A Self-Configurable and Self-Adjustable Digital Twin For a Production Process

A case study at FOCUS-ON

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Challenge the future

A Self-Configurable and Self-Adjustable Digital Twin For a Production Process

A case study at FOCUS-ON

by

D.F. Edens

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PREFACE

In front of you, you find my master thesis to obtain the degree of Master of Science at the Delft University of Technology. It is the result of nine months of hard work in collaboration with FOCUS-ON. First of all, I would like to thank the graduation committee of the University for their support in this research. I would like to thank my daily supervisor, Frederik Schulte, for his continuous support, thinking with me in the process, but most importantly, keeping my spirits up. Finding the right goal has not always been easy during this project, but Frederik managed to challenge me during all our online meetings to set the right goal. Also, I would like to thank the chair of the thesis committee, Rudy Negenborn, for his supervision over the research and his input during our meetings. Secondly, I would like to thank FOCUS-ON for allowing me to execute this research within their beautiful company. Especially Gerwin, for his warm welcome at the production department of FOCUS-ON and his supervision over the project. Furthermore, I would like to thank Leonard for the fun and engaging discussions that helped me with the establishment of this thesis. I had a wonderful time graduating at FOCUS-ON, mostly thanks to the atmosphere and all the people. With the completion of my thesis comes an end to my life as a student. I would like to take the opportunity to thank my beloved family, for their unconditional support during the full duration of my studies. Also, a big thanks to the wonderful group of friends I have made during my time as a student.

D.F. Edens
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Abstract

Industry 4.0 being the fourth industrial revolution, builds further on the automation and information technologies of the previous industrial revolution. With the fourth industrial revolution the physical world and the virtual world are combined. A marriage between the digital and physical systems, these combined systems are called cyber-physical systems and consists of a physical component and a digital component. The digital component analyses information from the physical world, then it calculates or plans actions to steer the physical component to perform. A guideline for CPS implementation in industry is the unified system framework for general CPS applications. This framework is called the 5-level CPS structure, or 5C architecture. The five levels are: Smart connection, Data-to-information conversion, Cyber, Cognition and Configuration.
The digital part of a CPS is called the Digital Twin (DT). DT appears to offer a powerful an compelling application for manufacturing processes. The DT serves as a virtual replica of what is actually happening on the factory floor in near-real time. The DT can be used to optimize the operations of a manufacturing system by maximizing resource utilization, by balancing workload across resources, and minimizing inventory levels, with just-in-time deliveries.

FOCUS - ON is a joint venture between the companies: SAMSON and KROHNE. Their brand new product, the FOCUS-1 smart process node, combines the sensor, control valve and process control functions in one innovative unit. The FOCUS-1 will be produced in a completely new set up production facility in Dordrecht in the Netherlands. The production process is entirely digitalized: It has no paperwork. However, the production line is first try out. It is a so called greenfield project. A new company with a brand new product. Since the production line is a first of a kind, it is far from perfect. Therefore the production process is still under development and is continuously changing.
Before further large investments are done, there is need for more insight in the production process. A DT can provide this insight. This means that the DT should be able to reconfigure and adjust itself according to the increasing order demand. This requires that the DT should be at configuration level. However DTs are still in a developing phase and there is limited research done about DTs at configuration level. This research will propose a generic model for a self-configurable and self-adjustable DT for a production environment. The generic model DT model must be self-adjustable to an increase in order demand. The DT model will be used to gain more insight in the production process of FOCUS-ON and to propose adjustments in order to keep up with the increasing order demand. This brings us to the main question of this research:

"How would a self-configurable and self-adjusting DT, with a control agent, affect the performance of a fast-growing greenfield production line?"

A thorough system analysis of the FOCUS-ON production line is conducted to understand how the production process works, what the components are and how they interact with each other. Furthermore a literature review is conducted to identify which Key Performance Indicators (KPIs) can be used for a production process and the best simulation method for a production process. On the basis of this knowledge a DT model is developed according to the 5C architecture that is self-configurable and self-adjustable to a growth in order demand. The FOCUS-ON production line is equipped with barcode scanners. With these scanners the barcode attached to the order is scanned when an orders arrives and leaves a work station. Creating timestamps linked to an order and station, creating the First level: Smart connection. The second level, Data-to-information Conversion, is responsible for generating meaningful information from the different data sources. The barcode scanners used in the production line are part of the TrackOnline system. This digital system processes the timestamps data into information about the order processing times at the stations. The third and middle level, Cyber, acts as the central information hub in the 5C architecture. At this level all the information is gathered and we can speak of a digital representation of the real-world system. A discrete event simulation model of the production line is developed to represent a digital representation of the real-world production line. The input for the model exists of the information from the previous levels and the current production line set-up. The output that the model generates is the next level, cognition level. The output consists of the following KPIs: Production lead times, operator occupancy and the average waiting times for a station. The configuration level is the highest of the 5C architecture. This level acts as a supervisory control. It is the feedback from the cyber world to the real world and by doing so, closing the CPS circle. The DT can self-configure the system to apply corrective and preventive decisions. The controller, implemented in the model, acts on the models output and makes adjustments to the dynamic simulation model. These adjustments to the digital model can be used as advice for the production management who can apply adjustments to the real-world production line. And hereby closing the CPS loop from physical to digital and from digital back to the physical world.

The developed DT model is validated according to expert validation: Results of the model matches the expectation of the production manager. Because the newly set-up production line is a greenfield project and the production has not yet fully started, the DT model could not be validated by other models or historical data. Predictive validation can not be done due to time restriction of the project. Therefore the DT model is validated by an expert, the production manager. According to his knowledge the performance monitoring of the DT model does represent the expected performance of the real world production line. Yet, it can not be proven that the developed DT model is a true digital version of the production line, nevertheless the DT model is still found suitable for the purpose of this research.

The results show that the production line of FOCUS-ON with the current set-up can handle an order demand of up to 85 orders a month. To achieve a production capacity to keep up with the forecast of the upcoming year, three more operators are needed. Furthermore, the results show that at an order load of 156 orders a month a bottleneck occurs at the calibration station. Although the number of operators working at the production line is less than the number of stations they can work at. Adding more operators does not increase the production capacity any further. A second calibration station is needed to prevent increasing waiting times. Based on the results can be concluded that a self-adjusting DT can keep a desired performance with an increasing order demand. This is done by making adjustment to the system and self-configuring the simulation according to these adjustments. And hereby providing knowledge of the system, which is of high value for a greenfield project. Finally, it is recommended for research in the future to extend the configuration capabilities of the DT.

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ACRONYMS

ATEX ATmosphères EXplosibles

CPS Cyber-Physical Systems

DT Digital Twin

ERP Enterpise Resource Planning

KPI Key Performance Indicator

PDL Process Description Language

TPS Toyota Production Systems

CONTENTS

1

INTRODUCTION

1.1. INDUSTRY 4.0

Industry 4.0 (also known as Industrial Internet of Things) was initially founded by the German government who created a new vision for their industries.[9] The term Industry 4.0 is used for the fourth industrial revolution, hence the 4.0. This implies that this revolution has been preceded by three other industrial revolutions. The first industrial revolution took place in the second half of the 18th century. Mechanical production facilities were introduced by steam and water power. The second industrial revolution started from the 1870s with the upcoming of electricity and mass production. The third industrial revolution set in the 1970 with the digital computer. Advanced electronics developed the automation of production further. The four industrial revolutions are shown below in figure 1.1. Industry 4.0 being the fourth industrial revolution, it builds further on the automation and information technologies of the previous industrial revolution. With the fourth industrial revolution the physical world and the virtual world are combined. A marriage between the digital and physical systems, these combined systems are called Cyber-Physical Systems (CPS). These systems are capable to connect with other systems via machine-to-machine communication through the Internet of things. And these systems are steered by gathering information, Big data, that is obtained with the use of sensors or other gathering devices [10].

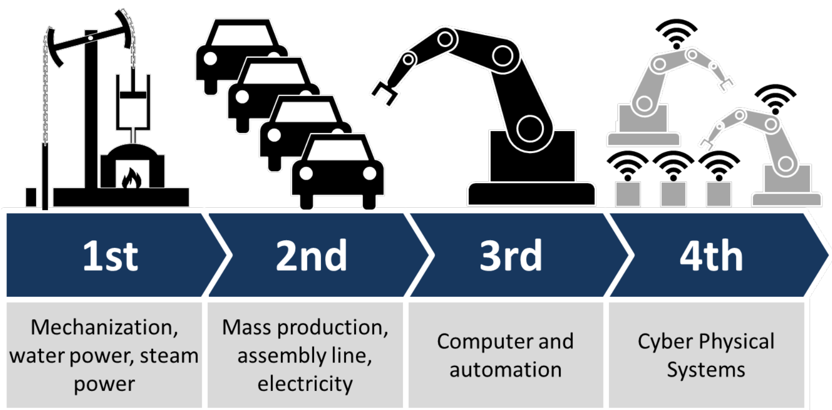


Figure 1.1: The four industiral revultions [1].

1.1.1. CYBER-PHYSICAL SYSTEMS

CPS consists of a physical component and a digital component. The digital component analyses information from the physical world, then it calculates or plans actions to steer the physical component to perform. The leaps between the cyber and physical components are shown in figure 1.2. CPS is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities [11].

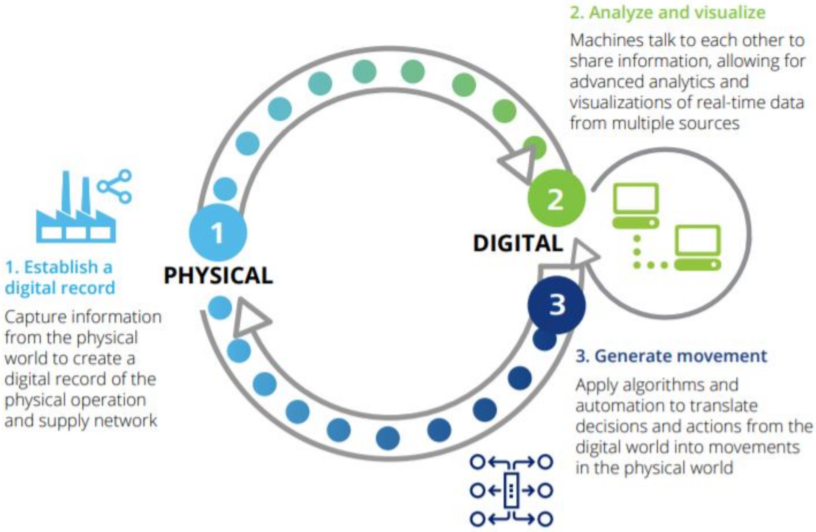


Figure 1.2: The physical-to-digital-to-physical leap. Source: Deloitte Center for Integrated Research.

As a guideline for CPS implementation in industry, Lee et al. have designed an unified system framework for general CPS applications [2]. This framework is called the 5-level CPS structure, or 5C architecture. As illustrated in figure 1.3 the 5C architecture is outlined as follows: Smart connection, Data-to-information conversion, Cyber, Cognition and Configuration .

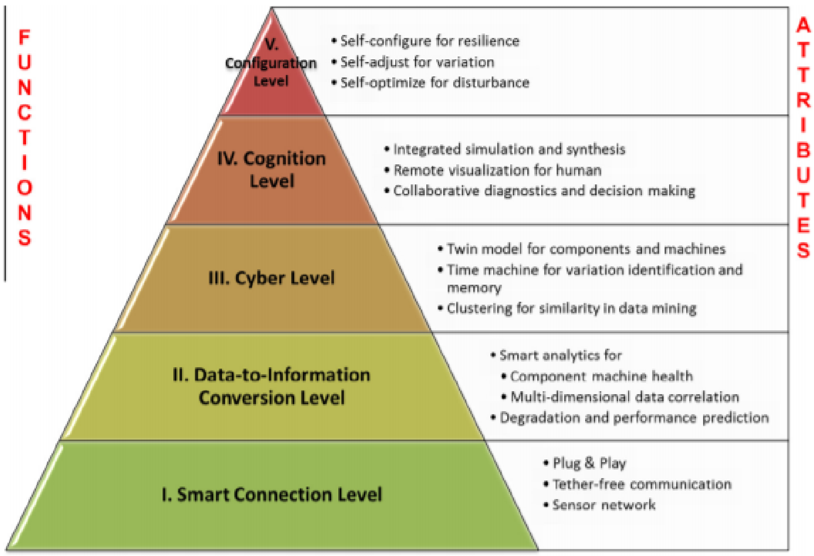


Figure 1.3: 5C architecture for implementation of Cyber-Physical System [2].

1.1.2. DIGITAL TWIN

The digital part of a CPS is called the Digital Twin (DT). The DT is limited to the digital model. In contrast to the CPS that is characterized by a physical asset and its DT. Although, the DT is only digital, it cannot exist without its physical counter part [12]. The DT can be seen as a method of achieving the convergence between the physical and virtual world [13]. Hence, the DT is a prerequisite for the development of a CPS [14]. The DT is a digital representation of a real-world entity therefore it contains both the structure and the dynamics of its real-world counterpart. By updating itself with real time data it represents a near real-time status of the its physical counterpart. The DT also contains the history of the physical entity. By simulating 'what-if' scenarios, the DT provides better insight in the behaviour of the system. It makes it possible to 'see' in the future of the physical system [15].

1.1.3. PRODUCTION ENVIRONMENTS

Especially for manufacturing processes, DT appears to offer a powerful an compelling application [5]. The DT serves as a virtual replica of what is actually happening on the factory floor in near-real time. The DT can be used to optimize the operations of a manufacturing system by maximizing resource utilization, by balancing workload across resources, and minimizing inventory levels, with just-in-time deliveries [15]. According to Garner, half of large industrial companies will use DTs in 2021, resulting in a 10% improvement in effectiveness for those organizations [16].

1.2. FOCUS-ON

FOCUS - ON is a joint venture between the companies: SAMSON and KROHNE. SAMSON, founded in 1907 in Mannheim, Germany, is a specialist in control valves for the process industry. Also originating in flow technology, KROHNE was founded in 1921 in Duisburg, Germany and specializes in process instrumentation. Through years of experience and world class engineering, both companies are on top in their field. In 2017, the CEO's of both companies took the first steps towards an extensive collaboration. And in September 2019 the joint venture FOCUS-ON was founded. FOCUS-ON wants to realize the full potential of the process industry, improving continuity and efficiency. With the objective: to develop, manufacture and market autonomous control solutions for process Industry 4.0 environments. Their product, the FOCUS-1 smart process node, combines the sensor, control valve and process control functions in one innovative unit.

1.3. PROBLEM STATEMENT AND LITERATURE GAP

The FOCUS-1 will be produced in a completely new set up production facility in Dordrecht in the Netherlands. The production process is entirely digitalized and has no paperwork. However, the production line is first try out. It is a so called Greenfield project. A new company with a brand new product. There is no prior knowledge available for the production of such devices. Therefore the production line is designed from scratch. Since the production line is a first of a kind, it is a far from perfect. Therefore the production process is still under development and is continuously changing. FOCUS-ON expects a fast growth in sales of the FOCUS-1. Therefore they need to increase the production capacity accordingly. Before further large investments are done, there is need for more insight in the production process. A DT can provide this insight. This means that the DT should be able to reconfigure and adjust itself according to the increasing order demand. This requires that the DT should be at configuration level. However DTs are still in a developing phase and there is limited research done about DTs at configuration level. Most research is about DTs at cognition level [17] [18] [19] [20]. Research about DTs and cofiguration level is limited. The research that is done, is about the configuration of the planning [21] [22] [14]. Research about a DT that is self-adjustable to growth in a 5C CPS architecture is lacking.

1.4. RESEARCH GOAL AND QUESTIONS

This research will propose a generic model for a self-configurable and self-adjustable DT for a production environment. The generic model DT model must be self-adjustable to an increase in order demand. The model will be used to gain more insight in the production process of FOCUS-ON and to propose adjustments in order to keep up with the increasing order demand. This brings us to the main question of this research paper:

"How would a self-configurable and self-adjusting DT, with a control agent, affect the performance of a fast-growing greenfield production line?"

In order to answer the main research question, several sub-questions are created to establish a firm guideline:

- *"What is the difference between a DT and a simulation?"*, *"What does 5C configuration level means for a DT?"*, *"What modelling type is best for representing a production environment?"* and *"What are the Key Performance Indicators for a production environment?"*
- *"What are the components of the production process and how do they interact with each other?"*, *"Which sensors are used in the production line and what data do they gather?"*, and *"How does the FOCUS-1 production line currently perform?"*

- *"How should the DT of the FOCUS-1 production line be modelled?"*
- *"Is the developed DT a valid representation for different and various cases?"*
- *"How does the production process performs in its current form?"*, and *"Which adjustment are needed for the production line to keep up with the increasing order demand?"*

1.5. RESEARCH METHODOLOGY

The problem of this research will be addressed according to the Delft system approach. This research starts with a literature review of DT for a production environment to find relevant information for this research and to provide this research with a theoretical background. Secondly, an analysis of the FOCUS-ON production line and its components is conducted. With this information a DT model will be developed according to the 5C architecture. This model will be verified and validated. Next the model will be used to conduct experiments. The results of the experiment will be analyzed to determine the performance of the production line in order to answer the main question.

1.6. RESEARCH OUTLINE

The remainder of this research is structured as follows: Chapter 2 discusses the latest literature with topics related to the issues addressed in this research. Chapter 3 consists of a description and a system analysis of the production facility of FOCUS-ON. Chapter 4 describes the development of a DT model. In Chapter 5 the DT model is verified and validated. Chapter 6 provides an experimental plan and discussions on the experiment results. Finally, Chapter 7 presents the conclusion of this research. Moreover, several recommendations are made for further research and for FOCUS-ON.

2

LITERATURE

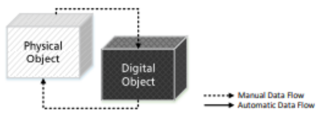
This chapter will look into the literature to answer these sub-questions:*"What is the difference between a DT and a simulation?", "What does 5C configuration level means for a DT?", "What modelling type is best for representing a production environment?"* and *"What are the Key Performance Indicators for a production environment DT?"* Section 2.1 elaborates the difference between a DT and a simulation. Section 2.2 describes the 5C configuration level for a DT. Section 2.3 discusses the simulation modelling techniques for a production environment DT. Section 2.4 discusses the KPIs for a production process. Finally, section 2.5 summarizes the answers of the sub-question of this chapter.

2.1. DT OR SIMULATION

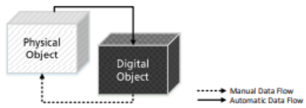
The idea of a DT: a virtual, digital equivalent to a physical product was first introduced as a concept for product life cycle management by Grieves in 2002 [23]. The model was originally named the Mirrored Spaces Model [24], and later changed to the Information Mirroring Model [25]. It was in 2011 that the model was named 'Digital Twin', a name that John Vickers of NASA coined for the model. NASA used the DT as a method to simulate and analyse in order to predict the structural behaviour of an aircraft [26]. NASA defined the DT as: *"An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin."* [27] In the research field, the more detailed definition by Glaessgen and Stargel [28] is used: *"Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin."* [29]

For manufacturing systems, Garetti et al. [30] presented the following definition for a DT: *The DT consists of a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behaviour of the production system at each life cycle phase in real time."* [31] In the literature the term DT is used slightly different over the disparate disciplines. Therefore Kirziger et al.[3] have proposed a a classification of DTs into three subcategories: Digital Twin, Digital Shadow and Digital Model, according to their level of data integrations. In a Digital Model, shown in figure 2.1a there is not any form of automated data exchange between the physical object and the digital object. All data exchange is done manual. Hence, changes of the physical part, have no direct effect on the digital part and vice versa. A Digital Shadow, shown in figure 2.1b, has an one-way data flow. Changes in the physical part leads to change in the digital part. If the data flows are fully integrated in both directions, it is referred to as a Digital Twin, shown in figure 2.1c. Changes in the physical or digital parts, leads to change in the counter part.

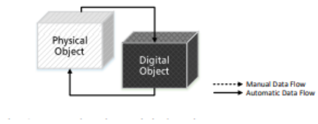
Describing the DT as a digital replica of a physical 'thing', it looks close like a simulation. Yet, there is a considerable difference. Simulations focuses only on 'what if' scenarios. They do not look at what is currently happening in the real world, but focus on what could happen. DTs on the other hand, have a near real-time synchronization with the real world and can therefore provide a high-fidelity representation of the operational dynamics of its real world counterpart [32]. For example: For manufacturing processes, this means that a DT can be used for monitoring, control, diagnostics and prediction [12]. Because of these capabilities,



(a) Data flow in a Digital Model



(b) Data flow in a Digital Shadow



(c) Data flow in a Digital Twin

Figure 2.1: Levels of data integrations between the physical and digital counter. [3]

DTs are also seen as the next generation of simulation [4]. Figure2.2 illustrates these generations of modelling, simulation an optimization technology. These generations are consecutive: Individual Application, Simulation Tools, Simulation-Based Design and Digital Twin Concept.

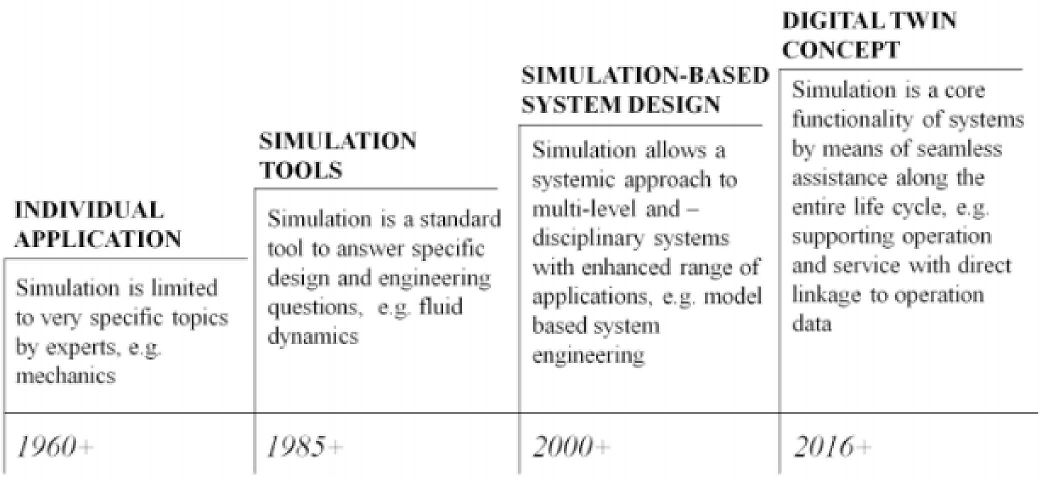


Figure 2.2: Next wave in Simulation enabled by Digital Twins. [4]

2.2. 5C CONFIGURATION LEVEL FOR A DT

In order to get a better understanding of what the configuration level is and what it means for a DT. The 5-level CPS structure, or the 5C architecture, developed by Lee et al. [2] will be described by explaining all the 5 levels. Figure 2.3 shows an overview of the 5 levels and the applications and techniques associated with each level. Below the picture, each level of the 5C architecture is described in detail.

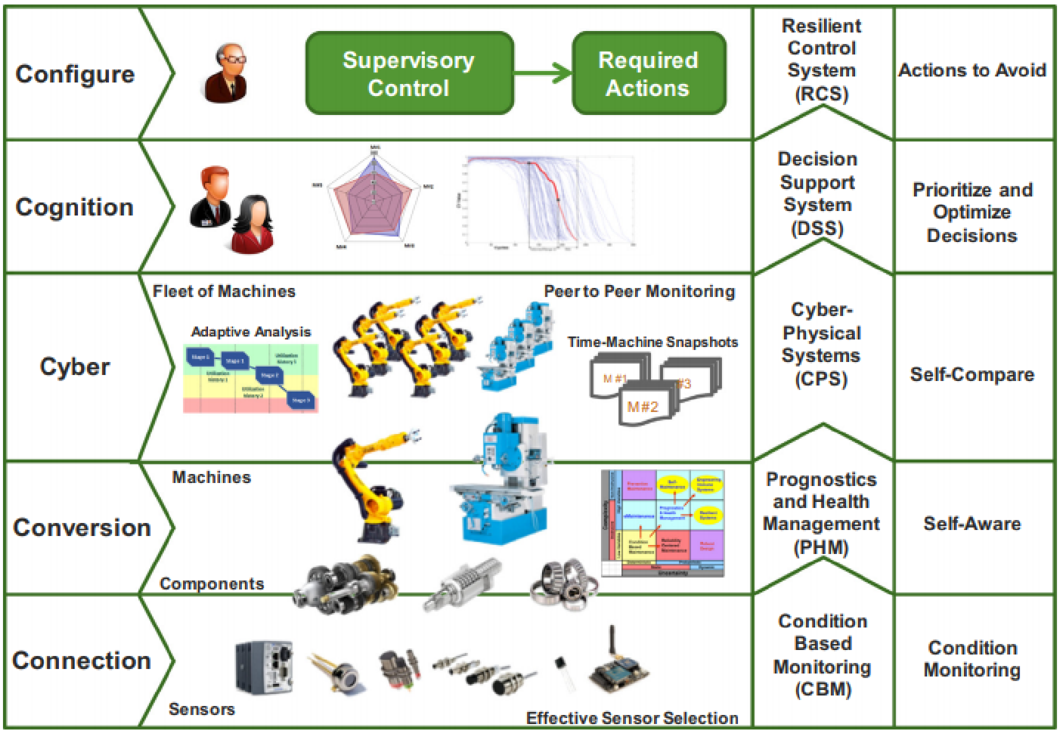


Figure 2.3: Applications and thechniques associated with each level of the 5C architecture. [2]

SMART CONNECTION

Smart connection the lowest level. This level is responsible for the making the connection between the physical to the digital world. This is done by sensors that acquire accurate and reliable data. Next to sensors, the data could also be obtained from enterprise manufacturing systems such as: Enterprice Resource Planning (ERP) and Manufacturing Execution Systems.

DATA-TO-INFORMATION CONVERSION

The second level, Data-to-information Conversion, brings self-awareness to machines. This level is responsible for generating meaningful information from different data sources, which can be achieved using algorithms for prognostics and health management.

CYBER

The third and middle level, Cyber, acts as the central information hub in the 5C architecture. At this level all the information is gathered. And we can speak of a digital representation of an real world object or system, a digital model. Analytic are used to extract information about the status of individual components, machines and the system.

COGNITION

The fourth level, called the cognition level, information is generated to present the acquired knowledge from the monitored systems. This can be presented to experts, other components and operators to support the decision making. If the information is presented to users, it is important that proper info-graphics are used to completely transfer the acquired knowledge.

CONFIGURATION

The configuration level is the highest of the 5C architecture. This level acts as a supervisory control. It is the feedback from the cyber world to the real world and by doing so, closing the CPS circle. Now the CPS can self-configure the system to apply corrective and preventive decisions, which have been made in the cognition level. An example of a DT that is at configuration level is that of Liu et al. [33]. They presented a digital twin-driven methodology for rapid individualised designing of automated flow-shop manufacturing system. With use of bi-level programming they propose an idea of iterative design optimization between static configuration and dynamic execution. Their proposed DT prototype can provide a optimal design because of this optimisation engine. An other example: Weyer et al. [4] have implemented and validated a framework for CPS modular production environments. When a new device is added to the simulation, a new CPS instance is created and can be immediately simulated and in case of a successful virtual commissioning, the tool can send feedback to the operator to carry out the reconfiguration process.

2.2.1. DT IMPLEMENTATION

Deloitte has proposed a DT conceptual architecture for implementation of a DT for a production process [5]. This architecture is illustrated in figure 2.4. It has similarities with the 5-level CPS structure proposed by Lee et al.

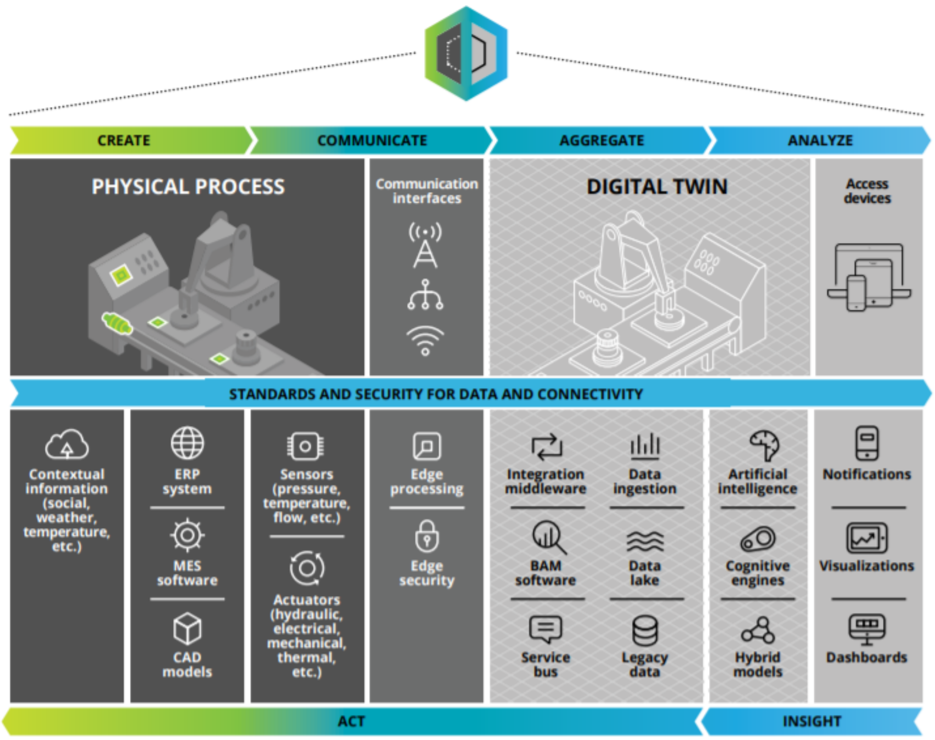
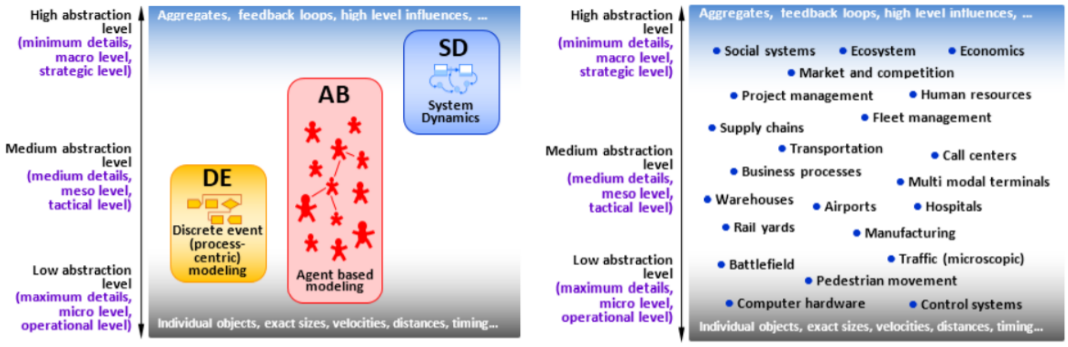


Figure 2.4: DT conceptual architecture by Deloitte University press.[5]

The architecture consists of a sequence of six steps: Create, communicate, aggregate, analyze, insight and act. **Create**: Equip the physical process with sensors to operational data from the physical world. **Communicate**: The communicate step makes the connectivity between the physical process and the digital platform. Similar to the 5C Connection Level. **Aggregate**: The data is gathered into a data repository, processed and prepared for analytics. Similar to the 5C Conversion Level. **Analyze**: In this step, the data is analyzed and generates insights. Similar to 5C Cyber level. **Insight**: The analytics are presented through dashboards with visualizations, highlighting unacceptable differences in the performance of the digital twin model and need action. Similar to 5C Cognition level. **Act**: At this step the actionable insights from the previous steps are fed back to the physical world and digital process to achieve the desired performance of the digital twin. This interaction completes the closed loop connection between the physical world and the digital twin. Similar to the 5C Configuration Level.

2.3. SIMULATION MODELLING

For modern simulation modelling there are three types of modelling methods: Discrete event simulation, agent based simulation and system dynamics simulation. Where each method has a specific range of abstraction [6]. See figure for an overview of the abstraction levels of the simulation modelling methods. Below the figure the simulation methods are described further.



(a) Simulation modelling methods. (b) Applications of simulation.

Figure 2.5: The abstraction level of the simulation modelling methods and their applications.[6]

2.3.1. DISCRETE EVENT SIMULATION

Discrete event modelling supports an abstraction level from low to medium. It uses a top-down architecture and is used to observe time-based behaviour within a system. Each event occurs at a particular instant in time and marks a change of state in the system. Between consecutive events, no change in the system is assumed to occur; thus the simulation time jumps directly to the occurrence time of the next event [34]. According to Flores-Garcia et al. who did a case study at a South Korean manufacturing company, developing a DT, discrete event simulation is insufficient in characterization of DTs for CPS in production logistics [35]. However, the results also indicate that the use of discrete event simulation may promote the development of DTs and can be used to improve production performance.

2.3.2. AGENT BASED SIMULATION

Agent based simulation modelling can be used for a broad range of abstraction. From highly abstract models, where the agents represent companies, to very detailed models where the agents represent physical objects. These agents act and interact with each, according to defined simulation rules. The individual actions and behaviour of the agents influence and determine the system performance. Contrary to discrete event simulation, Agent based uses a bottom-up architecture. Agent based simulation is suitable to model and simulate industrial processes [36]. An comparison between agend based simulation and discrete even simulation is made by Yin and Mckay [7]. See table 2.1 for an overview of the key characteristics of agent based simulation and discrete event simulation.

Table 2.1: The key characteristics of discrete event simulation and agent based simulation side by side. [7]

Discrete-event simulation	**Agent-based simulation**
Top-down modelling approach.	Bottom-up modelling architecture.
Focus on modelling overall system processes in detail.	Focus on modelling individual agents and interactions between them.
A centralized simulation system architecture, i.e., a given simulation has one thread of control.	A decentralized simulation model architecture, i.e., each agent has its own thread of control
The modeled system performance is related to the defined system process.	The modeled system performance is not defined in the simulation model but emerges from the autonomous agents' actions, interactions and decision-makings.
The identification of queues is a key consideration in overall system performance.	Queueing issues are not defined.
Model inputs are often based on objective data, e.g., that has been collected from the system that is being modeled.	Model inputs are often based on theories and subjective data related to the agents' behaviors.
Entities in the simulation model are process steps related to other steps but with no capacity to act independently; the performance of the overall system depends on relationships between process steps.	Individual agents can use their own initiative and make decisions that influence the behavior of the overall system.

2.3.3. SYSTEM DYNAMICS SIMULATION

System dynamics assumes the highest level of abstraction of all the modelling methods. It ignores the fine details of a system (e.g. individual properties of people, products, or events) and produces a general representation of a complex system. Due to its high abstraction level, this method is most suitable for long-term strategic modelling and simulation.

2.3.4. SIMULATION TOOLS

For manufacturing environments there is professional simulation software available. Examples are SIMATIC[1] from Siemens, DELMIA[2] from Dassault System and AnyLogic[3]. These powerful process simulation tools come with specially designed libraries that simplifies the simulation of complex manufacturing systems and operations. Which can be very useful when designing detailed models of production facilities and managing material workflows. Downside of these professional software tools is that they have a high price. However, AnyLogic provides a free student version. Yet, the simulation functions in this version are limited. Simulation can also be done with open source software such as python. However, this kind of free software has no specially designed libraries for production environments and 3D animation capabilities.

2.4. PRODUCTION PROCESS KPIS

KPIs are management techniques employed to enable efficient and effective monitoring of businesses, and are generally acknowledged to be a set of measures critical to the current and future success of any organization [37]. For production processes there a numerous KPIs available. The three mostly common are: cycle time, takt time and lead time, and are often interchangeably used in manufacturing.

Cycle Time is the actual time spent working on producing an order, measured from the start of the first task to the end of the last task. Cycle time includes both value-added time as well as non-value-added time. Cycle time is calculated by the total production time divided by the units produced. For single piece flow unit with time step in minutes:

$$CycleTime[min] = FinishTime[min] – StartTime[min]$$

[1]https://new.siemens.com/global/en/products/automation/topic-areas/simulation-for-automation.html
[2]https://www.3ds.com/products-services/delmia/
[3]https://www.anylogic.com/manufacturing/

If units are produced in batches, The cycle time becomes:

$$CycleTime[minutes/units] = \frac{FinishTime–StartTime}{UnitsProduced}$$

Takt Time is the amount of time an order needs to be completed to meet the customer's on-time delivery deadline. The amount of time between one part being completed and the next part being completed must be the same or less than the takt time, or we can assume that the parts will not be produced per the customer's schedule.

$$TaktTime = \frac{AvailableTime[min]}{CustomerDemand}$$

For example, an order for 160 units has been placed at the beginning of the week and is due at the end of the week. The available time is 40 hours, and the demand is 80 units. Using the formula, we divide 40 by 160 and get a Takt Time of 1/4 hour. Meaning, that one unit must be completed every 15 minutes to meet the customer demand.

Lead Time is the total time it takes from the initial product order to the final delivery.

$$LeadTime = OrderDelivered - OrderRecieved$$

A variant of the Lead Time is the Production Lead Time: The time it takes one order to move all the way through a production process from start to finish (minutes, hours, etc.). The Production Lead Time is also known as Total Product Cycle Time.

An other common KPI for production is asset utilization. For example the utilization of the workforce: The percentage of time employees spend making effective contributions. The workforce utilization is calculated as follows:

$$WorkforceUtilization[\%] = (ActualWorkTime[m]/TotalWorkTime[m])x100[\%]$$

Word wide is the Toyota Production Systems (TPS) seen as the standard for "wold class manufacturing". The TPS is a management system that organizes manufacturing and logistics for the automobile manufacturer, including interaction with suppliers and customers. The system is a major precursor of the more generic lean manufacturing [38]. Three terms often used together in the TPS that collectively describe waste are: Muda, Mura and Muri.

- **Muda**: Any activity that consumes resources without creating value for the customer.
- **Mura**: Unevenness in an operation.
- **Muri**: Overburdening equipment or operators

TPS originally identifies seven forms of Muda or waste. Which can be remembered by the acronym TIMWOOD. The seven types are named and elaborated below:

- **Transport**: Moving products that are not actually required to perform the processing.
- **Inventory**: All components, work in process and finished product not being processed.
- **Motion**: People or equipment moving or walking more than is required.
- **Waiting**: Waiting for the next production step.
- **Overproduction**: Production ahead of demand.
- **Over Processing**: Resulting from poor tool or product design resulting extra activity.
- **Defects**: The effort involved in inspecting for and fixing defects.

2.5. CHAPTER SUMMARY

In this chapter the the answers to the first set of sub-questions is given. Section 2.1 elaborates the difference between a DT and a standard simulation. Section 2.2 describes the 5C Configuration level in combination with a DT. Section 2.3 explains the different modelling types. Lastly, in section 2.4 the KPIs for a production are introduced. Now that the literature is known, the production line of FOCUS-ON system will be discussed in the next chapter.

3

SYSTEM ANALYSIS

In this chapter an analysis of the production line of FOCUS-ON will be presented. The production of the FOCUS-1 will be discussed. This chapter will present the answers to the following sub-question: *"What are the components of the production process and how do they interact with each other?"*, *"Which sensors are used in the production line and what data do they gather?"*, and *"How does the FOCUS-1 production line currently perform?"* The system analysis is based on: Observations from the work floor, conversations with people that are involved in the process, the work instructions and internal reports. First, the product that is produced in the production process is introduced: The FOCUS-1. Next the whole production line will be discussed. All the main components of the production process will be described. Furthermore the performance of the production line and the individual station will be discussed. Finally, a summary of this chapter will be presented. Disclaimer: Since FOCUS-ON is a start up and are still in their build up phase. There are developments in the production process. Therefore it is possible that in-time this analysis of the production process of the FOCUS-1 may become inaccurate or even obsolete. This system analysis dates from week 3 of 2021.

3.1. THE PRODUCT: FOCUS-1

The FOCUS-1 smart process node combines the sensor, control valve and process control functions in one device. It is the first product launched by FOCUS-ON. See figure 3.1 for a picture of the device. The FOCUS-1 is suited for a pipe diameter of 80 mm (DN80, 3 inch). And consist of four main components: Body, Electronics (E-house), actuator and plug and seat. Shown in figure 3.2. For each of these main components multiple variants are possible. For example: For the body DN80, four flow pressure variations are available: CL150, CL300, PN16 PN40. This makes it possible that the FOCUS-1 can be modified to the desires of the customer. In attachment B a complete overview of all the available options for the main components is shown. In the second quarter of this year (2021) the production of the DN100 version, suited for a pipe diameter of 100 mm, will start. And at the end of the year the production of the DN50, suited for a pipe diameter of 50 mm, starts.

Figure 3.1: FOCUS-1 device. Source: FOCUS-ON

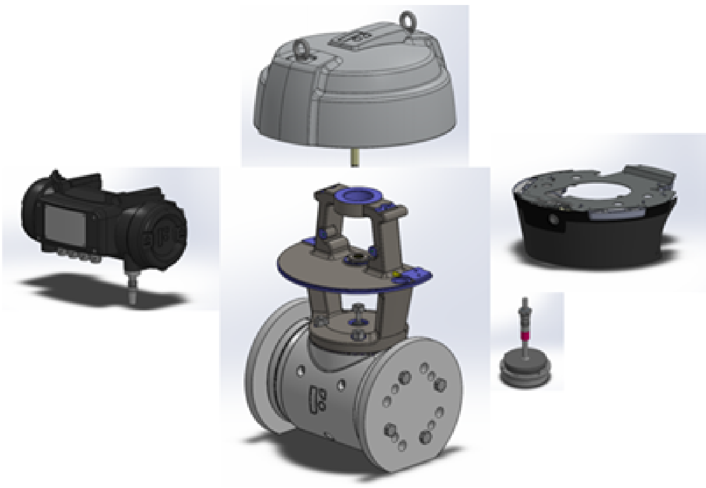


Figure 3.2: Left: E-house, Top mid: Actuator, bottom mid: Body, top right: Cover and bottom right: Plug and seat. Source: FOCUS-ON

3.2. PRODUCTION LINE

The production line is located in building K2 at the Krohne facility in Dordrecht, in The Netherlands. At this location, the FOCUS-1 is assembled from parts. All the parts are supplied, FOCUS-ON does not manufacture parts themselves. In figure 3.3 pictures of the production are shown. Figure3.4 shows a schematic layout of the production hall. The grey arrows indicate the inbound and outbound flows: Inbound of stock and shipments of FOCUS-1 orders. The black arrow shows the main production flow of a FOCUS-1 production order. The orange arrows indicate all the production steps between the work stations. A schematic view of al the production steps is shown in figure 3.5. Each block indicates a station. These station are described in detail in the next section.

Figure 3.3: The production line of FOCUS-ON

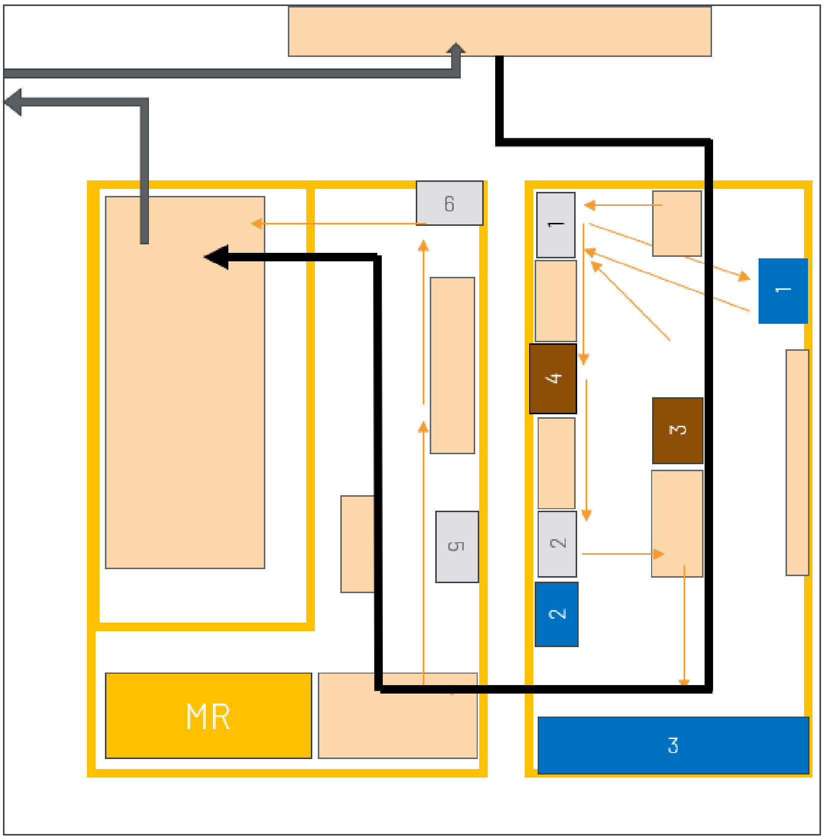


Figure 3.4: Floor plan of the production process. Source: G.Hament

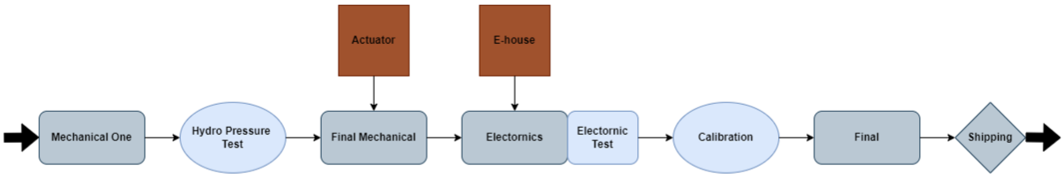


Figure 3.5: Schematic view of the production process.

3.3. Main Components of the Production Line

In the section the main components of the production line are discussed. These components are involved and have an influence on the production process.

3.3.1. Production Carts

The FOCUS-1 is build on a cart. These carts make it possible to move the FOCUS-1 along the production line from station to station. There are currently 4 carts at the production line. See figure 3.6 for a picture of a production cart.

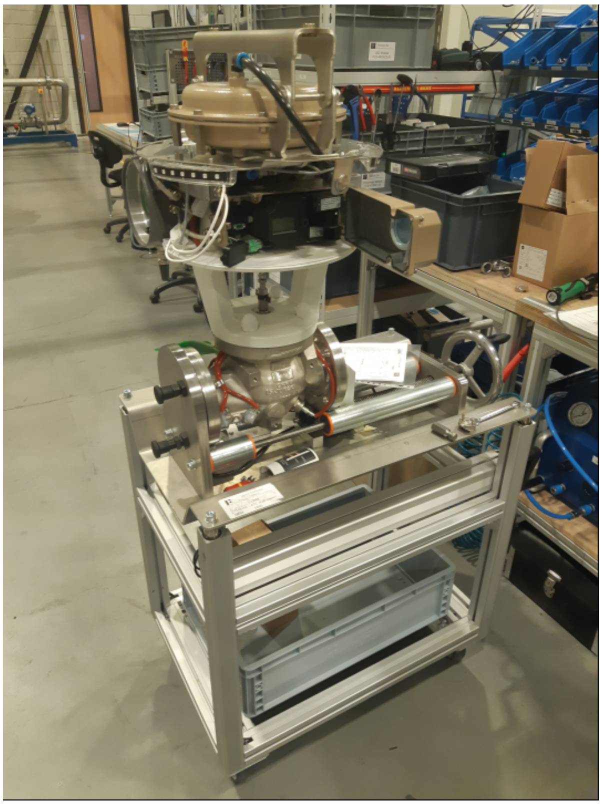


Figure 3.6: A production cart with a FOCUS-1 device on it.

3.3.2. Workforce

In the production process there are currently four people involved. There are three people in production. They work at the workstations (except the shipment station) and assemble the FOCUS-1. The other person is responsible for the logistics. This person makes sure the inbound supplies are stocked in the main inventory. The local inventories are stocked with goods from the main inventory. And operates the shipment and packaging station. The operators have a 40 hour work week. The shifts are from 07:30 to 16:15. These shifts include 2 breaks: An coffee break in the morning of 15 minutes and a lunch break of 30 minutes. Twice a week there is a team meeting of 30 minutes.

3.3.3. Cranes
Because the FOCUS-1 is a heavy device (approximately 90 kg) and some parts are too heavy to lift, two type of cranes are used in the production process. An overhead crane and a mobile crane. There are 2 overhead cranes that can reach all the stations except: Final assembly and shipping. These station are not located underneath the overhead crane.

3.3.4. Workstations
In this section all the workstations are discussed. A short descriptions of the process at each station type is given. All the workstations are equipped with the tools needed for the assembly process. And are equipped with local inventory, this way the worker has everything within reach. In figure 3.7 the first workstation of the process is shown: Mechanical 1 assembly. All the workstations are also equipped with a computer and a scanner and are steered by the TrackOnline application. Due to this application the entire production process is paperless. The application creates a digital product file for every work order and keeps track of which parts are assembled into the device and updates the product file of the device with the parts.

Figure 3.7: The mechanical 1 work station. Equipped with all the tools and stock.

Mechanical 1 assembly
This is the first station of the production line. First the body is placed on a cart. The work number is slammed into the body. Next, four transducers and two PT sensors are installed on the body. Then the bonnet is placed

on the body. Because the bonnet is a heavy part, a crane is used to install the bonnet on the body.

HYDRO PRESSURE AND LEAKAGE TEST

First the device is put in to the test station with the use of the mobile crane. To connect the device to the test station: Blindflensen are attached to the body of the device. First a hydro pressure test is conducted, followed by a leakage test. After the tests: the device is disconnected from the test station. The blindflensen are removed and the device is placed back on a cart with the use of the mobile crane.

SUB-ASSEMBLY: ACTUATOR

At this station the actuator is assembled. One step of the assembly is to glue a bolt stuck. It stakes 20 minutes before the glue is dry. When the actuator is assembled, it is placed in the local inventory with the mobile crane. Currently there are four different actuators: the 350 and 750, both are available in the version air to close and air to open. The time to produce an actuator is approximately the same for all the variants.

FINAL MECHANICAL ASSEMBLY

At this station the bracket is attached to the device. The actuator is installed with the crane. The positioner and the pneumatic module are also installed on the device.

SUB-ASSEMBLY ELECTRONICS

At this station the electronic house (e-house) for the FOCUS-1 is assembled. When it is finished it is placed the local storage. Currently there are two versions of the e-house: An explosion safe version, ATEX, and a normal version, NONEX.

ELECTRONIC ASSEMBLY AND TESTING

This station has two steps: At the first step the e-house is installed on the device and all the wires are connected and the electronics are tested. At the second step, the software is installed on the device and the configuration file is loaded onto the device.

CALIBRATION AND PERFORMANCE TEST

The overhead crane is used to place the device into the calibration test station. Three tests are done at this station: Calibration, auto tune and control performance. If the device passes the tests, it is placed back onto a cart with the overhead crane.

FINAL ASSEMBLY

At the final assembly station covers plates are placed on the actuator, the e-house and valves. Now the FOCUS-1 is fully assembled. The device is placed on a transport pallet with the mobile crane or the overhead crane.

PACKAGING AND SHIPPING

First the a sticker with the specifications is placed onto the device. However, the device needs to be lifted with the mobile crane to place the sticker in the right place. The device will be attached to the pallet with two hotmelt bands. Then the air filter regulator, the documentation map and Quickstart guide are added to the package. A cardboard box is place over the pallet and attached with straps. A layer of tape is used over the straps. Finally, the packing slip is attached to the box. Now the FOCUS-1 device is ready for shipment.

3.4. SENSORS AND DATA ACQUISITION

The TrackOnline application collects data about the productions process. This data is acquired by scanning the barcodes of the work orders with a hand scanner by the operators. The application registers the times when a work order arrives at the station and when the work order is released from the station. This data makes it possible to know exactly how long a work order is at a station, the waiting time between the stations and the total cycle time of the production of one device. The data is linked to an operator, therefore the data can also be used to measure the performance of the operator. In figure 3.8 an example of the data gathered of one specific order is shown. It shows the start and end time at each station. Furthermore, it shows the calculated process time of each station and the total production lead time. Note that this information has a flaw. The system measures the absolute time, not the actual time worked on the device. If a operator has a break during a process, the measured time is not representative. Or it could also happen that the work shift ends during a process and the work it picked up the next day.

Werkorder	Serienumn	Productiecel	Tijdstip start	Tijdstip gereed	Doorlooptij	Operator	Totale doorlooptijd werkorder
20200134	190001	Mechanical assembly	24-11-2020 13:17:50	24-11-2020 13:22:18	5	Gerwin Ha	14400
		Pressure test	24-11-2020 14:36:56	24-11-2020 15:16:16	40	Gerwin Ha	-
		Final mechanical assembly	26-11-2020 08:10:50	26-11-2020 08:25:48	15	Gerwin Ha	-
		Electronics assembly	03-12-2020 08:04:41	03-12-2020 08:05:33	1	Gerwin Ha	-
		Final assembly	04-12-2020 09:07:15	04-12-2020 13:36:11	269	Gerwin Ha	-
		Subassembly Actuator	26-11-2020 07:54:35	26-11-2020 07:55:26	1	Gerwin Ha	-
		Subassembly E-housing	26-11-2020 10:00:01	26-11-2020 10:07:04	7	Gerwin Ha	-
		Packaging, documentation and shipping	04-12-2020 13:50:38	04-12-2020 13:52:24	2	Gerwin Ha	-

Figure 3.8: Data gathered by the trackonline system for one device. Note that the process times are not representative due to the fact that the operators were not scanning correctly according to procedure.

The company uses an Enterpise Resource Planning (ERP) system from Exact [1]. This system provides real time data about the stock and orders. The orders are planned with the program: Vplan [2]. This program is a planning tool. This tool is used to plan the orders for production and places the work orders in TrackOnline so the operators know what to produce.

3.5. PRODUCTION LINE PERFORMANCE

The production has not yet fully started, resulting in limited available data regarding the process times of the stations. Furthermore, the TrackOnline tool is not always correctly used by the operators. Hence, the available data in TrackOnline is not reliable. In order to gain a more realistic information about the process times of the station, time measurements by hand are conducted. In figure 3.9 these measurements are shown.

		werkstations							
meting		mechanica	hydrotest	Final mechinical	electroniics assembl	kalibratie en te	final assembly	electronics sı	actuator sub
	1	00:43:12	01:04:43	00:47:25	01:06:39	01:10:19	00:51:37	00:43:17	00:25:45
	2	00:32:23	01:12:48	00:42:45	00:53:51	00:58:33	00:43:33	00:34:27	00:23:09
	3	01:21:34	00:42:47	00:52:11	01:02:41	01:07:48	00:36:24	00:38:30	00:20:04
	4	00:53:22	00:35:06	00:27:52				00:31:17	00:21:50
	5	00:37:58		00:50:41					00:51:02
	6								
average		00:52:38	00:53:51	00:42:33	01:01:04	01:05:33	00:43:51	00:36:53	00:22:42

Figure 3.9: Time measurements by hand: Source: Kerker & van de Wijngaart

Due to the limited available data about the process times of the stations, the current performance of the production line is not yet known. However, according to the production manager, who designed the production line, it is assumed that for every operator, one device should be produced per work day. So for the current set-up of three operators, three devices per day should be produced. FOCUS-ON has ambitious plans and expects a fast growth in sales of the FOCUS-1 device, resulting in a fast growth of order demand for the production line. The current order demand is six orders a month, the production forecast shows that in the end of this year the order demand grows up to 145 orders a month. The order demand forecast from the production report is shown in figure 3.10.

[1] https://www.exact.com/nl/producten/productie
[2] https://www.vplan.nl/nl/

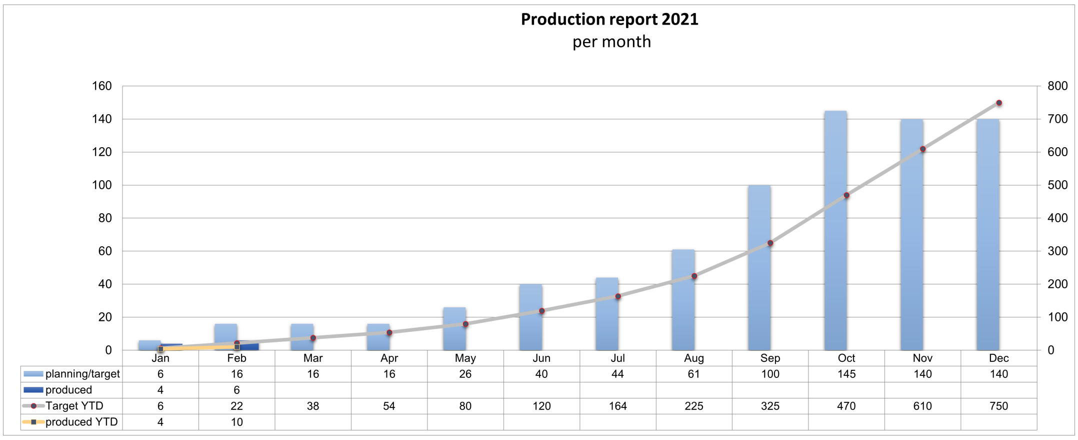


Figure 3.10: Order demand forecast. Source: FOCUS-ON

3.6. Chapter Summary

This chapter has observed the production facility of FOCUS-ON. Section 3.1 introduces the product made in the facility. Section 3.2 and 3.3 answer the first sub-question by given an overview of the production process and all its components. Section 3.4 answers the second sub-question by getting more into detail about the sensors and data available in the production process. Lastly, section 3.5 answers the third sub-question by discussing the current performance of the production line and the order demand forecast for the upcoming year.

4

Model Development

This chapter elaborates the development of the Digital Twin model that will be used to answer the main question of this research. At the end of this chapter, this sub-question will be answered: *"How should the DT of the FOCUS-1 production line be modelled?"* The sections of this chapter are consecutively: DT process design, data collection and aggregation, modelling method, model boundaries and assumptions, model input, output and KPIs, conceptual model and finally the simulation objects, processes, as well as the interactions between the objects.

4.1. Digital Twin process design

The development of the DT for the production line of FOCUS-ON will be done according to the 5C architecture for CPS and the similar DT architecture from Deloitte. The first level, smart connection, already exist. The production line is equipped with sensors (barcode scanners) that capture data from the real world and hereby make the leap from the physical world to the digital world. Furthermore, FOCUS-ON uses digital systems that contain information about the physical production, for example the ERP system. The second level, data-to-information conversion, is achieved by collecting all the raw data from the sensors and convert this into information. Section 4.2 describes this conversion. The obtained information is analysed in a DT model of the production line. This digital replica of the production line is the cyber level. The development of this DT is described later on in this chapter. The DT model generates information about the production line. This information will be presented by using info-graphics to present the acquired knowledge and by doing so, acquire cognition level. To achieve the configuration level, a controller will be added that can make adjustments to the DT in order to maintain a desired performance when the order load increases. The steps of the DT design based on the 5C architecture are shown in figure 4.1.

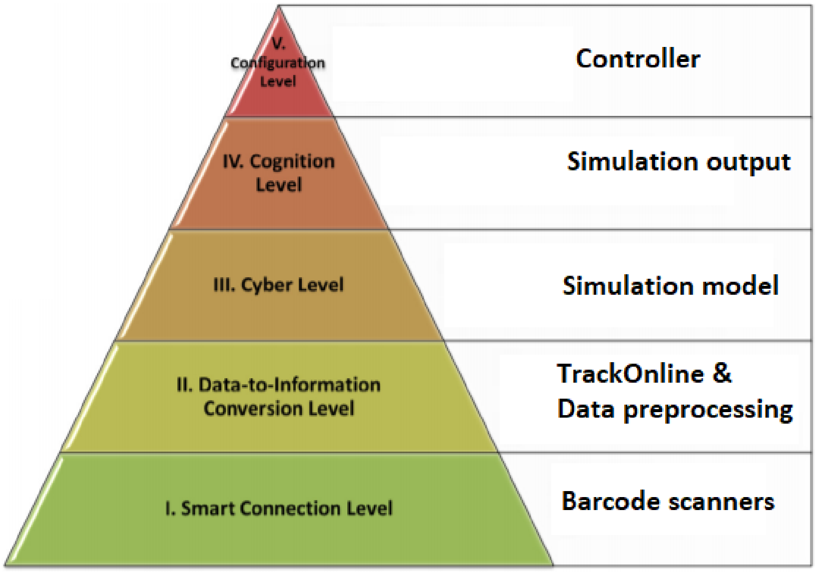


Figure 4.1: DT design steps to create a self-configurable and self-adjustable DT.

Note that this research only focuses on the digital part of the CPS system, the DT. Therefore, adjustments made by the controller will not be applied in the real world. These adjustments to the production line in the DT can be used as a support decision making for the production management. Hence, a closed CPS loop will not be accomplished in this research. The connection between the digital and physical part is shown in figure 4.2.

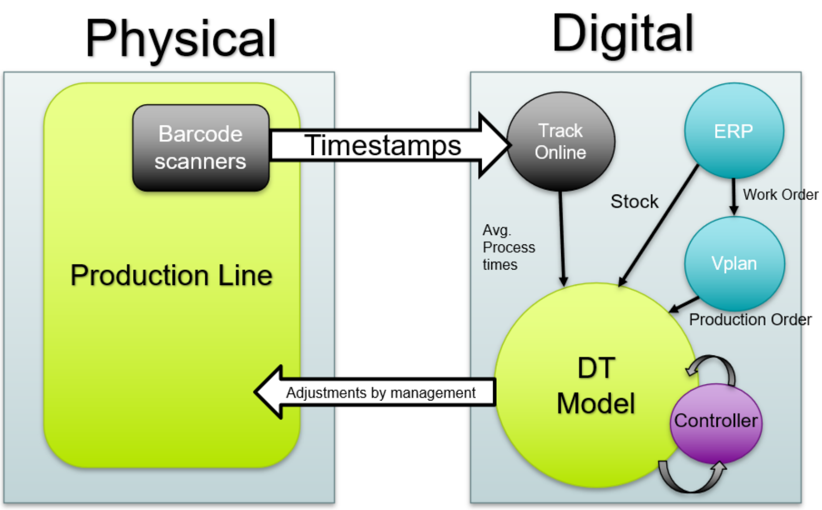


Figure 4.2: The Leap from physical to digital and vice versa. for the FOCUS-ON production process.

4.2. DATA COLLECTION AND AGGREGATION

There are three data sources that can provide the DT model with (near) real-time information. These data sources are TrackOnline, EXACT and Vplan. Below, the data that these systems collect and/or contain are discussed and how this data can be used in the model.

VPLAN:

The order planning tool. This data source contains the amount of orders and the configuration of those orders. However, due to the limited orders placed, this data in not available. Therefore, this research assumes that of the produced orders: 50% is DN50, 40% is DN80 and 10% is DN100 and 80% of these orders have an ATEX e-house and 20% a NONEX e-house. These ratios are expected by the company. For the expected number of orders the order demand forecast, shown in figure 3.10 is used.

EXACT:

EXACT is the ERP system that FOCUS-ON uses. This system provides a real-time information about the stock level of the parts. However, this system only contains the total amount of stock. It does not distinguish the local stock at the stations and the main stock.

TRACKONLINE:

This system processes the data gained from the barcode scanner at the production stations. It analysis the timestamps of the order. From this it links timestamps to the the barcode, which is coupled to an order and calculates the process times at each station of the concerned order. The TrackOnline output is shown in figure 4.3. TrackOnline uses minutes as time step. Currently the system has only one user account to which the process times are coupled. TrackOnline only calculates the process times of the stations for each individual order. Therefore this data needs to be processed further before it can be used as input for the DT model.The timestamps of all the orders are combined to calculate the average process times for each station and how they are distributed.

Werkorder	Serienumn	Productiecel	Tijdstip start	Tijdstip gereed	Doorlooptij	Operator	Totale doorlooptijd werkorder
20200134	190001	Mechanical assembly	24-11-2020 13:17:50	24-11-2020 13:22:18	5	Gerwin Ha	14400
		Pressure test	24-11-2020 14:36:56	24-11-2020 15:16:16	40	Gerwin Ha	-
		Final mechanical assen	26-11-2020 08:10:50	26-11-2020 08:25:48	15	Gerwin Ha	-
		Electronics assembly	03-12-2020 08:04:41	03-12-2020 08:05:33	1	Gerwin Ha	-
		Final assembly	04-12-2020 09:07:15	04-12-2020 13:36:11	269	Gerwin Ha	-
		Subassembly Actuator	26-11-2020 07:54:35	26-11-2020 07:55:26	1	Gerwin Ha	-
		Subassembly E-housin	26-11-2020 10:00:01	26-11-2020 10:07:04	7	Gerwin Ha	-
		Packaging, documentat	04-12-2020 13:50:38	04-12-2020 13:52:24	2	Gerwin Ha	-

Figure 4.3: TrackOnline information output of a single order.

The processed data from the TrackOnline output is shown in figure 4.4. However, the process times do not give a accurate representation of the real world production process times. Due to the lack of orders produced, resulting in limited data, and the scanning system not used properly by the operators. For example, figure 4.3 shows that the process time for the Electronic assembly station is 1 minute, when in reality it is about 50 minutes. Therefore, this information can not be used. The average process times information from TrackOnline does not match with the real world production line process times.

Cells	Mean
Row Labels	**Average of Doorlooptijd productiecel**
	2
Calibration and performance test	0,5
Electronics assembly	10,28571429
Final assembly	45,16666667
Final mechanical assembly	47,42857143
Mechanical assembly	56,57142857
Packaging, documentation and shipping	15,33333333
Pressure test	17,83333333
Software upload and installation	0
Subassembly Actuator	1,333333333
Subassembly E-housing	40,16666667
(blank)	
Grand Total	**27,67272727**

Figure 4.4: TrackOnline information output processed.

Based on the measurements made by hand and experience of the production operators and management the average process times, the deviations and the distributions are determined and shown in table 4.1. The process times have a normal distribution.

Table 4.1: Mean process times and the deviation the stations in minutes.

Station	Mean	Deviation	Lowerbound
MechOne	52	5	40
HydroPressureTest	20	2	15
FinalMech	42	5	30
Electronic	51	4	40
Calibration	65	5	45
Actuator	23	2	15
Ehouse	37	5	30
Final	44	5	35
Shipping	30	5	25

4.3. SOFTWARE AND MODELLING METHOD

The most obvious simulation software for this research would be the DELMIA software package from Dassault. DELMIA is integrated in the 3DEXPERIENCE platform that FOCUS-ON already uses. Data from the CAD software (Solidworks) can be transferred seamlessly into the DT. However, the DELMIA software package is expensive. In consultation with the management of FOCUS-On it is decided that with the current state of the company, no costs will be made for simulation software. A good alternative would be a free student version of a professional simulation software, for example AnyLogic. However, those versions are limited, and can not be used without a student license. Therefore This research chooses to develop a model under the Python programming language for the reason that Python is an emerging, free, and open-source language; which makes it very popular among software developers. Resulting in a lot of learning material available on the internet. In a production line, it can be assumed that the system states shift at discrete time points. Therefore, the discrete-event simulation method will be used in this research. The DT model will be an object-oriented model at the order level. This means that each of the production line components is modelled as objects with chains of processes that interact with each other. There are also some options for Python-based discrete event simulation software, e.g. SimPy[1] and Salabim[2]. The Salabim software package is used during the Masters and therefore familiar. Accordingly, this research opts for the Salabim software package. The Salabim software is run under JetBrain's PyCharm[3] software as the application development environment.

4.4. MODEL BOUNDARIES AND ASSUMPTIONS

Boundaries of the model can be depicted as shown in figure 4.5.

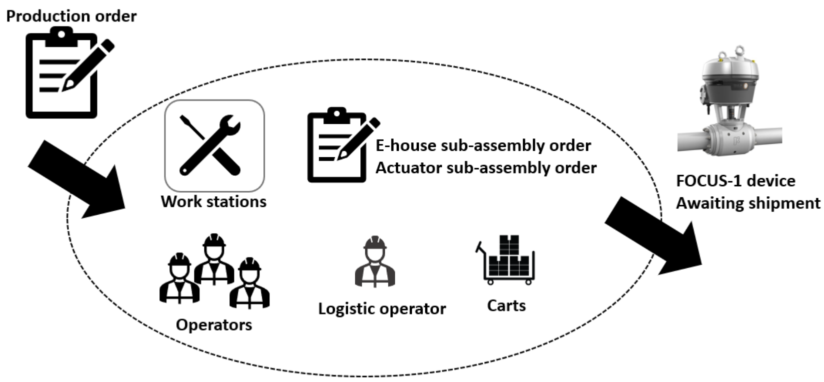


Figure 4.5: Boundaries of the DT model.

This research focusses only on the production process and not on the supply chain. Therefore this research assumes that the stock is always sufficient. The boundaries of the model are the stock of the production line and the production line itself. Orders are placed into the production line and move on a cart along

[1] https://simpy.readthedocs.io/en/latest/
[2] https://www.salabim.org/
[3] https://www.jetbrains.com/pycharm/

the work stations which are operated by a an operator. The last station of the line is the shipping station, which is operated by an logistics operator. After the last station the finished orders await shipment to the customers. The time steps of the model are in minutes, because the process times of the stations is given in minutes as input for the model by TrackOnline. Other assumptions regarding the simulation model are listed as follows:

- In the real world, a work day consists of 8 hours and breaks in between. The model will run continuously and will not take into account: Lunch breaks, work shifts, and start up and shut down time. In the model, a month exists of 21 workdays, where a workday consists of 8 hours.
- In the real world, the stations are placed closely together and travel times between the stations are far less than a minute. Therefore, the travel times between the station are neglected.
- Every employee has the same skill level and can work at all the stations. This is because TrackOnline only has one operator account and can not distinguish different operators. Furthermore it is demanded by the company that all the operators have a skill level that is desired by the company.
- There is no difference in process times between different product variants. For example the assembly time of a actuator ATO350 is the same as actuator ATC750 and the DN100 does not take more time than a DN80. This is because: TrackOnline does not distinguish different variants and it is confirmed by the operators that the different variants do not differ in process time.
- Due to the long delivery time of 6 weeks, the planner has the freedom to schedule the orders and spread the workload. Therefore it is assumed that the workload is equally spread over a month.
- The use of cranes is not taking into account. This is because a crane is only used for a brief moment. The usage time is part of the process time of a station.
- It is assumed that devices can not fail at a test at a test station. For example the hydro-pressure test. According to the production manager; the chance that a device fails a test is extremely low.
- It is assumed that an order should be completed within one working day (8 hours).
- The orders are processed at the first available station of a specific station type, if more than one station of a type is used.

4.4.1. MODEL INPUT, OUTPUT AND KPIS

The input for the simulation consists of the production line configuration (the number of each station), the number of operators, the number of carts and the measured process times, see table 4.1. The order demand and order configuration are generated by sampling functions implemented in Salabim. The input of the model is illustrated on the left side in figure 4.6.

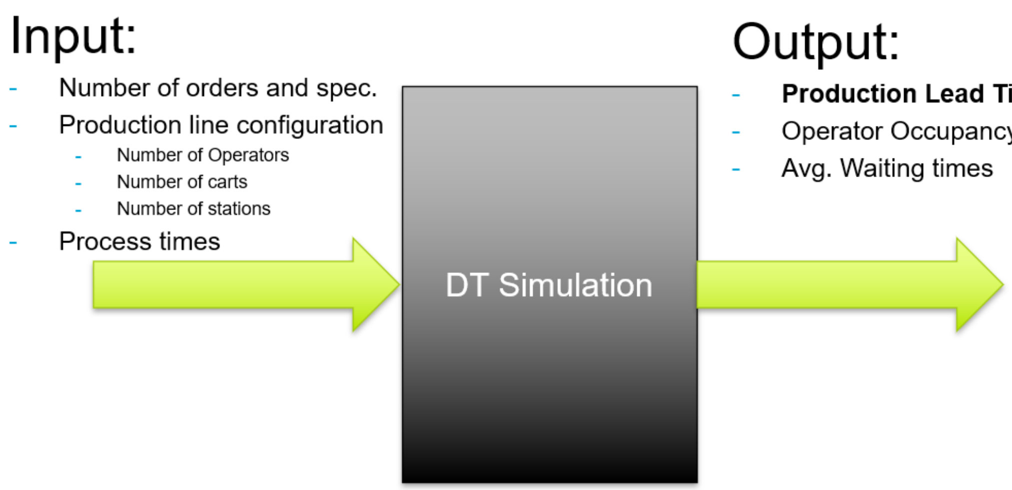


Figure 4.6: The input and output of the simulation model.

On the right side in figure 4.6 the output of the simulation model is shown. The output consists of: Production lead times [minutes], the average waiting times of an order in a queue for a Station [minutes] and the operator occupancy [%]. These are also the performance indicators of the system. Salabim provides a monitor function which allows these indicators to be tracked during the simulation. The data of the monitored parameters can represented as graphs and charts by using numeric Python software packages, such as matplotlib [4].

4.5. CONCEPTUAL MODEL

The model will be at order level. Based on the boundaries of the model: The production order flow through the production process is illustrated in figure 4.7. Production orders are placed in the production line and leave the production line as finished FOCUS-1 devices, awaiting shipment.

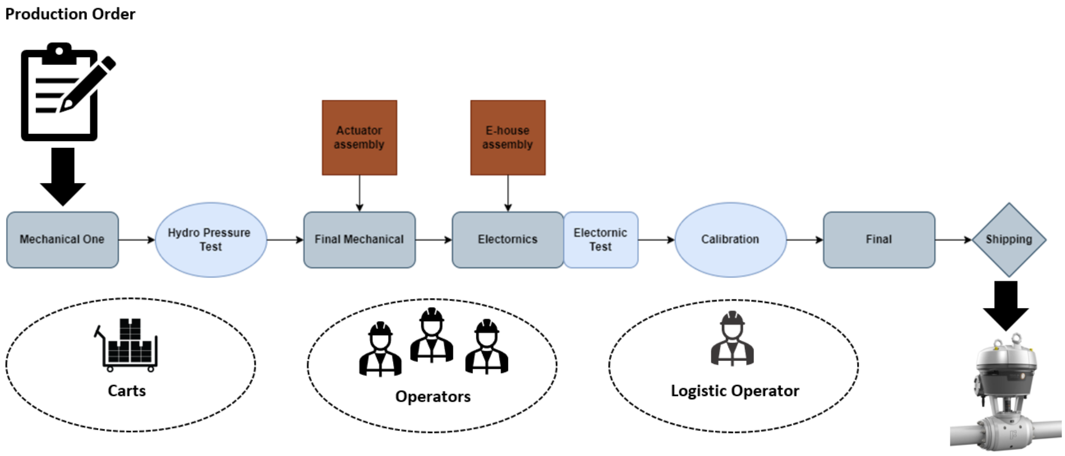


Figure 4.7: Conceptual process flow.

4.6. OBJECTS OF THE SIMULATION MODEL

The model in this research consists of the objects and resources listed in table 4.2 along with their states, and functions. Objects can be either active of passive. Passive objects do not have a process embedded in them. In the upcoming part of this chapter the objects and resources will be discussed further.

[4]https://matplotlib.org/

Table 4.2: All the components of the DT model

Name	Type	State	Function
Operator	Resource	Passive	Works at workstations
Logistic Operator	Resource	Passive	Works at the shipping station
Cart	Resource	Passive	To pass the order from station to station
Order	Object	Active	Main flow identity of the model
Ehouse Order	Object	Passive	Sets Ehouse Sub assembly to work
Actuator Oder	Object	Passive	Sets Actuator Sub assembly to work
Order generator	Object	Active	Generates orders
MechOneStation	Object	Active	Workstation
HydroPressureStation	Object	Active	Workstation
FinalMechStation	Object	Active	Workstation
ElectronicStation	Object	Active	Workstation
CalibrationStation	Object	Active	Workstation
FinalAssemblyStation	Object	Active	Workstation
ShippingStationStation	Object	Active	Shippingstation
ActuatorStation	Object	Active	Workstation
EhouseStation	Object	Active	Workstation
Controller	Object	Active	Adjusts the model

4.6.1. RESOURCES

The Operators, Logistic Operator and the Carts are modelled as resources. A resource has always a capacity. This capacity will be specified at time of creation, and can change over time. The capacity of the resources in this resources are integers and can not be zero. The capacity is specified by the input of the model. Resources have a queue containing all components trying to claim from the resource. And a queue claimers containing all components claiming from the resource. Operators are claimed by workstations, the Logistic Operator is claimed by the shipping station and Carts are claimed by an Order. Salabim provides a command to show the occupancy of a resource. Below the command is shown for the resource 'Operators': occupancy of a resource:

$$Operators.occupancy.mean()$$

4.6.2. ORDERGENERATOR

The OrderGenerator creates the build Orders of the FOCUS-1 that needs to be produced in the production line.

ATTRIBUTES:

- Month: The current month.
- Demand: The order demand of the current month.
- Wait.Time: The time between the arrival of Orders at the production line.

PROCESS DESCRIPTION LANGUAGE (PDL):

- Repeat:
  - Create Order with all its attributes
  - Place Order in the Order Queue
  - Calculated Wait.time
  - Hold for Wait.time

The attribute Wait.Time is calculated on the Demand of the current month. See equation below for the calculation.

$$Time.in.month = 21[days] * 8[hours] * 60[minutes] = 10080 minutes$$

$$Wait.Time = \frac{10080}{Demand}$$

The attributes of the Orders are created according to the sales expectations to the sales forecast. Below the sampling of the body is given as an example. The sales forecast is that 40% of the orders will be a DN80, 10% a DN100 and 50% a DN50.

$$Order.Body = sim.Pdf(('DN80', 40, 'DN100', 10, 'DN50', 50)).sample()$$

4.6.3. ORDER

The Orders are the main flowing entity in the model. When they are created by the Order Generator, they are immediately assigned with their attributes. When they are created they first create sub-assembly orders and wait for two days before their production starts.

ATTRIBUTES:

- Body: The type of body .
- Actuator: The type of actuator.
- Ehouse: The type of Ehouse.
- Handled: A sim.state that is triggered by the FinalAssemblyStation.
- Packed: A sim.sate that is triggered by the ShippingStation.

PDL:

- Create ActuatorOrder
- Place ActuatorOrder in the ActuatorStations Queue
- If an ActuatorStation = passive, activate it
- Create EhouseOrder
- Place EhouseOrder in the EhouseStations Queue
- If an EhouseStation = passive, activate it
- Wait for 2 days
- Save Starttime
- Request a Cart, wait until a Cart is assigned
- Enter MechOneStations Queue
- If a MechOneStation = passive, activate it
- Wait until 'handled'
- Release Cart
- Wait until 'packed'
- Save endtime and calculate Production Lead Time

The Production lead time for the Orders (main flow) is calculated by the starttime of the Order and end time of the Order. See calculation below:

$$ProductionLeadTime[min] = Endtime - Starttime$$

As stated before it is assumed that Orders should be finished in one work day. Therefore The production Lead time may not exceed 480 minutes.

4.6.4. EHOUSEORDER
EhouseOrders are passive objects, so they have no process assigned to them. When they are created by an Order they are immediately assigned with their attribute. The EhouseOrder is used the make an E-house sub assembly.

ATTRIBUTES:
- Type: ATEX or NONEX.

4.6.5. ACTUATORORDER
ActuatorOrders are passive objects, so they have no process assigned to them. When they are created by an Order they are immediately assigned with their attribute. The ActuatorOrder is used the make an actuator sub assembly.

ATTRIBUTES:
- Type: ATO350, ATO750, ATC350 or ATC750.

4.6.6. MECHONESTATION
The mechanical one station is the first station of the production main line. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:
- myOrder: The Order that is processed at the station.

PDL:
- Repeat:
-
  - If MechOneStations Queue is empty, self-passivate
  - myOrder = first Order waiting in MechOneStations Queue
  - Claim an Operator and wait until one is assigned.
  - Calculate process time
  - Hold for process time
  - Place myOrder in the HydroPressureStations Queue
  - If a HydroPressureStation is passive, activate it
  - myOrder is NONE
  - Release the Operator

4.6.7. HYDROPRESSURESTATION
This is the second station of the production main line. At this station the hydro and pressure test are conducted. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:
- myOrder: The Order that is processed at the station.

PDL:
- Repeat:
-
  - If HydroPressureStations Queue is empty, self passivate
  - myOrder = the first Order waiting HydroPressureStations Queue
  - Claim an Operator and wait until one is assigned.
  - Calculate process time

- Hold for process time
- Place myOrder in the HydroPressureStations Queue
- If a HydroPressureStation = passive, activate it
- myOrder is NONE
- Release the Operator

4.6.8. FinalMechStation

This final mechanical station is the third station of the production main line. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.

PDL:

- Repeat:
- - If FinalMechStations Queue is empty, self passivate
  - myOrder = the first Order waiting in FinalMechStations Queue
  - If Stock[myOrder.Actuator]= 0
  - - Wait until Stock[myOrder.Actuator]> 0
  - Claim an Operator and wait until one is assigned.
  - Stock[myOrder.Actuator] -= 1
  - Calculate process time
  - Hold for process time
  - Place myOrder in the ElectronicStations Queue
  - If an ElectronicStation = passive, activate it
  - myOrder is NONE
  - Release the Operator

4.6.9. ElectronicStation

The electronic station is the fourth station of the main production line. The electronics are installed and a software check is done. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.

PDL:

- Repeat:
- - If ElectronicStations Queue is empty, self passivate
  - myOrder = the first Order waiting in ElectronicStations Queue
  - If Stock[myOrder.Ehouse]= 0
  - - Wait until Stock[myOrder.Ehouse]> 0
  - Claim an Operator and wait until one is assigned.
  - Stock[myOrder.Ehouse] -= 1
  - Calculate process time
  - Hold for process time
  - Place myOrder in the CalibrationStations Queue
  - If an CalibrationStation = passive, activate it
  - myOrder is NONE
  - Release the Operator

4.6.10. CALIBRATIONSTATION

The calibration station is the fifth station of the production main line. It is operated by an operator. The time to reconfigure the calibration station to the right pipe diameter size is 20 minutes. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.
- myConfiguration: The configuration of the Calibration loop, can it fit the bodytype

PDL:

- Repeat:
-
  - If CalibrationStations Queue is empty, self passivate
  - myOrder = the first Order waiting in CalibrationStations Queue
  - Claim an Operator and wait until one is assigned.
  - If myOrder.Body =! myConfiguration
  -
    - Wait configuration time
    - myConfiguration = myOrder.Body
  - Calculate process time
  - Hold for process time
  - Place myOrder in the FinalAssemblyStations Queue
  - If an FinalAssemblyStation = passive, activate it
  - myOrder is NONE
  - Release the Operator

4.6.11. FINALASSEMBLYSTATION

The final assembly station is the sixth station of the main production line. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.

PDL:

- Repeat:
-
  - If FinalAssemblyStations Queue is empty, self passivate
  - myOrder = the first Order waiting in FinalAssemblyStations Queue
  - Claim an Operator and wait until one is assigned.
  - Calculate process time
  - Hold for process time
  - myOrder.'Handled'.trigger
  - Place myOrder in the ShippingStations Queue
  - If an ShippingStation = passive, activate it
  - myOrder is NONE
  - Release the Operator

4.6.12. ShippingStation

This is the last station of the production line. It is operated by a logistic operator. After this station the orders await shipment. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.

PDL:

- Repeat:
- - If ShippingStations Queue is empty, self passivate
  - myOrder = the first Order waiting in ShippingStations Queue
  - Claim a Logistics Operator and wait until one is assigned.
  - Calculate process time
  - Hold for process time
  - myOrder.'Handled'.trigger
  - myOrder is NONE
  - Release the Logistic Operator

4.6.13. ActuatorStation

The sub-assembly station were the actuators are sub assembled. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.

PDL:

- Repeat:
- - If ActuatorStations Queue is empty, self passivate
  - myOrder = the first ActuatorOrder waiting in ActuatorStations Queue
  - Claim an Operator and wait until one is assigned.
  - Calculate process time
  - Hold for process time
  - Stock[myOrder.type] += 1
  - myOrder is NONE
  - Release the Operator

4.6.14. EhouseStation

The sub-assembly station were the electronic housings are sub assembled. It is operated by an operator. The process time is calculated by:

$$sim.Bounded(sim.Normal(Mean, Deviation), Lowerbound])$$

ATTRIBUTES:

- myOrder: The Order that is processed at the station.

PDL:

- Repeat:
  - If EhouseStations Queue is empty, self passivate
  - myOrder = the first EhouseOrder waiting in EhouseStations Queue
  - Claim an Operator and wait until one is assigned.
  - Calculate process time
  - Hold for process time
  - Stock[myOrder.type] += 1
  - myOrder is NONE
  - Release the Operator

4.6.15. CONTROLLER

The controller acts as a supervisory control. It is the feedback from the model output. The controller works as follows: After each month it checks if the production lead time of the last order does not exceed the threshold. The threshold is set at 480 minutes, one work day. If the production lead time is within the limit, the order load is increased with one. If the production lead time is above the threshold the controller makes an adjustment to the model and the simulation runs for an other month with the same order load. If the controller acts, it first checks the operator occupancy. If the occupancy is higher than 98% it adds an extra operator to the model. If the operator occupancy did not exceed the threshold the controller checks the waiting times for the stations in the main line. It checks first the first station, mechanical one, in line and as last the last station, the shipping station. If the average waiting time for a station type exceeds 60 minutes it will adjust the model by adding an extra station of that type. For the stations Final Mechanical and Electronic assembly: it checks first if the stock alarm is active. This means that the main line is waiting for a sub-assembly. If so, the controller add an Actuator sub-assembly station instead of a Final Mechanical station or an Ehouse sub-assembly station instead of Electronics station. If a Shipping station is added, a logistic operator will be added at the same time. Note that the controller does not take the carts into account. This assumption is made because it was not a requirement by the operation manager of FOCUS-ON. Because the amount of carts can easily be increased and require not a large investment.

PDL:

- Repeat:
  - Hold for one month
  - If last production lead time > Max allowed lead time
    - If Operator occupancy > 0.98
      - Increase Operator capacity with 1
    - Else:
      - If avg. waiting time of station type > 60
      - Create station of that type and add to model
      - If station type = shipping station: Increase Logistic Operator capacity with 1
  - Else:
    - Increase Order demand with 1

4.7. CHAPTER SUMMARY

In this chapter the answer to the sub question related to the development of the model are presented. The DT model is based on the 5C architecture and the simulation model is built according to the Delft System Approach. Functions will process the input and generate an output which are the performance indicators of the production process. The controller makes adjustments to the model on the basis of the model output and hereby making the DT self-adjustable. Before the DT model can be used to answer the main question of this research: It must be first verified and validated. This is done in the next chapter.

5

Implementation, Verification and Validation

This chapter will answer the sub-question: *"Is the developed DT a valid representation for different and various cases?"*. Section 5.1 describes the implementation of the DT model. Section 5.2 examines if the model behaves as intended. Section 5,3 examines if the DT model is a valid DT model of the FOCUS-1 production process. Lastly, section 5,4 summarizes the chapter.

5.1. Implementation

The implementation of the DT model is done under the Python programming language: Python version 3.9 64bit. The Python-based discrete event simulation software that is used is Salabim: Version 21.1.4. For the application development environment the program PyCharm version 2020.3.3 is used. The DT model is run on a Lenovo Thinkbook with a Intel(R) Core(TM) i5-1035G1 at 1.00 GHz processor.

5.2. Verification

Salabim allows traces of the simulation to be monitored. The trace can be printed to the monitor of the PyCharm IDE by toggling trace=True in the main code. In this way, the monitor is updated with the current process in the simulation. The monitor shows three columns: In the left column the user can see the current simulation time with the current object that is doing a certain process. In the middle column the current process in the simulation in shown, in the right column the annotation regarding the current object or process is shown. In figure 5.1 the trace monitor is shown.

```
332                            order.11                           enter ReadyTime
335                            shipping.0                         release 1 from Lenny
323                            shipping.0 passivate               mode=Down
150+   2217.373 order.11       current
505                            order.11 ended
139+   2244.000 order.13       current
141                            order.13                           request 1 from Cart priority=inf
141                            order.13                           claim 2 from Cart priority=inf
141                            order.13 request honor Cart        scheduled for   2244.000 @  141+
141+   2244.000 order.13       current
142                            order.13                           leave OrderQ
143                            order.13                           enter Mech1orderQ
146                            stationmechone.0 activate          scheduled for   2244.000 @  167+ mode=Down
148                            order.13 wait                      scheduled for        inf @  148+
167+   2244.000 stationmechone.0   current
169                            order.13                           leave Mech1orderQ
171                            stationmechone.0                   request 1 from Ops priority=inf
171                            stationmechone.0                   claim 2 from Ops priority=inf
171                            stationmechone.0 request honor Ops scheduled for   2244.000 @  171+ mode=Down
171+   2244.000 stationmechone.0   current
175                            stationmechone.0 hold +40.071      scheduled for   2284.071 @  175+ mode=Active
253+   2247.073 electroassembly.0  current
255                            order.12                           enter CalibrationQ
258                            calibration.0 activate             scheduled for   2247.073 @  272+ mode=Down
261                            electroassembly.0                  release 1 from Ops
```

Figure 5.1: Salabim Trace Monitor: In the most left column the current simulation time is shown. Next to it is the current object regarding the process. Next to that is the current process. The most right column shows an annotation regarding the current object or process.

The simulation processes can also be visualized with the animation window function that is provided in Salabim. The animation function can show orders that are in queues and show the states of stations. An animation window has been made during the model development so that the modelled processes can be indicated from it. The animation window is shown in figure 5.2. The animation window shows input data, the status of the stations by their colour: Beige means the station is not in operation. Red means that an order has arrived at the station and the station waits for an operator. Green means that an operator is working at that station. Furthermore, it shows all the orders that are waiting at each station. Together with the trace monitoring function, this animation window can be used to verify the behaviour of the model by giving a visualization of the simulation.

Figure 5.2: Animation window of the DT model of the FOCUS-1 Production line: a schematic view.

In order to check the behaviour of the model, some test runs are conducted. These runs have a different configuration from the real problem configuration, which is intendedly made so that the problem becomes simpler and the capabilities of the model could be further examined. The DT model is subjected to the following verification tests:

- The OrderGenerators generates the orders correctly according to the demand input.
- Negative sub-assembly stock is not possible.
- The number of orders ready for shipment is equal to the number of orders placed into the production line. No orders got stuck or lost in the system. Output equals the input.
- Input variables check, for example: Increasing processing times lead to a higher Production Lead Time.
- Adjustments by the controller are correctly updated into the model.

The models passed all the tests and therefore can be concluded that the DT model behaves as specified.

5.3. Validation

Validation checks if the simulation model is suitable to represent the system in the real world. Yet, it is not possible that a model fully represents the real world system. Therefore, 100% proof for validation does not exist. Validation can be done by comparing the results from the simulation model with historical data [39]. However, due to the fact the fact this production line is a green field project and production has not yet started, no historical data is available. Validation it is not possible to validate the DT with historical data. Comparing the results of the developed DT model with an other model can also not be done, because this is a first model of the production line. Predictive validation can not be done because of time restriction of this project. Therefore, it will be tried to validate the DT model by face validity or 'expert validation'. In table 5.1 the most commonly used methods to validate a model are listed.

Model Validation Method	Description
Comparison to Other Models	Results of the simulation model being validated are compared to results of other (valid) models.
Face Validity	Asking experts about the system whether the model and/or its behavior are reasonable. For example, is the logic in the conceptual model correct and are the model's input-output relationships reasonable?
Historical Data Validation	If historical data exist, part of the data is used to build the model and the remaining data are used to test whether the model behaves as the system does.
Parameter Variability – Sensitivity Analysis	This technique consists of changing the values of the input and internal parameters of a model to determine the effect of output on the model's behavior. The same relations should occur in the model as in the real system.
Predictive Validation	The model is used to predict the system's behavior. The system's behavior and the model's forecast are compared to determine if they are the same.

Table 5.1: Common Simulation Model Validation Methods [8]

The performance of the DT model of the FOCUS-ON production line is shown in figure 5.3. The DT model is run with the current set-up of 3 operators. Furthermore, the wait time of 2 days between the sub-assembly orders and main assembly order is reduced to 60 minutes. Because a long wait time results in a false operator occupancy value in the start of the simulation run. And for a continuous production flow it does not matter. The max order load for the line with the current set-up of 3 operators is 85 orders a month. At 86 orders a month the production lead time exceeds the threshold and and the production line can not handle the order load anymore.

With 3 operators and a month existing of 21 work days: 85 orders a month is equal to about 1.35 order per operator per day. When taking in consideration that a more reasonable effective work time for operators is about 80%, the production is approximately comes to 68 orders a month. Which is equal to 1.08 order per operator per day. These results are presented to the production manager, who designed the real world production line. According to the production manager these results match the expectations of the production line: It is expected that for every operator atleast 1 device should be built per day.

In conclusion, the DT model can not be validated on the basis of historical data or other models. Therefore, the models lacks a strong validation and it can not be proven that the developed DT model is a true digital version of the production line. However, according to expert knowledge the performance monitoring of the DT model does represent the expected performance of the real world production line. And therefore the developed model can be used to answer the main question of this research.

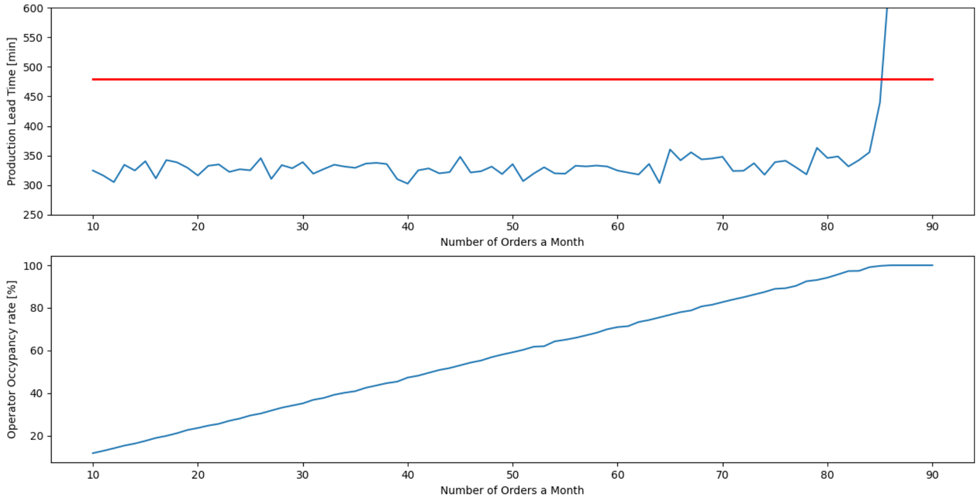


Figure 5.3: Results Validation run. At load of 86 orders a month the capacity of the line is exceeded.

5.4. CHAPTER SUMMARY

In this chapter the model is verified and validated. The conducted verification tests show that the developed DT model behaves as specified. The DT model could not be validated by historical data due to lack of data. However, it is still founded suitable for simulating the performance of the FOCUS-1 production line and used to answer the main question of this research. Because according to expert knowledge the performance monitoring of the DT model does represent the expected performance of the real world production line.

6

Experiment and Results

This chapter will answer the last group of sub-questions: *"How does the production process performs in its current form?"* and *"Which adjustments are needed for the production line to keep up with the increasing order demand?"* In section 6.1 of this chapter an experimental plan will be presented to evaluate the performance of the production line. The experiments and the results of this experiment will be presented in section 6.2. These results are used to answer the main question of this research: *"How would a self-configurable and self-adjusting DT, when implemented as a control agent, affects the performance of a fast-growing greenfield production line?"* Lastly, Section 6.3 summarizes the chapter.

6.1. Experimental plan

Results from the validation test show that the current set-up of the production line can handle a max order demand of 85 orders a month. The output from the model shows that at this order demand the operator occupancy is maxed out: An operator occupancy of 100 % is reached. FOCUS-ON has the ambition to grow rapidly. The order forecast for the upcoming year is shown in table 6.1. The order forecast shows order demands higher than 85 a month. This means that adjustments need be made to the production line to handle those order loads. Therefore, the DT model will run with the controller turned on to see how the controller acts a supervisory control and makes adjustments to the DT model to maintain a production lead time of under 480 minutes while the order demand increases. For these experiment the same configuration input for the DT model is used as with the validation run: The current set-up of stations, 3 operators, 1 logistic operator and 40 carts.

Table 6.1: Order demand forecast.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Order demand:	8	16	16	16	26	40	44	61	100	145	140	140

6.2. Results

In figure 6.1, the results are shown from the production line DT with an order demand up until 150 a month. The controller has made the following adjustments to maintain a desired performance: at a demand of 86 a month a fourth operator is added. At a demand of 113 a fifth and at 142 a sixth operator is added. This means that the managements needs to hire one new operator before September and two more before October.

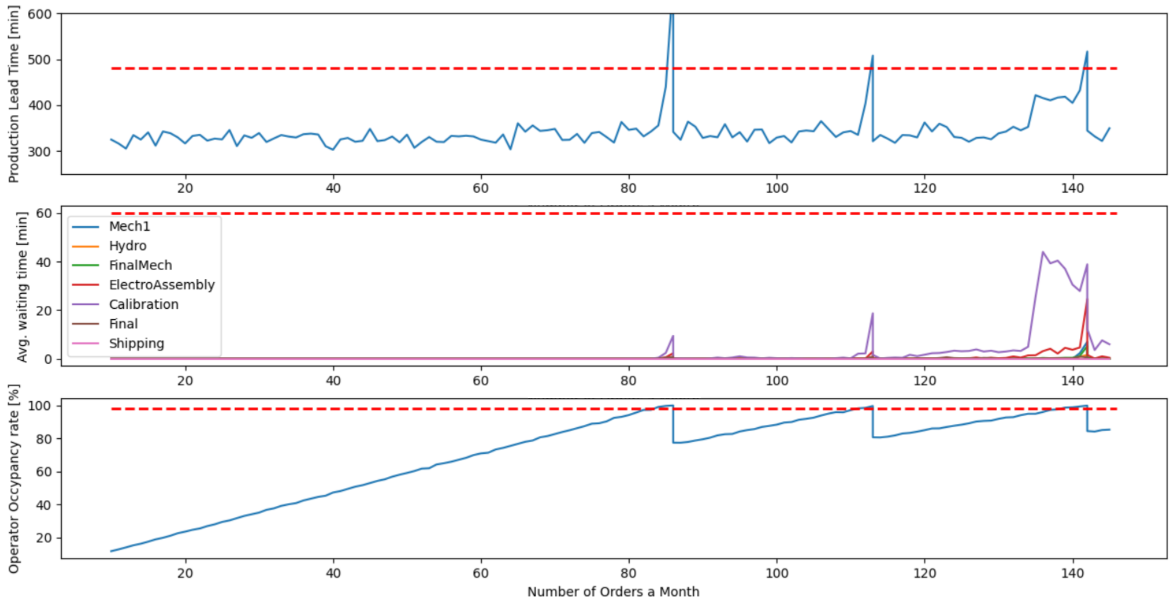


Figure 6.1: Performance of the FOCUS-ON production line DT. With an order load ranging from 10 until 150 a month.

Next, the DT model is run with an order demand increased to 200 a month. This is done to check the production line limit of the current set-up of the stations. The results of this experiment are shown in figure 6.2. And the adjustments made by the controller to keep the production lead times under 480 minutes are presented in table 6.2.

Table 6.2: Production line adjustments needed to handle the monthly order demand.

Monthly Order Load	Adjustment Measure
86	Number of operators is set to 4
113	Number of operators is set to 5
142	Number of operators is set to 6
156	A Calibration station is added
171	Number of operators is set to 7
194	A Mechanical One station is added
194	Number of operators is set to 8
200	An Electrotronics station is added

The results in figure 6.2 and table 6.2 show that at an order demand of 156 a month, a bottleneck occurs at the calibration station. Although the number of operators working at the production line is less than the number of stations they work at. Namely, 6 operators and 8 work stations. Adding more operators does not increase the production capacity anymore. A second calibration station is needed to prevent increasing waiting times.

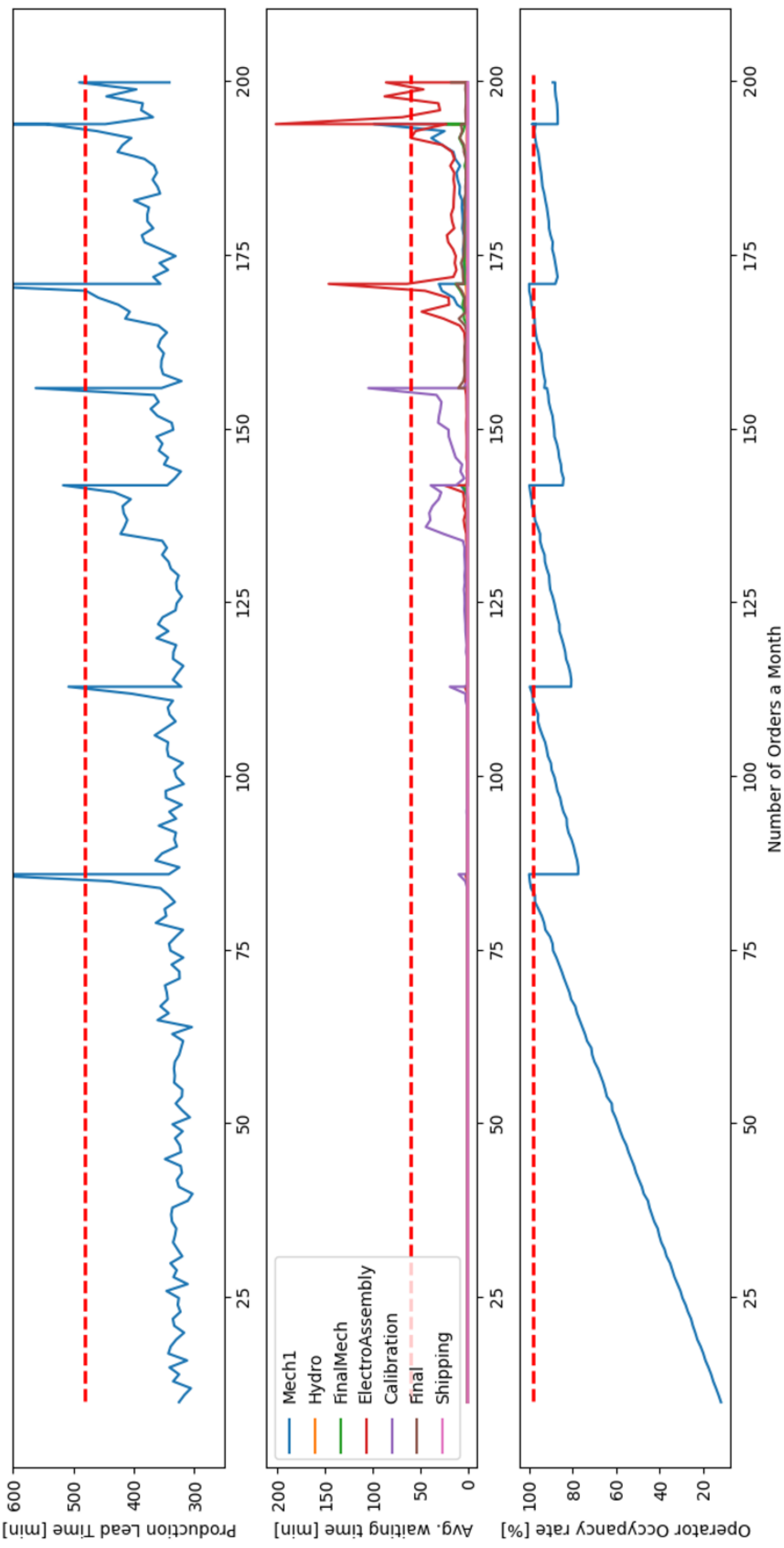


Figure 6.2: Performance of the FOCUS-ON production line DT. With an order load ranging from 10 until 200 a month.

6.3. CHAPTER SUMMARY

In this chapter an experimental plan is proposed and executed. The results of the first test show that FOCUS-ON needs 3 more operators to handle the order demand forecast. The second test shows that the calibration station the first bottleneck is in the main production line. On the basis of these results, the main question will be answered in the next and final chapter.

7

CONCLUSION

This final chapter concludes the research. Section 7.1 summarizes all the answers to the sub-questions. Subsequently, the main question of this research will be answered. Section 7.2 addresses the points of discussion of this research and Sections 7.3 and 7.4 provides recommendations. The recommendations are divided into recommendations for further academic research and recommendations for FOCUS-ON.

7.1. CONCLUSION

"What is the difference between a DT and a simulation?"
There is a considerable difference between a DT and a simulation. Simulations focuses only on 'what if' scenarios. They do not look at what is currently happening in the real world, but focus on what could happen. DTs on the other hand, have a near real-time synchronization with the real world and therefore they can be used for monitoring, control, diagnostics and prediction. The DT concept can be seen as the next generation of simulation technology.

"What does 5C configuration level means for a DT?"
This level acts as a supervisory control. It is the feedback from the cyber world to the real world and by doing so, closing the CPS circle. Now the CPS can self-configure the system to apply corrective and preventive decisions, which have been made in the cognition level. This also means that the DT model should be able to process these actions and if necessary rebuild the simulation model.

"What modelling type is best for representing a production environment?"
For modern simulation modelling there are three types of modelling methods: Discrete event simulation, agent based simulation and system dynamics simulation. Where each method has a specific range of abstraction. System dynamics assumes the highest level of abstraction of all the modelling methods. It ignores the fine details of a system (e.g. individual properties of people, products, or events) and produces a general representation of a complex system. Due to its high abstraction level, this method is most suitable for long-term strategic modelling and simulation. Due to this high abstraction level, system dynamics simulation is not suitable to model a production environment. Discrete event modelling supports an abstraction level from low to medium. It uses a top-down architecture and is used to observe time-based behaviour within a system. Discrete event simulation is insufficient in characterization of DTs for CPS in production logistics. However, the use of discrete event simulation may promote the development of DTs and can be used to improve production performance. Agent based simulation modelling can be used for very detailed models where the agents represent physical objects. These agents act and interact with each, according to defined simulation rules. The individual actions and behaviour of the agents influence and determine the system performance. Therefore the characteristics of the system could be modelled better. Conclusion, agent based modelling is the best type to simulate a production environment.

"What are the Key Performance Indicators for a production environment?"
For production processes there a numerous KPIs available. The three mostly common are: Cycle time, takt time and lead time, and are often interchangeably used in manufacturing. This research uses as main KPI the

Production Lead Time: The time it takes one order to move all the way through a production process from start to finish. The Production Lead Time is also known as the Total Product Cycle Time. Word wide is TPS seen as the standard for "wold class manufacturing". TPS is a major precursor of the more generic lean manufacturing. Three terms often used together in the TPS that collectively describe waste: are Muda, Mura and Muri. TPS identifies seven forms of Muda or waste. Which can be remembered by the acrocnym TIMWOOD: Transport, inventory, motion, waiting, overproduction, overprocessing and defects. This research uses the waiting times at stations to identify bottlenecks. An other common KPI for production is asset utilization. This research uses a variant on the operator utilization: the operator occupancy. This is done to check if the number of operators working has an impact on the main KPI of this research: The Production Lead Time.

"What are the components of the production process and how do they interact with each other?"
The production line of FOCUS-ON is investigated in Chapter 3 as object of interest for this research. At this production line the FOCUS-1 device is assembled. The production line consists of a main line with the following stations in consecutive order: MechanicalOne, HydroPressureTest, FinalMechanical, Electronic Assembly, Calibration, Final and Shipping. Next to the main line there are two station that make sub-assemblies: Actuator station, that makes actuators for the FinalMechanical station and an Ehouse sub-assembly station that makes the electronic housing for the Electronic assembly station. All the station are operated by operators, except the shipping station, that one is operated by a logical operator. The device is build on a cart and is moved along the production line on that cart.

"Which sensors are used in the production line and what data do they gather?"
The production line is equipped with barcode scanners. The scanners are part of the TrackOnline system. This system processes the data gained from the barcode scanner at the production stations. It analysis the timestamps of the order. From this it links timestamps to the the barcode, which is coupled to an order and calculates the process times at each station of the concerned order. Other systems that provide data of the production line are: EXACT and Vplan. Exact is the ERP system that FOCUS-ON uses. This system provides a real-time information about the stock level of all the parts. However, this system only contains the total amount of stock. It does not distinguish the local stock at the stations and the main stock. Vplan is the order planning tool. This system contains the amount of orders and the configuration of the orders.

"How does the FOCUS-1 production line currently perform?"
Currently there is not much known about the performance of the FOCUS-1 production line. This is due to the fact the production as not yet fully started and there are continuously small changes made to the production process. The process times of each station are measured by hand to gain some data. According to the production management: At least one device should be made per day for every operator working. Trial runs shows that a product can be build within 6 hours

"How should the DT of the FOCUS-1 production line be modelled?"
Chapter 4 has presented a DT model description. The FOCUS-ON production line is modelled based on the 5C Architecture. The barcode scanner represent the first level: Smart Connection. The TrackOnline system en data preprocessing from the second level: Data-to-Information Conversion. The Cyber level is the simulation model. The output of the simulation model is the Cognition level. And the controller acts on the output and represents the configuration level. The simulation method used is DES. The stations are modeled as objects as are the FOCUS-1 orders. The operators and carts are modeled as resources. When an order is created, it first creates the sub-assembly orders before it moves along the main production line. If there is more than one station of a station type, the order goes to the first available station of that type. The controllers adjust the model by adding extra operators or stations.

"Is the developed DT a valid representation for different and various cases?"
The trace monitor and animation function of Salabim are used to observe if the DT model behaves as it is specified. The conducted verification tests show that the developed DT model behaves as specified. The DT model can not be validated on the basis of historical data or other models. Therefore, the models lacks a strong validation and it can not be proven that the developed DT model is a true digital version of the production line. However, according to expert knowledge, the performance monitoring of the DT model does represent the expected performance of the real world production line. And therefore the developed model can be used to answer the main question of this research.

"How does the production process performs in its current form?"
The validation experiment shows that with the current set-up of the production line and 3 operators it is possible to handle a workload of up to 85 orders a month.

"What are the adjustment are needed for the production to keep up with the increasing demand?"
Chapter 6 presents the results from the self-adjustable DT of the production line. The results show that for September an extra operator is needed and for October two more. The results also show that at an order demand of 156 a month an extra calibration station is needed. At that order demand not the operator capacity is the bottleneck but the process time of the calibration station. For all the adjustments that are made by the DT for an order load of 200 a month, see table 6.2 in Chapter 6.

"How would a self-configurable and self-adjusting DT, with a control agent, affect the performance of a fast-growing greenfield production line?"
From the results from the experiment can be concluded that a self-adjusting DT can keep a desired performance with an increasing demand. This is done by making adjustment to the system and self-configure the simulation model according to these adjustments. And hereby providing knowledge of the system, which is of great value for a greenfield production line. The self-adjusting DT provides the production management with essential knowledge about the production capacity limitations. Furthermore, it provides the knowledge about which adjustments need to be made to keep up with an increasing order demand. The required investments in the production line. Finally, the DT model provides information about the production line dynamics by exposing potential bottlenecks.

MARGINAL INSIGHTS

The self-adjusting DT provides the production management with knowledge of the work load limitations. Next, it provides the knowledge on which adjustments need to be done to keep up with the increasing work load. Furthermore, the DT model shows potential bottlenecks and hereby gives the production management better insights in the production line. The adjustments to the production line of FOCUS-ON to keep up with the increasing demand are presented in chapter 6. The self-adjustable and self-configurable DT provides knowledge about the greenfield production line that is needed to make investments in the production line to increase the production capacity.

7.2. POINTS OF DISCUSSION

There are some points of discussion which could argue the conclusions and the developed DT model. First of all, this research uses DES, which is not the best choice for a production process DT model according to the literature. Agent based simulation modeling is the preferred choice. Furthermore, assumption where made that simplified the model. For example: All the operators have the same skill level. Operators play a main role in the production process and are simplified to a single resource. In reality, each operator has a different skill level and favorite work stations. Due to the limited production in real life, the data that was gathered was limited. The limitation of data resulted that the validation only could be done by expert validation. Further, this research uses the term DT which is debatable. The connection from the digital world to the physical world is not automated. Those actions need to be done manually. Therefore, the model is more of a Digital Shadow. Although the data flow from the physical world to the digital world is automated, it still needs to be insert in the model manually and therefore it could be argued it is just a digital model.

7.3. RECOMMENDATIONS FOR FURTHER RESEARCH

As stated in the previous section, the simulation method used in this research is not the preferred choice. Therefore it is recommended to develop a future model according to the agent based simulation method. The model development phase of this research is constrained by the time limitation of this research. Therefore, the level of details that are given in this model is also limited. In order to have a more valid model, it is recommended for future research to expand the model by introducing other important parameters. For instance the hands on tool time and the skill level of the operators. Furthermore, this research only focused on self-adjustment to order demand growth and assumed that the order load is equally spread over a month. Therefore it is recommend that for future research the DT model would be extended with a controller that optimizes the planning of the work orders. The next recommendation concerns the floor plan of the production facility. The presented model does not take into account the available space or the movements between the production stations. It is recommend that future models do include this information for a more detailed and realistic presentation of the real world. The final recommendation concerns the automation of the leap from the digital world to the real world. This DT model provides knowledge for the production management about adjustments that are needed to keep up with the growth. This DT does not make adjustments to the real world system on its own.

7.4. RECOMMENDATIONS FOR FOCUS-ON

The first recommendations concerns the planning. Produce the different sizes of the FOCUS-1 in series to reduce amount of time the configuration station needs to be reconfigured. Furthermore there is need for more information from the data. Make the process times of the stations operator specific. This information can be used to measure the performance of each individual operator and used for optimal planning. The final recommendation is to extend the DT model by adding stock level information to determine supply chain safety stock level and location.

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A

Research Paper

A Self-Configurable and Self-Adjustable Digital Twin For a Production Process

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Abstract—**Digital Twins are a key component of Industry 4.0. They are a digital representation of a real-world entity containing both the structure and the dynamics of its real-world counterpart. The use of Digital Twins appears to offer a powerful an compelling application for production processes. A Self-configurable and self-adjustable Digital Twin is developed for the Greenfield production process of FOCUS-ON. FOCUS-ON expects a fast growth in order demand and needs to adjust their production line accordingly. A Digital Twin is developed according to the 5C architecture. The Digital Twin proposes adjustments to the production line to keep up with the increasing order demand.**

Index Terms—**Digital Twin, Self-Configurable, Self-Adjustable, Real-time production environment, Greenfield, FOCUS-ON**

I. Introduction

Industry 4.0 was initially founded by the German government who created a new vision for their industries. [1] The term Industry 4.0 is used for the fourth industrial revolution, hence the 4.0. This implies that this revolution has been preceded by three other industrial revolutions. The first industrial revolution took place in the second half of the 18th century. Mechanical production facilities were introduced by steam and water power. The second industrial revolution started from the 1870s with the upcoming of electricity and mass production. The third industrial revolution set in the 1970 with the digital computer. Advanced electronics developed the automation of production further. Industry 4.0 being the fourth industrial revolution, it builds further on the automation and information technologies of the previous industrial revolution. With the fourth industrial revolution the physical world and the virtual world are combined. A marriage between the digital and physical systems, these combined systems are called cyber-physical systems (CPS). These systems are capable to connect with other systems via machine-to-machine communication through the Internet of things. And these systems are steered by gathering information, Big data, that is obtained with the use of sensors or other gathering devices [2].

A. CPS

CPS consists of a physical component and a digital component. The digital component analyses information from the physical world, then it calculates or plans actions to steer the physical component to perform. CPS is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities [3]. As a guideline for CPS implementation in industry, Lee et al. have designed an unified system framework for general CPS applications [4]. This framework is called the 5-level CPS structure, or 5C architecture. As illustrated in figure 1 the 5C architecture is outlined as follows: Smart connection, Data-to-information conversion, Cyber, Cognition and Configuration.

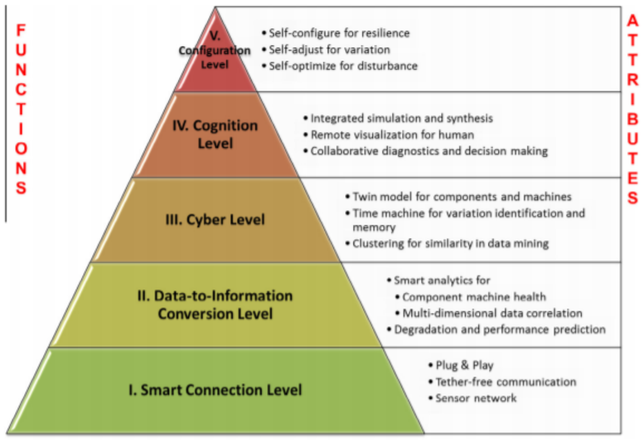

Fig. 1. 5-level CPS structure [4].

B. Digital Twin

The digital part of a CPS is called the Digital Twin (DT). The DT is limited to the digital model. In contrast to the CPS that is characterized by a physical asset and its DT. Although, the DT is only digital, it cannot exist without its physical counter part [5]. The DT can be seen as a method of achieving the convergence between the physical and virtual world [6]. Hence, the DT is a prerequisite for the development of a CPS [7]. The DT is a digital representation of a real-world entity therefore it contains both the structure and the dynamics of its real-world counterpart. By continuously updating itself with real time data it represents a near real-time status of the its physical counterpart. The DT also contains the history of the physical entity. By simulating 'what-if' scenarios, the DT provides better insight in the behaviour of the system. It makes it possible to 'see' in the future of the physical system [8].

C. Production Process DT

Especially for production processes, DT appears to offer a powerful an compelling application [9]. The DT serves as a virtual replica of what is actually happening on the factory floor in near-real time. The DT can be used to optimize the operations of a manufacturing system by maximizing resource utilization, by balancing workload across resources, and minimizing inventory levels, with just-in-time deliveries

[8]. According to Garner, half of large industrial companies will use DTs in 2021, resulting in a 10% improvement in effectiveness for those organizations [10].

DTs are relatively new and are still in a developing phase. Most of the research that is conducted is at 5C cognition level [11] [12] [13] [14]. The research conducted at the highest 5C level, configuration level, is limited and focusses mainly on the the production planning [7] [15] [16]. The aim of this research is to contribute to the research of production DTs at configuration level by proposing a DT model that is self-configurable and self-adjustable to growing order demand. And by doing so, providing the production management with insight information about the production line. The remainder of this research is focussed on creating a DT model that is self-adjustable DT model for the production line of FOCUS-ON. FOCUS-ON is a joint venture between the companies: SAMSON and KROHNE. FOCUS-ON wants to realize the full potential of the process industry, improving continuity and efficiency. With the objective: to develop, manufacture and market autonomous control solutions for process Industry 4.0 environments. Their product, the FOCUS-1 smart process node, combines the sensor, control valve and process control functions in one innovative unit.The FOCUS-1 will be produced in a completely new set up production facility in Dordrecht in the Netherlands. Section II discusses the development of the DT model according to the 5C architecture. The results of this section are used in Section III, which discusses the use case of this research. Finally, Section V presents the conclusion of the research, the points of discussion and several recommendations for further research are presented

II. Methodology

A thorough system analysis of the FOCUS-ON production line is conducted to understand how the production process works, what the components are and how they interact with each other. Figure 4 shows a schematic process view of the production line. Furthermore a literature review is conducted that allowed the author to identify which Key Performance Indicators (KPIs) can be used for a production process and the best simulation method for a production process. On the basis of this knowledge a DT model is developed according to the 5C architecture that is self-configurable and self-adjustable to a growth in order demand.

A. Smart Connection Level

Smart connection is the lowest level. This level is responsible for making the connection between the physical to the digital world. This is done by sensors that acquire accurate and reliable data. The FOCUS-ON production line is equipped with barcode scanners. With these scanners the barcode attached to the order is scanned when an orders arrives and leaves a work station. Creating time-stamps linked to an order and station. Next to the sensors, the Enterprise Resource Planning system provides real-time data about the stock levels. And a planning tool, Vplan, provides information about the order amount and the order configurations.

B. Data-to-Information Conversion Level

The second level, Data-to-information Conversion, is responsible for generating meaningful information from the different data sources. The barcode scanners used in the production line are part of the TrackOnline system. This digital system processes the timestamps data into information about the location of an order and the process time of each individual order at a specific station. Further processing of this information provides the average process times for each station step in the production line. This information is used as input for the cyber level.

C. Cyber Level

The third and middle level, Cyber, acts as the central information hub in the 5C architecture. At this level all the information is gathered and we can speak of a digital representation of the real-world system. A simulation model of the production line is developed to represent a digital representation of the real-world production line. Although agent based modelling is best suited for a production process [17], this research opts for a discrete event simulation (DES) because of financial and practical reasons. DES is insufficient in characterization of DTs for CPS in production logistics. However, the use of DES may promote the development of DTs and can be used to improve production performance [18]. The input for the model exists of the information from the previous levels and the current production line set-up. The output that the model generates is the next level, cognition level.

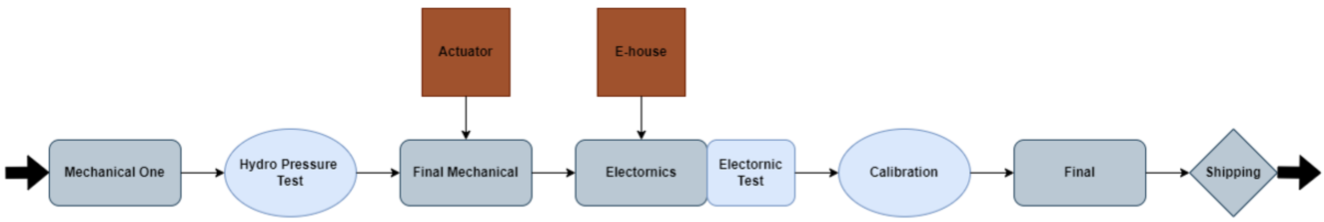

Fig. 2. Schematic view of the FOCUS-ON Production line.

D. Cognition Level

The fourth level, called the cognition level, information is generated, to present the acquired knowledge from the monitored systems. This can be presented to experts, other components and operators to support the decision making. Because the information is also presented to the production management, a proper info-graphic is used to present the acquired knowledge. The output of the model acts as the cognition level. The output consists of the following KPIs: Production Lead Times, operator occupancy and the average waiting times for a station.

E. Configuration Level

The configuration level is the highest of the 5C architecture. This level acts as a supervisory control. It is the feedback from the cyber world to the real world and by doing so, closing the CPS circle. Now the CPS can self-configure the system to apply corrective and preventive decisions, which have been made in the cognition level. The controller implemented in the model acts on the output of the model and makes adjustments to the model. The controller works as follows: After each month it will check that the production lead time of the last order does not exceed the threshold (i.e., the production capacity is not overloaded). If the production lead time is within the limit, the order load will be increased with one. If the production lead time is above the threshold the controller will make an adjustment to model and the simulation runs for an other month with the same order load. If the controller acts, it will first check the operator occupancy. If occupancy does not exceed the threshold it will look at the average waiting times of the stations in the main line. If the average waiting time for a station type is to high, the controller will adjust the model by adding an extra station of that type. These adjustments to the digital model can be used as advice for the production management who can apply adjustments to the real-world production line. And hereby closing the CPS loop from physical to digital and from digital back to the physical world. These leaps are illustrated in Figure 3.

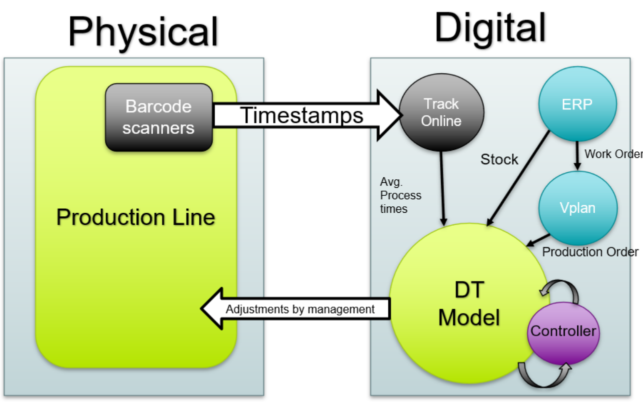

Fig. 3. Leap between the physical and digital world.

III. Results

A. Validation

Validation checks if the model is suitable to represent the system in the real world. Yet, it is not possible that a model fully represents the real world system. Therefore, 100% proof for validation does not exist. The developed DT model is validated according to expert validation: Results of the model matches the expectation of the production manager. Because the newly set-up production line is a greenfield project and the production has not yet started, the DT model could not be validated by other models or historical data. Predictive validation can not be done due to time restriction of the project. Therefore the DT model is validated by an expert, the production manager. According to his knowledge the performance monitoring of the DT model does represent the expected performance of the real world production line. Yet, it can not be proven that the developed DT model is a true digital version of the production line, nevertheless the DT model is still found suitable for the purpose of this research.

B. Case: Order demand growth

As stated in the introduction: FOCUS-ON has a great ambition and expects a fast growth. According to their order demand forecast for the upcoming year, they expect an order demand of up to 145 orders a month. To keep up with this growth their newly designed production line needs to adjust accordingly. Their current set-up of the production line consists of single stations and 3 operators working at the line. Figure 3 shows the output of the DT model. The adjustments made by the controller to keep production lead time at a satisfactory level are presented in table I.

TABLE I
Production Line Adjustments

Monthly Order Load	Adjustment Measure
86	Number of operators is set to 4
113	Number of operators is set to 5
142	Number of operators is set to 6
156	A Calibration station is added
171	Number of operators is set to 7
194	A Mechanical One station is added
194	Number of operators is set to 8
200	An Electrotronics station is added

The output of the model show that the production line of FOCUS-ON with the current set-up can handle an order load of up to 85 orders a month. To achieve a production capacity to keep up with the forecast of the upcoming year, three more operators are needed. Furthermore, the results show that at load of 156 orders a month a bottleneck occurs at the calibration station. Although the number of operators working at the production line is less than the number of stations they work at. Adding more operators does not increase the production capacity anymore. A second calibration station is needed to prevent increasing waiting times.

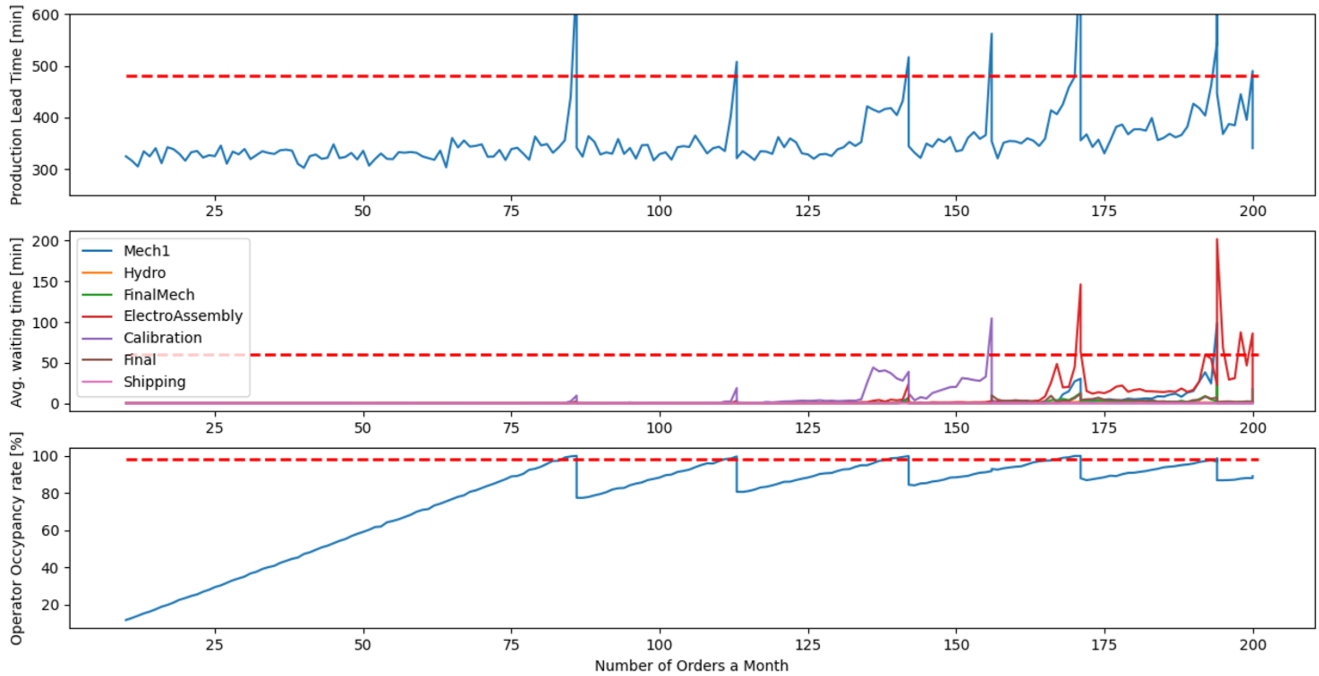

Fig. 4. DT model output: The KPIs of the production process. Top: Production Lead Time in minutes Threshold set at 480 minutes. Middle: Average waiting time of an order at a production step in minutes. Threshold set at 60 minutes. Bottom: Operator occupancy in percentage. Threshold set at 98%.

IV. Conclusion, Discussion and Recommendations

A. Conclusion

From the results from the experiment can be concluded that a self-adjusting DT can keep a desired performance with an increasing demand. This is done by making adjustment to the system and self-configure the simulation model according to these adjustments. And hereby providing knowledge of the system, which is of great value for a greenfield project. The self-adjusting DT provides the production management with essential knowledge about the production capacity limitations. Furthermore, it provides the knowledge about which adjustments need to be made to keep up with the increasing order load. The required investments in the production line. The adjustments to the production line of FOCUS-ON to keep up with the increasing demand are presented in table I. Finally, the DT model provides information about the production line dynamics by exposing potential bottlenecks.

B. Discussion

There are some points of discussion which could argue the conclusions and the developed DT model. First of all, this research uses DES, which is not the best choice for a production process DT model according to the literature. Agent based simulation modeling is the preferred choice. Furthermore, assumption where made that simplified the model. For example: All the operators have the same skill level. Operators play a main role in the production process and are simplified to a single resource. In reality, each operator has a different skill level and favorite work stations. Due to the limited production in real life, the data that was gathered was limited. The limitation of data resulted that the validation only could be done by expert validation. Furthermore, this research uses the term DT which is debatable. The connection from the digital world to the physical world is not automated. Those actions need to be done manually. Although the data flow from the physical world to the digital world is automated, it still needs to be insert in the model manually and therefore it could be argued it is just a digital model.

C. Recommendations future research

As stated in the previous section, the simulation method used in this research is not the preferred choice. Therefore it is recommended to develop a future model according to the agent based simulation method. The model development phase of this research is constrained by the time limitation of this research. Therefore, the level of details that are given in this model is also limited. In order to have a more valid model, it is recommended for future research to expand the model by introducing other important parameters. For instance the hands on tool time and the skill level of the operators. Furthermore, this research only focused on self-adjustment to order demand growth and assumed that the order load is equally spread over a month. Therefore it is recommend that for future research the DT model would be extended with a controller that optimizes the planning of the work orders. The next recommendation concerns the floor plan of the production facility. The presented model does not take into account the available space or the movements between the production stations. It is recommend that future models do include this information for a more detailed and realistic presentation of the real world. The final recommendation concerns the automation of the leap from the digital world to the real world. This DT model provides knowledge for the production management about adjustments that are needed to keep up with the growth in order demand. The developed DT in this research does not make adjustments to the real world system.

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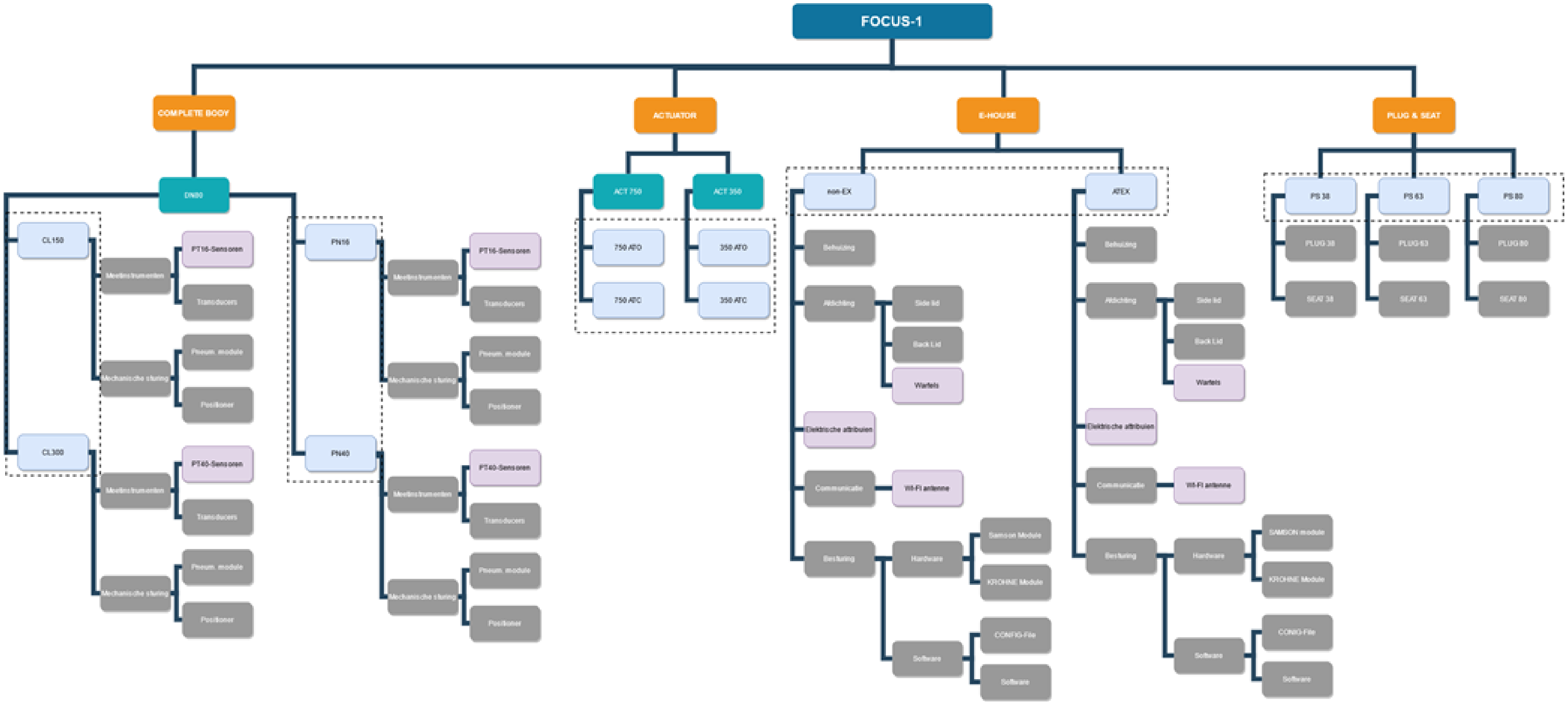
B

Product Breakdown


FOCUS-1
COMPLETE BODY
DN80
CL150
Meetinstrumenten
PT16-Sensoren
Transducers
Mechanische sturing
Pneum. module
Positioner
CL300
Meetinstrumenten
PT40-Sensoren
Transducers
Mechanische sturing
Pneum. module
Positioner
PN16
Meetinstrumenten
PT16-Sensoren
Transducers
Mechanische sturing
Pneum. module
Positioner
PN40
Meetinstrumenten
PT40-Sensoren
Transducers
Mechanische sturing
Pneum. module
Positioner
ACTUATOR
ACT 750
750 ATO
750 ATC
ACT 350
350 ATO
350 ATC
E-HOUSE
non-EX
Behuizing
Afdichting
Side lid
Back Lid
Wartels
Elektrische attributen
Communicatie
Wi-Fi antenne
Besturing
Hardware
Samson Module
KROHNE Module
Software
CONFIG-File
Software
ATEX
Behuizing
Afdichting
Side lid
Back Lid
Wartels
Elektrische attributen
Communicatie
Wi-Fi antenne
Besturing
Hardware
SAMSON module
KROHNE Module
Software
CONIG-File
Software
PLUG & SEAT
PS 38
PLUG 38
SEAT 38
PS 63
PLUG 63
SEAT 63
PS 80
PLUG 80
SEAT 80