMS because of initially significantly longer queueing time in Scenario 1.
In conclusion, scenario showed substantial reduction of performance in all systems. RMS resulted fastest delivery time and best overall performance followed by MMS with highest utilization and system effectiveness. Efficiency performance was most lowered in RMS, effectiveness decreased most in MMS and RMS, and delivery performance declined most in MMS. MMS had highest overall performance reduction compared to

scenario 1. Indicators changed the least in DMS due to initially lower-level performance results to which increased station downtime had lower impact.

Table 12. Failure scenario results. Part 1.

Failure scenario results	**Short MTTF & Short MTTR**			**Long MTTF & Long MTTR**			**Short MTTF & Long MTTR**		
Overal statistics	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Production output	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Total time (min)	16,768	16,696	18,490	17,108	16,966	18,767	18,868	18,818	20,546
Buffer capacity	1	1	1	1	1	1	1	1	1
Total downtime (min)	5196	4839	5638	7759	7203	8318	23,666	22,451	25,392
Average station utilization	94.1%	87.7%	92.5%	92.3%	87.5%	91.1%	83.8%	79.2%	83.1%
Average throughput time (min)	297	283	416	304	301	414	332	319	438
Total setup time (min)	15,210	-	-	15,215	-	-	15,233	-	-
Efficiency	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Availability	87.4%	94.1%	88.8%	86.0%	91.2%	87.0%	78.3%	82.2%	78.3%
Allocation efficiency	99.9%	97.3%	92.0%	99.9%	95.8%	91.7%	99.7%	95.3%	91.3%
Technical efficiency	96.5%	96.7%	96.5%	94.8%	95.2%	94.9%	85.7%	86.3%	85.8%
Utilization efficiency	87.5%	96.7%	96.5%	86.1%	95.2%	94.9%	78.5%	86.3%	85.8%
Allocation ratio	54.9%	52.0%	39.0%	54.4%	49.6%	39.8%	54.6%	51.2%	40.9%
Production process ratio	48.0%	50.3%	37.7%	46.8%	47.2%	37.7%	42.9%	44.1%	35.1%

Table 13. Failure scenario results. Part 2.

Failure scenario results	**Short MTTF & Short MTTR**			**Long MTTF & Long MTTR**			**Short MTTF & Long MTTR**		
Effectiveness	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Throughput rate (per hour)	3.6	3.6	3.2	3.5	3.5	3.2	3.2	3.2	2.9
Setup-ratio	9.3%	-	-	9.2%	-	-	8.4%	-	-
Blockage ratio	0.1%	2.3%	6.5%	0.1%	3.5%	6.4%	0.2%	3.3%	5.8%
Starvation ratio	2.2%	9.3%	3.1%	2.8%	8.1%	3.2%	3.1%	8.5%	3.6%
WIP	16.3	15.0	17.3	16.3	15.4	17.4	16.1	15.0	17.4
Delivery	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Average throughput time per product (min)	297	283	416	304	301	414	332	319	438
Average queueing time per product (min)	117	132	240	122	145	234	132	148	242
Minimum order time (min)	141	136	153	155	135	151	139	136	150
Maximum order time (min)	451	411	467	498	529	538	547	539	556
Standard Deviation of throughput time (min)	43	41	41	49	54	50	57	58	48

Table 14. Percentage change to Scenario 1. Failure scenarios.

Comparison to scenario 1	**Short MTTF & Short MTTR**			**Long MTTF & Long MTTR**			**Short MTTF & Long MTTR**		
Overal statistics	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Total time (min)	+3.3%	+3.0%	+3.4%	+5.4%	+4.6%	+5.0%	+16.2%	+16.1%	+14.9%
Total downtime (min)	+5196	+4839	+5638	+7759	+7203	+8318	+23666	+22451	+25392
Average station utilization	-3.1%	-2.7%	+5.2%	-4.9%	-2.8%	+3.8%	-13.5%	-11.2%	-4.2%
Average Throughput Time (min)	+3.6%	+2.4%	+6.5%	+6.3%	+8.7%	+5.7%	+16.0%	+15.5%	+12.0%
Total setup time (min)	-0.3%	-	-	+0.0%	-	-	-0.2%	-	-
Efficiency	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Availability	-2.8%	-3.2%	-2.5%	-4.2%	-6.1%	-4.2%	-11.9%	-15.1%	-12.9%
Allocation efficiency	+0.0%	+0.0%	+0.7%	+0.0%	-1.5%	+0.4%	-0.1%	-2.0%	+0.0%
Technical efficiency	-3.5%	-3.3%	-3.5%	-5.2%	-4.8%	-5.1%	-14.3%	-13.7%	-14.2%
Utilization efficiency	-2.9%	-3.3%	-3.5%	-4.2%	-4.8%	-5.1%	-11.8%	-13.7%	-14.2%
Allocation ratio	-0.2%	+0.4%	+2.6%	-0.7%	-1.9%	+3.3%	-0.5%	-0.4%	+4.4%
Production process ratio	-1.7%	-1.3%	+1.2%	-2.9%	-4.3%	+1.3%	-6.9%	-7.4%	-1.4%
Effectiveness	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Throughput rate (per hour)	-3.2%	-2.9%	-3.3%	-5.1%	-4.4%	-4.7%	-14.0%	-13.8%	-13.0%
Setup-ratio	-0.4%	-	-	-0.5%	-	-	-1.3%	-	-
Blockage ratio	-0.0%	-0.2%	-0.8%	-0.0%	+1.0%	-0.8%	+0.1%	+0.8%	-1.4%
Starvation ratio	+0.1%	+0.2%	-9.8%	+0.6%	-1.0%	-9.8%	+0.9%	-0.6%	-9.4%
WIP	+0.6%	+0.2%	+5.1%	+0.6%	+2.7%	+5.7%	-0.3%	+0.2%	+6.1%
Delivery	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Average throughput time per product	+3.6%	+2.4%	+6.5%	+6.3%	+8.7%	+5.7%	+16.0%	+15.5%	+12.0%
Average queueing time per product	+4.0%	+1.4%	+2.0%	+8.2%	+11.5%	-0.4%	+17.1%	+13.7%	+2.9%
Minimum order time	+2.8%	+0.7%	+12.9%	+13.4%	+0.1%	+11.0%	+1.5%	+1.1%	+10.5%
Maximum order time	+2.9%	-12.0%	+5.2%	+13.5%	+13.3%	+21.3%	+24.7%	+15.3%	+25.4%
Standard deviation of throughout time	+6.9%	+0.0%	+12.7%	+22.2%	+32.2%	+38.7%	+42.4%	+43.7%	+33.0%

5.3.3 Effect of WIP

The following scenarios called Buffer 5 and Buffer 10 presents the effect of WIP by manipulating buffer size of stations. According to Grznár et al. (2019) optimal buffer level reduces unnecessary WIP level and improve throughput time leading to reducing total operational costs. The goal of this simulation test is to increase the number of products in production to measure the flexibility of the systems. To remind, these scenarios do not simulate any station failures or maintenance. In first scenario the buffer can contain maximum of five products and in second scenario 10 products. In Buffer 5 simulation, it was measured average WIP level of 40 meaning 40 unfinished products in system simultaneously throughout the manufacturing. In Buffer 10 scenario the average amount was 70. Results are by default compared to scenario 1 to see performance change to other scenarios.

In buffer 5 scenario (see table 15) overall statistics shows that increasing buffer reduce total production time and marginally increase station utilization. This on other hand increase remarkably order throughput time. Total production time in DMS increase slightly but also raise station utilization by +7% (look table 16). Throughput time is the least inclined in RMS providing notably faster throughput time per product. Meanwhile MMS succeeds in finishing all products first with highest station utilization rate.

When looking at efficiency perspective, allocation ratio and production process ratio drops dramatically. From availability to utilization efficiency the results are closely same as in scenario 1. Still, DMS slightly improve its availability and allocation efficiency by +1.7%. Largest decline in allocation ratio and process ratio is in MMS by tremendous -33% and -30%. RMS overall results are the highest and lowest in DMS. Despite this, percentual change is lowest in DMS. Due to DMS significantly lower ratios in Scenario 1, DMS has already longer queueing time thus additional waiting does not have so crucial impact. In MMS the setup time additionally decreases the process ratio. Performance reduction was higher in MMS than the rest.

Throughput rate regarding effectiveness remained same level as in scenario 1 even though lead time increased. Blockages seem to decrease a little in RMS and DMS whereas MMS remained unchanged. Starvation maintained almost same in RMS, slightly declined in MMS but significantly lowered in DMS by -9.7%. Reduction can be explained with increased buffer size. WIP was increased by 27 in MMS, 20 in RMS and 29 in DMS indicating notably faster production flow in RMS. MMS production flow is slowed by setup times but does not justify the large gap. Overall effectiveness performance is highest in MMS. Comparing to Scenario 1, throughput rate increase was highest in MMS, blockages and starvations dropped most in DMS and WIP level inclined the least in RMS. As mentioned, throughput time rises greatly because of increase in buffer size. From delivery perspective, RMS maintains its notably faster throughput time whereas order execution is slowest on DMS. Queueing time per product is surprisingly significantly smaller in RMS where MMS has provided lowest result in previous scenarios. Also, RMS manage to keep deviation of order execution time lower meaning more consistent production times. Negative performance change to Scenario 1 was lowest in RMS whereas rose most in MMS.

Increasing buffer size to five seems to decrease slightly total production however increasing remarkably product lead time. Even if station utilization increased in MMS and DMS, overall efficiency performance suffers. Increased buffer size reduces blockings and starvation, but significantly adding more WIP slowing overall production flow. This can be seen from delivery results. From flexibility perspective, RMS seem to manage buffer changes best by maintaining faster production flow while maintaining good results in other performance indicators. Overall performance change was smallest in DMS and notably higher in MMS compared to scenario 1 meaning increased buffer size may cause problems in MMS.

In Buffer 10 simulation test, buffer size was increased to ten products per stations. When looking overall statistics results in table 15, the total time in MMS increased slightly from the result of Scenario 1 (see table 16) while RMS and DMS time surprisingly decreased marginally. When looking at tremendous queueing time increase it seems that product routing in MMS have problems when WIP size increases too much. There was substantial difference between throughput time where RMS time was one third less than in MMS and over two thirds lower than in DMS. Other indicators remained same level as in Buffer 5 scenario. Negative performance change was highest in MMS.

For efficiency, results were similar to Buffer 5 where they were highest in RMS followed by MMS. Change to Scenario 1 was smallest in DMS and highest in MMS. All systems allocation ratio and production process ratio declined substantially from Buffer 5 results where it dropped most in MMS. In RMS, increased number of orders helps utilizing more stations specially in product processing stage 4 where three stations were placed. From MMS perspective, because products can be processed two times in a row in same station can have negative impact on station efficiency when products are not routed so often causing further stations waiting for products to be processed. For DMS, the increased buffer size keeps stations busier longer meaning better utilization, but product time in system is increased greatly due to long waiting times resulting in low allocation ratio and process ratio. When looking at effectiveness results, these are again similar as in Buffer 5 where MMS provided best overall result. DMS provides most notable changes as blockings decrease -2.5% and starvations by -10%. WIP level is significantly lower in RMS than others being around 55 products. From performance change view, RMS and DMS resulted equal and MMS lowest. Delivery results show extreme increase for all systems in indicators. Average product lead time is remarkably lower in RMS as noted before. Product queueing time is significantly lower now in RMS than MMS. Meanwhile DMS has clearly higher execution and queueing time per product as expected. RMS throughput time deviation is also notably lowest.

Results when increased buffer size to 10 shows that larger buffers mean dramatically longer throughput time per product. Moreover, indicators like station utilization, allocation ratio, production process ratio decreases while WIP, queueing time, and order time deviation increases. As mentioned, RMS resulted quickest total production time, order lead time and lowest WIP. MMS had most significant negative performance change where delivery performance decreased the most. It can be concluded that RMS provide most flexibility and better performance regarding production scenarios with need for larger buffer sizes.

Table 15. Buffer 5 and Buffer 10 results.

	Buffer 5			**Buffer 10**		
Overal statistics	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Production output	1000	1000	1000	1000	1000	1000
Total time (min)	16133	16194	17910	16316	16149	17885
Buffer capacity	5	5	5	10	10	10
Total downtime	0	0	0	0	0	0
Average station utilization	97.8%	89.8%	94.3%	96.6%	89.4%	93.5%
Average throughput Time (min)	722	598	899	1212	904	1404
Total setup time (min)	15020	-	-	14943		
Efficiency	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Availability	90.3%	98.0%	93.0%	90.4%	98.6%	94.2%
Allocation efficiency	99.8%	98.0%	93.0%	99.9%	98.6%	94.2%
Technical efficiency	100%	100%	100%	100%	100%	100%
Utilization efficiency	90.5%	100.00%	100%	90.5%	100%	100%
Allocation ratio	21.8%	23.8%	17.5%	13.0%	15.8%	11.2%
Production process ratio	19.7%	23.8%	17.5%	11.8%	15.8%	11.2%
Effectiveness	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Throughput rate (hour)	3.7	3.7	3.4	3.7	3.7	3.4
Setup-ratio	9.5%	-	-	9.5%	-	-
Blockage ratio	0.2%	1.9%	5.79%	0.12%	1.2%	4.75%
Starvation ratio	1.2%	9.4%	3.27%	1.6%	9.4%	2.87%
WIP	43.4	35.5	45.4	73	55	74.6
Delivery (minutes, per product)	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Average throughput time	722	598	899	1212	904	1404
Average queueing time	549	453	730	1040	760	1237
Minimum order time	136	133	150	138	135	152
Maximum order time	1146	796	1036	1994	1263	1754
Standard deviation of throughput time	141	118	183	310	250	413

Table 16. Buffer 5 and Buffer 10 percentage change to Scenario 1.

Comparison to scenario 1	**Buffer 5**			**Buffer 10**		
Overal statistics	MMS	RMS	DMS	MMS	RMS	DMS
Total time	-0.6%	-0.1%	+0.2%	+0.5%	-0.4%	+0.0%
Average station utilization	+0.5%	-0.5%	+7.0%	-0.7%	-0.9%	+6.2%
Average Throughput Time	+152%	+116%	+129%	+323%	+227%	+259%
Total setup time	-1.6%	-	-	-2.1%	-	-
Efficiency	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Availability	+0.1%	+0.7%	+1.7%	+0.2%	+1.4%	+3.0%
Allocation efficiency	-0.0%	+0.7%	+1.7%	+0.0%	+1.4%	+3.0%
Technical efficiency	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Utilization efficiency	+0.1%	0.0%	0.0%	+0.2%	0.0%	0.0%
Allocation ratio	-33.3%	-27.7%	-19.0%	-42.1%	-35.8%	-25.2%
Production process ratio	-30.0%	-27.7%	-19.0%	-38.0%	-35.8%	-25.2%
Effectiveness	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Throughput rate	+0.6%	+0.1%	-0.2%	-0.5%	+0.4%	-0.0%
Setup-ratio	-0.2%	-	-	-0.2%	-	-
Blockage ratio	+0.0%	-0.6%	-1.5%	-0.0%	-1.3%	-2.5%
Starvation ratio	-1.0%	+0.3%	-9.7%	-0.6%	+0.3%	-10.1%
WIP	+167%	+136%	+176%	+349%	+266%	+354%
Delivery	**MMS**	**RMS**	**DMS**	**MMS**	**RMS**	**DMS**
Average throughput time	+152%	+116%	+129%	+323%	+227%	+259%
Average queueing time	+388%	+248%	+210%	+824%	+484%	+426%
Minimum order time	-0.5%	-1.3%	+10.1%	+0.7%	+0.3%	+11.8%
Maximum order time	+161%	+70.4%	+133%	+355%	+170%	+295%
Standard Deviation of throughput time	+252%	+191%	+404%	+671%	+517%	+1037%

5.3.4 Scenario ranking

This chapter summarizes scenario outcomes and manufacturing systems will be ranked according to results of KPIs. Systems are ranked in table 19. In addition, table 17 illustrates how ranking results were calculated. First, manufacturing systems are ranked by each indicator. Number one signify which system performed best and number three imply which performed worst. At the end of each performance view, the numbers are counted together to determine which system performed best in overall from that perspective. Finally, all ranking results are counted together which determines the overall performance in particular scenario.

Table 18 presents example of calculating percentage change ranking and score. These measures relative change in indicator results when compared to Scenario 1. It indicates how much performance changes when considering effect of failures, repairs, and work-in-process. The percentage change ranking is calculated same way as mentioned above. The overall percentage change score is counted from average of total results in all performance perspectives (i.e., score for MMS would be average of 7, 14, 9 and 7 in failure scenario 1). The score will be used in scenario ranking. This method of calculation was chosen so that the percentage change does not gain too much weight in the evaluation. Overall statistics is also considered in scenario ranking because it consists of vital indicators for evaluating total performance. Here, station downtime is disregarded because it does not reflect system’s performance. Throughput time is evaluated two times in overall statistics and delivery view to gain more weight to its importance. Lower total points per performance perspective indicates better overall result.

Table 17. Example of calculating performance ranking in Scenario 1.

Scenario ranking	***1=Best result, 3=Lowest Result. Scenario 1***						
Overall statistics	**MMS**	**RMS**	**DMS**	**Effectiveness**	**MMS**	**RMS**	**DMS**
Total time (min)	2	1	3	Throughput rate (per hour)	1.5	1.5	3
Average station utilization	1	2	3	Blockage ratio	1	2	3
Average throughput time (min)	2	1	3	Starvation ratio	1	2	3
				WIP (Work in Process)	2	1	3
Total	***5***	***4***	***9***	**Total**	***5.5***	***6.5***	***12***
Ranking	***2***	***1***	***3***	**Ranking**	***1***	***2***	***3***
Efficiency	**MMS**	**RMS**	**DMS**	**Delivery**	**MMS**	**RMS**	**DMS**
Availability	3	1	2	Average throughput time (per product)	2	1	3
Allocation efficiency	1	2	3	Average queueing time (per product)	1	2	3
Utilization efficiency	3	1.5	1.5	Standard Deviation of throughput time	2	3	1
Allocation ratio	1	2	3	**Total**	***5***	***6***	***7***
Production process ratio	2	1	3	**Ranking**	***1***	***2***	***3***
Total	***10***	***7.5***	***12.5***	***Total scenario results***	***MMS***	***RMS***	***DMS***
Ranking	***2***	***1***	***3***	***Total Scenario points***	***25.5***	***24***	***40.5***
				Scenario ranking	**2**	**1**	**3**

Table 18. Example for calculating percentage change score.

Comparison to Scenario 1	**Short MTTF & Short MTTR**						
Overal statistics	**MMS**	**RMS**	**DMS**	***Efficiency***	**MMS**	**RMS**	**DMS**
Total time	+3.3%	+3.0%	+3.4%	Availability	-2.8%	-3.2%	-2.5%
Total downtime (min)	5196	4839	5638	Allocation efficiency	0.0%	0.0%	+0.7%
Average station utilization	-3.1%	-2.7%	+5.2%	Technical efficiency	-3.5%	-3.3%	-3.5%
Average Throughput Time	+3.6%	+2.4%	+6.5%	Utilization efficiency	-2.9%	-3.3%	-3.5%
Total setup time (min)	-0.3%	-	-	Allocation ratio	-0.2%	+0.4%	+2.6%
				Production process ratio	-1.7%	-1.3%	+1.2%
Percentage change ranking	2	1	3	**Percentage change ranking**	2	3	1
	-	**-**	**-**		2.5	2.5	1
	3	2	1		2.5	1	2.5
	2	1	3		1	2	3
					3	2	1
					3	2	1
Total	***7***	***4***	***7***	***Total***	***14***	***12.5***	***9.5***
Effectiveness	**MMS**	**RMS**	**DMS**	***Delivery***	**MMS**	**RMS**	**DMS**
Throughput rate	-3.2%	-2.9%	-3.3%	Average throughput time	+3.6%	+2.4%	+6.5%
Setup-ratio	-0.4%	-	-	Average queueing time	+4.0%	+1.4%	+2.0%
Blockage ratio	0.0%	-0.2%	-0.8%	Minimum order time	+2.8%	+0.7%	+12.9%
Starvation ratio	+0.1%	+0.2%	-9.8%	Maximum order time	+2.9%	-12%	+5.2%
WIP	+0.6%	+0.2%	+5.1%	Standard deviation of throughout time	+6.9%	0.0%	+12.7%
Percentage change ranking	2	1	3	**Percentage change ranking**			
	3	2	1		2	1	3
	2	3	1		3	1	2
	2	1	3		2	1	3
Total	***9***	***7***	***8***	***Total***	***7***	***3***	***8***
					MMS	**RMS**	**DMS**
				Total score	**37**	**26.5**	**32.5**
				Percentage change score	**9**	**7**	**8**

Table 19. Scenario ranking results.

Results Ranking	**Scenario 1**			**Scenario 2**			**Scenario 3**		
	MMS	RMS	DMS	MMS	RMS	DMS	MMS	RMS	DMS
Overall Statistics	5	4	9	4	5	9	5	5	8
Efficiency	10	7.5	12.5	12.5	7	16.5	12	8	16
Effectiveness	5.5	6.5	12	5	7	12	5.5	7.5	11
Delivery	5	6	7	6	3	9	5.5	5.5	7
Total	**25.5**	**24.0**	**40.5**	**27.5**	**22.0**	**46.5**	**28.0**	**26.0**	**42.0**
Ranking	**2**	**1**	**3**	**2**	**1**	**3**	**2**	**1**	**3**
	Short MTTF & MTTR			**Long MTTF & MTTR**			**Short MTTF & Long MTTR**		
Overall Statistics	5	5	8	5	5	8	5	5	8
Efficiency	12.5	8	15.5	13	8	15	13	8	15
Effectiveness	5.5	7.5	11	5.5	7.5	11	5.5	7.5	11
Delivery	6	4.5	7.5	4	6	8	5	6	7
%Change*	9	7	8	8	9	7	9.5	9	5.5
Total	**38**	**32**	**50**	**35.5**	**35.5**	**49**	**38**	**35.5**	**46.5**
Ranking	**2**	**1**	**3**	**1.5**	**1.5**	**3**	**2**	**1**	**3**
	Buffer 5			**Buffer 10**			Lower points mean better performance. *Percentage change to Scenario 1. Determined by percentage change score.		
Overall Statistics	4	6	8	5	5	8			
Efficiency	13	8.5	14.5	13	8.5	14.5			
Effectiveness	5.5	7.5	11	5.5	7.5	11			
Delivery	6	3	9	6	3	9			
%Change*	9.5	7.5	7	10.5	7	6.5			
Total	**38**	**32.5**	**49.5**	**40**	**31**	**49**			
Ranking	**2**	**1**	**3**	**2**	**1**	**3**			

According to the ranking table, RMS provided best overall results almost in every scenario. In most cases MMS was ranked second and DMS the third. In overall statistics perspective, MMS and RMS performs almost equally. MMS excels in higher station utilization whereas RMS have faster throughput time and total production time. In terms of efficiency, RMS produce notably better results. MMS weaknesses are availability and utilization efficiency burdened by setup time. Without this, overall efficiency would increase, and total production time would be shortened. The effect can be seen when above indicators are compared to MMS allocation efficiency and allocation ratio which include set up time as station busy time. Effectiveness is highest in MMS in all scenarios followed by RMS. Throughput rate is closely same for MMS and RMS almost in every scenario. The difference between the two is MMS have substantially lower blockage and starvation ratio whereas RMS have lower WIP level. From delivery perspective, RMS generally performs better than MMS and provides faster throughput time almost every scenario. In turn, queueing time in MMS is lower than RMS. DMS produced lowest results in efficiency, effectiveness, and delivery perspectives.

It seems that there is noticeable difference in performance between DMS and modern systems. Positive in DMS is that performance percentage change is lowest in most scenarios when comparing results to Scenario 1. This means that relatively DMS performance was least affected from failures and buffer changes when compared to scenario 1 results. Here, inferior performance in Scenario 1 makes percentage change notably smaller. Still, in flexibility scenarios the production performance remained notably lower level than in other two system. Meanwhile RMS performed better measured by percentage change compared to MMS. Furthermore, RMS provided best results both in failure and WIP level simulated scenarios. This indicates better flexibility in view of station breakdown assurance and increasing buffer size on stations. Performance results remained similar when it was tested if increasing the product volume to ten thousand in all scenarios would have effect to scenario results.

5.4 Critical thinking of results

When evaluating manufacturing systems based on acquired results, it should be considered restrictions of the simulation model, simulated scenario, indicator limitations, and results from other simulation test. Transportation of products between stations was not simulated meaning neglecting transportation time. From the systems, this would have the greatest impact in MMS, where products are moved most between stations, thus extending product-specific manufacturing time and total time. Moreover, stations are closer in RMS and DMS which would indicate shorter transportation times. Setup-time had notable impact to MMS manufacturing time which presented average of 10% of total throughput time per product. If setup time could be halved or removed, MMS would produce in some scenarios fastest total manufacturing time (see Scenario 1 and 3). On other hand, if setup time would have been implemented to RMS and DMS, MMS would provide fastest time in more scenarios.

Balancing station times have also crucial impact to production speed which was not conducted in this simulation. The effect of this especially emphasized in DMS, as it would significantly shorten the final production time and speed up the production flow. This was noted in Hoffman et al. (2019) where DMS orders were sequenced optimally resulting in faster throughput time and better station utilization than MMS in their simulation test. The experiment however also included interchangeable processes. Here it can be argued that sometimes order sequencing and interchange processes are not possible. For example, if producing only one type of product or product processing need to follow specific order. Moreover, balancing stations times can be sometimes extremely difficult e.g., when tasks times differs a lot from each other.

In simulation, programming and decisions regarding how production function logic is constructed can also affect the performance. For example, Schönemann et al. (2015) uses agent-based simulation frameworks compared to discrete-event modeling used in this study. This usually also means that functions in model are designed differently. However, similar results were obtained with Schönemann et al. (2015) where MMS provided higher utilization of stations with more robustness against failures than DMS. Moreover, decisions considering e.g., product routing strategy have influence to final manufacturing results. In this study, the routing strategy were constructed with similar priority where the aim was to route products to stations which had shortest waiting time.

Initial simulation inputs have also crucial effect to performance results. Some indicators were changed to see how they affect (e.g., failure times). Fixed inputs in scenarios were number of stations, amount of product types, number of process tasks, and demand volume. Adding stations would benefit most MMS and RMS which can easily balance the task load between stations. DMS would require additional line to see benefits. Removing stations in DMS is not generally possible because lines are designed to produce specific product. Effect to MMS and RMS is harder to estimate without simulation test however, lead time is expected to increase. Effect of adding new product types or process stages needs simulation test for further analysis. Still, the effect is expected to be largest in DMS whereas most manageable in MMS because of multiple routing possibilities, changeable routing strategy, and stations' ability to process multiple process tasks. This also applies to RMS on a smaller scale. RMS and DMS need rearrangement of stations if new process tasks are implemented while MMS does not. Demand change (i.e., order arrival input) would affect most DMS because station utilization changes according to volume. RMS is expected to be more flexible as additional stations in each stage can be removed/added depending on the volume change. MMS provides most customization for changing volumes where some stations can be even closed. (Schnönemann et al., 2015; Greschke et al., 2014; Koren & Shpitalni, 2010; Koren et al., 2018; Hoffman et al., 2019.)

In simulated scenarios order arrivals was kept large to measure performance using maximum capacity. Effect of total amount of produced products was tested by increasing produced number to ten thousand in all scenarios. This had no notable effect to results. Obviously, indicators play a major role in reflecting the level of production effectiveness and critically influencing the final conclusions. It is also important to know which sub-indicators the performance indicators include and what is their relation to indicator result. For example, allocation ratio compares actual unit idle time (AUBT) to actual order execution time (AOET) where AUBT includes stations downtime meaning if it rises the ratio gets better (Kang et al., 2016). When thinking performance perspectives, this study does not contain quality performance perspective. Quality assurance can be more difficult in MMS because multiple stations make same processing stages meaning when product quality error occurs, it can be harder to find which station caused this when compared to RMS and DMS where stations are placed according to production tasks.

When comparing to results to other studies, in Schönemann et al. (2015) simulation test, MMS excels DMS by production efficiency and flexibility to handle failures. Also, utilization was presented being higher in MMS. This corresponds to this research results. On other hand, before mentioned Hoffman et al. (2019) simulation test results indicate opposite where better utilization was accomplished with balanced DMS line. In Schönemann et al. (2015) study, product line was not balanced. Still, Hoffman et al. (2019) test acquires same conclusion that MMS adapts better to unanticipated disruptions however DMS had faster throughput time without failures. This differs from our results. Klos et al. (2019) simulation study states that breakdown of one station in MMS does not impact throughput time with proper buffer allocation. This might be the case in failures with shorter repair times where our test resulted with only slight increase although optimal buffer allocation was not implemented. Hoffman et al. (2019) conclude MMS being better to prioritize rush orders. They also note that MMS require optimal level of stations to increase routing flexibility to meet throughput objectives (Hoffman et al. 2019). These were not tested. Standard deviation of station utilization was noted to be higher in MMS than DMS according to Schönemann et al. (2015). In research this was not tested.

When comparing RMS to DMS, Koren and Shpitalni (2010) concludes that RMS provide better productivity than DMS in larger scale manufacturing with numerous stages and multiple stations per stage. This complies with our test results as RMS provided better productivity and speed than DMS in every scenario. They also mention DMS would in turn result in higher productivity if stations have high tolerance against disruptions (Koren & Shpitalni, 2010). In our testing, RMS also provided better results in scenario where disruptions were neglected. Downside for RMS is that for each new product outside product family production need to be redesigned (Koren et al., 2018). Unfortunately, currently there are no comparisons done between MMS and RMS to evaluate results gathered from this research.

6 Conclusions

6.1 Summary and findings

This research conducted the simulation experiment to evaluate matrix-structured manufacturing system as potential successor for dedicated manufacturing system in high-volume production. To compare MMS with other modern system with potential to replace DMS, reconfigurable manufacturing system was implemented as addition to simulation experiment. The focus was to compare manufacturing performance in following perspectives: system efficiency, effectiveness, delivery and flexibility. This was accomplished by calculating selected key performance indicators based on ISO 22400 standard. Additionally, some other indicators were implemented which was seen crucial to evaluate performance more extensively from selected performance perspectives. Simulation models were built reflecting each of three manufacturing system. Each model included ten workstations where two types of products were produced. Simulation experiment included multiple manufacturing scenarios where for example production volume, buffer size, failure occurrence and repair time changed according to scenario. After running simulation tests, raw simulation data was collected, filtered, and organized according to manufacturing system and scenario. This data was presented in simulation result tables. Finally, manufacturing systems were ranked according to performance results.

Results showed that RMS system produced best outcome in almost every scenario. RMS especially excelled from production efficiency, delivery and flexibility perspectives when compared to other systems. MMS strengths were high station utilization and production effectiveness. DMS produced lowest results in every performance perspective and scenario. Still, the relative performance change considering flexibility scenarios were smallest. When simulation results were compared to other conducted simulation tests in research field, the results included both the same and opposite conclusions. Many other studies got similar results regarding better performance in MMS than DMS in station failure simulated scenarios. On other hand, one research got particularly different simulation results where DMS performed better than MMS in overall. Other difference regarding RMS in literature was DMS capability to be more productive when workstations are robust. In this research RMS provided notably better productivity than DMS even in failure free manufacturing. Research stated that production system optimization level and scenario selection with its inputs have crucial affect to simulation results.

6.2 Answering research questions

Next, set research questions and hypothesis will be answered according to simulation results.

I) *How MMS and RMS perform compared to DMS regarding productivity and operational flexibility when considering production time and WIP?*

MMS and RMS system provided considerably shorter total manufacturing time and higher throughput rate than DMS in every simulated scenario. Total production time in MMS and RMS were from 9% to 20% shorter than in DMS depending on scenario. Largest difference in total time was measured in scenario 2 where occasional failures occurred and simulation time scale were longest. This clearly points that in longer time scale, MMS and RMS can substantially reduce needed production time. Again, optimization of DMS line is noted to produce significantly better total time. When comparing MMS and RMS, times were close to same in almost every scenario. More demanding production scenarios e.g., increased number of failures and growing buffer size would favour RMS according to the results. When considering the operational flexibility regarding WIP, both MMS and RMS had significantly smaller average WIP level than DMS in every scenario. Between MMS and RMS, the RMS had noticeably smaller WIP level in overall. This means that RMS can handle larger number of products in production simultaneously. Thus, buffer size changes do not affect RMS as much as MMS or DMS. Finally, when considering possibility to redesign production line with ability to produce multiple types of products simultaneously, both MMS and RMS seem to be suitable for replacing DMS in future production applications where productivity and flexibility are important to answer changing customer demand.

II) In which production scenarios MMS is more suitable than DMS or RMS according to the simulation results?

Considering simulation results, MMS provided fastest total manufacturing time and highest station utilization in Scenario 2. Manufacturing scenario illustrated high-volume production with occasional failures and normal size buffers. Moreover, MMS provided equal results with RMS in scenario where less frequent station failures with longer repair times occurred. MMS also resulted same with RMS in scenario 1 while providing notably higher station utilization. Key performance indicators point that MMS is superior in station utilization, allocation efficiency, and reducing blockings and starvation. Thus, MMS is suitable for production scenarios where these are considered important. MMS is also most customizable one from the three systems when considering modifying current production layout, process flow, station number or processed tasks. This makes it suitable for production with unknown demand and possible new product entries. From simulation results, it should be highlighted that buffer size optimization with effective product routing strategy are essential for MMS. Moreover, ways to minimize setup time can notably shorten the lead time. Furthermore, technical investments are necessary. Thus, MMS is less suitable for production cases where station buffers are larger size, or organization lacks knowledge and skills to implement modern production technology. MMS is recommended for manufacturing cases where high volume of mixed types of products even outside product family are produced. Because secondary products can be produced in addition to main product or its product family, large capital investment can be justified. Potential manufacturing industries include automotive industry for example.

III) What are the benefits and disadvantages of MMS when compared to RMS and DMS?

According to simulation results, MMS provides combination of high productivity with high station utilization. MMS performed best from effectiveness perspective in overall. Furthermore, MMS provides high allocation efficiency and ratio because of more extensive product routing and ability to process multiple process stages in one station. As mentioned in literature chapter, MMS can produce multiple types of products even outside product family. This is not possible for DMS whereas RMS is limited to product family. Secondary product manufacturing in addition to main product is also possible unlike in other systems. MMS provides ability to modify current production layout and process flow making it more flexible to future customer demand. Occasional station disruptions or maintenances does not stop production. Moreover, ways to minimize setup time can significantly increase MMS overall performance.

Still, RMS provides better overall efficiency and delivery performance when considering all scenarios. Moreover, availability and production process ratio are higher in RMS than MMS due to faster production flow. In MMS, WIP level need to be maintained relatively low. Too high WIP will cause problems in product routing. Multiple stations need to have ability to process same manufacturing stage to fully utilize MMS product routing and to balance station cycle time. MMS will require significant financial as well as technological investment and most likely a complete redesign of the current production system. Thus, implementation of MMS is extremely challenging. Currently, there is very little experience and knowledge implementing such a system. For this reason, the RMS system is a more viable option for many, as many features and structures resemble a traditional production system.

Based on the literature on the field, the following hypothesis were presented at the beginning of research:

- H1: MMS leads to highest efficiency when workstation utilization is considered.
- H2: DMS provides fastest throughput rate in failure free production scenarios.
- H3: RMS produce shorter production time than DMS in production scenarios where workstation failures occur.

According to simulation results, MMS provides noticeably higher station utilization than DMS or even RMS in scenario 1-3. Compared to RMS and DMS, MMS resulted average of 6.7% and 7.9% higher respectively. In failure scenarios the average gap was 5.2% and 1.1% and in buffer scenarios 7.6% and 3.3%. Thus, hypothesis one is valid. Results also highlight higher utilization of stations in DMS than in RMS. The result in DMS increased particularly in failure scenarios where failures acted as balancing factor for station cycle time. Meanwhile the other systems result decreased at same scenarios. However, if comparing overall efficiency results (see table 19) RMS provided highest results in every scenario when station utilization is neglected. For example, RMS produced higher results in station availability and production process ratio than MMS. These indicators where either same level or favouring MMS when compared to DMS. This implies that more comprehensive investigation regarding comparison of MMS and RMS production efficiency is needed.

Hypothesis two assumes DMS have highest production rate of the three when there are no station failures. Failure free scenarios in this research were Scenario 1 and Buffer 5 and Buffer 10 scenarios. In these scenarios when analysing throughput rate, it can be clearly noted hypothesis is invalid. MMS and RMS resulted significantly higher throughput rate and substantially lower total production time. However, balancing cycle time in DMS line is expected to substantially increase throughput rate as discussed in critical thinking of results section.

Hypothesis three expected RMS to produce shorter total production time than DMS in scenarios where station failures occurred. Hypothesis can be stated valid as RMS produced significantly faster production time both in failure simulated and failure free scenarios. The average gap of total production time was 14%. If RMS were compared to MMS, RMS provided slightly shorter total time than MMS in all scenarios except the scenario 2. As gap were generally marginal, the shorter time for MMS in scenario 2 suggests that longer simulation time scales could favour MMS if buffer size and failure occurrence stay at moderate level.

6.3 Managerial and research implications

Before implementing any modern manufacturing system investigated in this thesis, manufacturers should evaluate their current production system automation level. For example, MMS is heavily depended on high level of automation and decentralized production control system. RMS does not require as advanced level of automation, but to fully utilize its potential, investments are needed to implementing key characteristics such as scalability, integrability and modularity. In most cases current manufacturer's system does not possess these and thus redevelopment of system is needed. The simulation assumes that the actual work would still be done by humans utilizing machines instead of automated robots. This was considered with variance in task time in workstations. Fully automated workstations with robots could potentially remove variance in task time thus enabling possibility to fully optimize cycle time. This would improve performance most in RMS and DMS as MMS relies on individual station cycle time.

With presented performance results gathered from various scenarios, manufacturers can evaluate suitability of each system to their own production scenarios. Moreover, it is possible to compare investigated system from one or more prioritized performance perspectives. For example, if manufacturer prioritize throughput time of manufacturing system, research results clearly show better performance of RMS in this regard. Simulation models can also be copied to manufacturer's own simulation. In addition, constructed simulation models can be used to investigate each system characteristics, improving models to better reflect desired characteristics and utilized to designing customized version of system to specific manufacturing case. Here however, guidelines of designing specific manufacturing system should not be neglected. The study also showed that simulation tools are very effective in reflecting real production systems. Thus, simulation tools are believed to be particularly useful in the deployment of modern complex manufacturing systems.

For researchers, this research provides information specially regarding production performance comparison between MMS and RMS which has been absence during conducting this research. Presented simulation models provide one method to simulate investigated manufacturing systems and modify the models as desired to better suit the objective in study. Moreover, results can be used in comprehensive analysis of manufacturing systems performance evaluation with other simulation tests in field. Considering this, researcher should note the limitation of simulation models in this study discussed in chapter 4.2 and 5.4.

6.4 Recommendations for future research

For future research, it is hoped to see more simulation tests where MMS and RMS systems are compared. Both systems share similar goal of combining productivity with flexibility and scalability. Research also showed that these systems are more than suitable for replacing traditional DMS line. Still, it is advised to test systems where each production line is optimized according to inputs. Simulation tests combined with larger variety of manufacturing scenarios would help recognise possible benefits and drawback of each system and provide more reliable results. Implementing transportation times and production logistics to simulation is concerned crucial especially when testing real case scenarios. To compare performance more profoundly, more extensive range of performance indicators with new performance perspectives e.g., quality is advised to consider. Due to time schedule of this research, only fundamental indicators reflecting workstation and whole production level performance from selected performance perspectives were implemented. Finally, it is desired to witness real case studies in future regarding MMS implementation for replacing older manufacturing system.

References

Adams, J., Khan, H. T. A., & Raeside, R. (2014). *Research methods for business and so cial science students* (2nd ed.). SAGE Publications. Restricted access. Retrieved 2021-11-23, from https://ebookcentral.proquest.com

Alexopoulos K., Efthymiou K., Chryssolouris G. (2014). System. In: The International Academy for Production Engineering, Laperrière L., Reinhart G. (eds) CIRP Encyclopedia of Production Engineering. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-20617-7_6574

Allied Market research (2018). *Simulation Software Market by Component (Software and Services), Deployment Mode (On-premise and Cloud), and Industry Vertical (Architecture, Engineering, Construction (AEC), Aerospace & Defense, Automotive, Electrical & Electronics, Healthcare, and Others): Global Opportunity Analysis and Industry Forecast, 2018 – 2025*. Allied Market Research. Retrieved 2021-11-19, from https://www.alliedmarketresearch.com/simulation-and-analysis-software-market

Andersen A., Brunoe T.D., Nielsen K., Rösiö, C. (2017). Towards a generic design method for reconfigurable manufacturing systems: Analysis and synthesis of current design methods and evaluation of supportive tools. *Journal of Manufacturing Systems*, 42, 179–195. https://doi.org/10.1016/j.jmsy.2016.11.006

Anylogic. (2021a). *Simulation Software for Every Business Challenge*. The AnyLogic Company. Retrieved 2021-10-2, from https://www.anylogic.com/features/

Anylogic. (2021b). *Anylogic Simulation Software*. The AnyLogic Company. Retrieved 2021-10-2, from https://www.anylogic.com/

AnyLogic Help. (2021a). *Animating agents in flowcharts*. The AnyLogic Company. Retrieved 2021-10-4, from https://anylogic.help/library-reference-guides/process-modeling-library/animating-agents.html

Anylogic Help. (2021b). *Process Modeling Library*. The AnyLogic Company. Retrieved 2021-10-4, from https://anylogic.help/library-reference-guides/process-modeling-library/index.html#process-modeling-library

Anylogic Help. (2021c). *Defining model logic*. The AnyLogic Company. Retrieved 2021-10-4, from https://anylogic.help/anylogic/data/index.html

Anylogic Help. (2021d). Data analysis items. The AnyLogic Company. Retrieved 2021-10-4, from https://anylogic.help/anylogic/analysis/index.html

Anylogic. (2022). *Download AnyLogic*. Retrieved April 9, 2022, from https://www.anylogic.com/downloads/

Awwad, A., Khattab, A., & Anchor, J. (2013). Competitive Priorities and Competitive Advantage in Jordanian Manufacturing. *Journal of Service Science and Management*, 6(1), 69-79. https://doi.org/10.4236/jssm.2013.61008

Babulak, E., & Wang, M. (2010). Discrete Event Simulation: State of the Art. In (Ed.), Discrete Event Simulations. IntechOpen. https://doi.org/10.5772/9894

Banks, J., Carson, J. S., Nelson, B. L., & Nicol, D. M. (2013). Discrete-Event System Simulation: Pearson New International Edition (5th Edition). Pearson International Content. https://bookshelf.vitalsource.com/books/9781292037264

Bi Z. M., Lang S. Y. T., Shen W. & Wang L. (2008). Reconfigurable manufacturing systems: the state of the art. *International Journal of Production Research*, 46(4), 967-992. https://doi.org/10.1080/00207540600905646

Borshchev, A. (2013). The Big Book of Simulation Modeling: Multimethod Modeling with Anylogic 6. Anylogic North America.

Bortolini, M., Galizia, F. & Mora, C. (2018). Reconfigurable manufacturing systems: Literature review and research trend. *Journal of Manufacturing Systems*. 49, 93-106. https://doi.org/10.1016/j.jmsy.2018.09.005

Breda University. (2022). *How to search for information?* Breda University of Applied Sciences. Retrieved 2022-02-03 from https://buas.libguides.com/c.php?g=670074&p=4776470

Caggiano, A. (2014). Manufacturing System. In: The International Academy for Production Engineering. Laperrière L., Reinhart G. (eds), *CIRP Encyclopedia of Production Engineering*. Berlin: Springer. https://doi.org/10.1007/978-3-642-20617-7_6562

Charness, G., Gneezy, U. & Kuhn, A.M. (2012). Experimental methods: Between-subject and within-subject design. Journal of Economic Behavior and Organization, 81(1), 1 - 8. https://doi.org/10.1016/j.jebo.2011.08.009

Chryssolouris, G. (2006). *Manufacturing Systems: Theory and Practice* (2nd edition). Mechanical Engineering series. New York: Springer.

ElMaraghy, H., Monostori L., Schuh G., & ElMaraghy W. (2021). Evolution and future of manufacturing systems. *CIRP Annals - Manufacturing Technology*, 70, 635-658. https://doi.org/10.1016/j.cirp.2021.05.008

ElMaragphy, H.A. (2006). Flexible and reconfigurable manufacturing systems paradigms. *International Journal of Flexible Manufacturing Systems*, 17, 261-276. https://doi.org/10.1007/s10696-006-9028-7

Esmaeilian, B., Behdad, S. & Wang, B. (2016). The evolution and future of manufacturing: A review. *Journal of Manufacturing Systems*, 39, 79–100. https://doi.org/10.1016/j.jmsy.2016.03.001

Filz, M., Herrmann, C., & Thiede, S. (2019, October). *Simulation-Based Data Analysis to Support the Planning of Flexible Manufacturing Systems*. Paper presented at 18. ASIM Fachtagung Simulation in Produktion und Logistik: Chemnitz, Germany.

Freiheit, T., Shpitalni, M., Hu, S.J. & Koren, Y. (2003). Designing Productive Manufacturing Systems without Buffers. *CIRP Annals*, 52(1), 105-108. https://doi.org/10.1016/S0007-8506(07)60542-3

Fries, C., Wiendahl, H., & Assadi, A.A. (2020). Design concept for the intralogistics material supply in matrix productions. *Procedia CIRP,* 91, 33–38. https://doi.org/10.1016/j.procir.2020.02.147

Gola, Arkadiusz & SWI'C, Antoni. (2012). Directions of manufacturing systems' evolution from the flexibility level point of view. *Innovations in Management and Production Engineering*, 226-238.

Grznár, P., Gregor, M., Mozol, Š., Krajčovič, M., Dulina, L., Gašo., M., & Major, M. A. (2019). System to Determine the Optimal Work-in-Progress Inventory Stored in Interoperation Manufacturing Buffers. *Sustainability*, 2019 11(14), 3949. https://doi.org/10.3390/su11143949

Greschke, P., Schönemann, M., Thiede, S., & Herrmann, C. (2014). Matrix structures for high volumes and flexibility in production systems. *Procedia CIRP*, 17, 160 - 165. https://doi.org/10.1016/j.procir.2014.02.040

Gumasta, K., Gupta, S.K., Benyoucef, L.B. & Tiwari, M.K. (2011). Developing a reconfigurability index using multi-attribute utility theory. *International Journal of Production Research*, 49(6),1669-1683.
https://doi.org/10.1080/00207540903555536

Hemalatha, C., Sankaranarayanasamy, K. & Durairaaj, N. (2021). Lean and agile manufacturing for work-in-process (WIP) control. *Materials Today*: *Proceedings*, 46, 10334–10338. https://doi.org/10.1016/j.matpr.2020.12.473

Hofmann, C., Brakemeier, N., Krahe, C., Stricker, N. & Lanza, G. (2019). The Impact of Routing and Operation Flexibility on the Performance of Matrix Production Compared to a Production Line. In: Schmitt R., Schuh G. (Eds.), *Advances in Production Research* (p.155-165). WGP 2018, Cham: Springer. https://doi.org/10.1007/978-3-030-03451-1_16

Huang, S., Wang, G., Shang, X. & Yan, Y. (2018). Reconfiguration point decision method based on dynamic complexity for reconfigurable manufacturing system (RMS). *Journal of Intelligent Manufacturing*, 29, 1031 – 1043. https://doi.org/10.1007/s10845-017-1318-2

Huettemann, G., Gaffry, C. & Schmitt, R.H. (2016). Adaptation of Reconfigurable Manufacturing Systems for Industrial Assembly – Review of Flexibility Paradigms, Concepts, and Outlook. *Procedia CIRP*, 52, 112 – 117. https://doi.org/10.1016/j.procir.2016.07.021

IndustryArc (2021). *Simulation Software Market - Industry Analysis, Market Size, Share, Trends, Application Analysis, Growth and Forecast 2021 – 2026*. 2021-11-10 from https://www.industryarc.com/Research/Simulation-Software-Market-Research-500917

ISO (2014). *Automation systems and integration — Key performance indicators (KPIs) for manufacturing operations management. Part 2: Definitions and descriptions.*

ISO 22400-2:2014. Edition 1. Retrieved 2021-11-6 from https://www.iso.org/standard/54497.html

Kang, N., Zhao, C., Li, J., & Horst, J.A. (2016). A Hierarchical structure of key performance indicators for operation management and continuous improvement in production systems. *International Journal of Production Research*, 54(21), 6333-6350. https://doi.org/10.1080/00207543.2015.1136082

Khezri, A., Benderbal, H.H. & Benyoucef, L. (2021). Towards a sustainable reconfigurable manufacturing system (SRMS): multi-objective based approaches for process plan generation problem. *International Journal of Production Research*, 59(15), 4533-4558. https://doi.org/10.1080/00207543.2020.1766719

Kiran, D.R (2019). *Production Planning and Control: A Comprehensive Approach*. Chapter 18, pages 261-278. Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-818364-9.00018-4

Klos, S., & Patalas – Maliszewska, J. (2019). Analyses of Manufacturing System Matrix Structure for Preventive Maintenance using Computer Simulation. *Acta Mechanica Slovaca*, 23(1), 44-48. Doi: 10.21496/ams.2019.009.

Kombaya, J.V., Hamani, N. & Kermad, L. (2021, March). *Customization Measurement in Reconfigurable Manufacturing Systems (RMS)*. Paper presented at Proceedings of the 11th Annual International Conference on Industrial Engineering and Operations Management. Singapore 7.-11.3.2021. Singapore.

Koren, Y. (2006). General RMS Characteristics. Comparison with Dedicated and Flexible Systems. In: Dashchenko A.I. (Eds.), *Reconfigurable Manufacturing Systems and Transformable Factories* (p. 27-45). Berlin: Springer. https://doi.org/10.1007/3-540-29397-3_3

Koren, Y., Gu, X. & Guo, W. (2018). Reconfigurable manufacturing systems: Principles, design, and future trends. *Frontiers of Mechanical Engineering*, 13(2), 121–136. https://doi.org/10.1007/s11465-018-0483-0

Koren Y., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., & Van Brussel, H. (1999). Reconfigurable Manufacturing Systems. *CIRP Annals*, 48(2), 527-540. https://doi.org/10.1016/S0007-8506(07)63232-6.

Koren, Y., & Shpitalni, M. (2010). Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems*, 29(4), 130-141. https://doi.org/10.1016/j.jmsy.2011.01.001

Krajewski, L. J., Malhotra, N. K., & Ritzman, L. P. (2018). *Operations Management: Processes and Supply Chains* (12th edition. Global edition.). Pearson.

KUKA Systems (2016). *Matrix production: an example for Industrie 4.0*. KUKA Systems. Retrieved 2021-10-19 from https://www.kuka.com/en-de/industries/solutions-database/2016/10/matrix-production

Kuzgunkaya, O. & ElMaraghy, H.A. (2007). Economic and strategic perspectives on investing in RMS and FMS. *International Journal of Flexible Manufacturing Systems*, 19, 217 – 246. https://doi.org/10.1007/s10696-008-9038-8

Maler-Speredelozzi, V., Koren, Y. & Hu, S.J. (2003). Convertibility measurement of reconfigurable manufacturing systems. *CIRP Annals - Manufacturing Technology*, 52(1), 367-370. https://doi.org/10.1016/S0007-8506(07)60603-9

May, M.C., Schmidt, S., Kuhnle, A., Stricker, N., Lanza, G. (2021). Product Generation Module: Automated Production Planning for optimized workload and increased efficiency in Matrix Production Systems. *Procedia CIRP*, 96, 49-50. https://doi.org/10.1016/j.procir.2021.01.050

Mordor Intelligence (2021). *Simulation software market - growth, trends, covid- impact, and forecasts (2021 - 2026*). Retrieved 2021-11-12, from https://www.mordorintelligence.com/industry-reports/simulation-software-market

MOT Oxford Dictionary of English. (2021). MOT Oxford Dictionary of English: modelling. Kielikone Oy. Retrieved 2021-11-14 from www.sanakirja.fi/oxford_english/english-english/modelling

Mourtzis, D. (2020). Simulation in the design and operation of manufacturing systems: state of the art and new trends. *International Journal of Production Research*, 58 (7), 1927-1949. https://doi.org/10.1080/00207543.2019.1636321

Mourtzis, D., Doukas, D. & Bernidaki, D. (2014). Simulation in Manufacturing: Review and Challenges. *Procedia CIRP, 25*, 213-229. http://dx.doi.org/10.1016/j.procir.2014.10.032

Oxford Reference. (2022). economy, efficiency, and effectiveness. Oxford Reference. Retrieved 2022-03-22 from https://www.oxfordreference.com/view/10.1093/oi/authority.20110803095741475

Renzi, C., Leali, F., Cavazzuti, M. & Andrisano, A.O. (2014). A review on artificial intelligence applications to the optimal design of dedicated and reconfigurable manufacturing systems. *The International Journal of Advanced Manufacturing Technology*, 72, 403-418. https://doi.org/10.1007/s00170-014-5674-1

Rösiö, C. & Säfsten, K. (2013). Reconfigurable production system design – theoretical and practical challenges. *Journal of Manufacturing Technology Management*, 24(7), 998-1018. https://doi.org/10.1108/JMTM-02-2012-0021

Sachdeva, J. (2008). *Business research methodology*. Global Media. Restricted access. Retrieved 2021-11-29 from http://ebookcentral.proquest.com

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2007). *Research methods for business students*. Pearson Education UK. Restricted access. Retrieved 2021-09-02 from http://ebookcentral.proquest.com

Schmidtke, N., Rettmann, A. & Behrendt F. (2021). *Matrix Production Systems - Requirements and Influences on Logistics Planning for Decentralized Production Structures.* Paper presented at Proceedings of the 54th Hawaii International Conference on System Sciences. https://doi.org/10.24251/HICSS.2021.201

Schönemann, M., Herrmann, C., Greschke, P., & Thiede, S. (2015). Simulation of matrix-structured manufacturing systems. *Journal of Manufacturing Systems*, 37, 104–112. https://doi.org/10.1016/j.jmsy.2015.09.002

Setchi, R.M., & Lagos, N. (2004, June). *Reconfigurability and reconfigurable manufacturing systems: state-of-the-art review*. Paper presented at 2nd IEEE International Conference on Industrial Informatics. Berlin 24.—26.06.2004. https://doi.org/10.1109/INDIN.2004.1417401

Singh, A., Gupta, S., Mohammad, A., Gupta, P. (2017). Reconfigurable manufacturing systems: journey and the road ahead. *International Journal of System Assurance Engineering and Management*, 8, 1849–1857. https://doi.org/10.1007/s13198-017-0610-z

Stephens, M.P. (2019). Manufacturing Facilities Design & Material Handling: Sixth Edition. Purdue University Press. Restricted access. Retrieved 2021-09-03 from https://ebookcentral.proquest.com

Sule, D.R. (2007). Production Planning and Industrial Scheduling: Examples, Case Studies and Applications, Second Edition (2nd ed.). CRC Press. https://doi.org/10.1201/9781420044218

Tecnomatix Plant Simulation. (2018). Tecnomatix Plant Simulation Help. Retrieved 2022-04-09 from https://docs.plm.automation.siemens.com/content/plant_sim_help/15/plant_sim_all_in_one_html/en_US/

Trierweiler, M., Foith-Förster, P., & Bauernhans, T. (2020). Changeability of Matrix Assembly Systems. Procedia CIRP 93, 1127—1132. https://doi.org/10.1016/j.procir.2020.04.029

UKEssays. (2018). Research Onion - Explanation of the Concept. Retrieved 2021-10-09 from https://www.ukessays.com/essays/sychology/explanation-of-the-concept-of-research-onion-psychology-essay.php?vref=1

Visual Components. (2022). System Requirements: Visual Components 4.4. Retrieved 2022-04-08 from https://www.visualcomponents.com/system-requirements/

Winsberg, E. (2019). "Computer Simulations in Science", *The Stanford Encyclopedia of Philosophy* (Winter 2019 Edition), Edward N. Zalta (ed.). Retrieved 2021-10-06 from https://plato.stanford.edu/archives/win2019/entries/simulations-science/