R.A. Slingerland

Power & Free Conveyor Operation at the SEW Eurodrive Assembly Plant in a Cyber-Physical Production System Perspective

TU Delft

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By

R.A. Slingerland

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Supervisor:	Dr. W.W.A. Beelaerts van Blokland	
Thesis committee:	Dr. Ir. D.L. Schott,	TU Delft committee chair, 3mE
	Dr. W.W.A. Beelaerts van Blokland,	TU Delft committee member, 3mE
	Dr. J.M. Vleugel,	TU Delft committee member, CiTG
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TU Delft

Preface

With this master thesis, there comes an end to my studies in Delft. A time that I have enjoyed a lot; it was a good time in which both the studies and everything else shaped me to the person I am now. This last hurdle was often a challenge and I am grateful for everyone who helped me to get it done.

First I would like to thank my graduation committee for their help. Wouter Beelaerts van Blokland, as a daily supervisor, for his availability and the support on the theoretical background. Also for introducing me to the company SEW Eurodrive. Dingena Schott for bringing structure in my writing and thinking. Jaap Vleugel for participating in the committee.

Thanks to Matthijs Dolman from SEW Eurodrive, for his continuous support, enthusiasm about the topic and help with setting realistic goals.

I want to thank my wife Sylvia, you were always there, I am grateful for all the moments you helped me. I want to thank my parents for their support during the entire study time. Renske Oldenboom from MotiV for listening and asking the right questions, Maarten and Jeroen for giving feedback and all other study mates and friends I've worked with during this project.

I want to thank God who is above it all for providing wisdom, energy, perseverance and all the people around me to finish this thesis.

Dear reader, enjoy and know that I am available for a discussion on the content.

Ruben Slingerland
Delft, February 2023

Abstract

This master thesis focuses on the effect of variabilities in a Power & Free conveyor system on the flow continuity by an analysis on the product, process and production level (3P), a discrete-event simulation model and the theory of Cyber-Physical Production systems (CPPS) to control the product flow. Scenarios were evaluated with this model and the results show the effect of performance increase when variability decreases. Requirements are set to come to real-time control by developing this model into a digital twin as part of a CPPS. It can be concluded that the discrete-event model can be used to predict the performance and take control measures accordingly, subsequently real-time control is possible by implementing real-time sensor measurements in the model, thereby developing the model into a digital twin.

Summary

This research addresses a product flow in the assembly process of electrical drives at SEW Eurodrive Rotterdam which is subject to variations. Specifically in the final steps of this assembly process that is connected to each other by a Power & Free (P&F) conveyor. This P&F conveyor is a type of overhead conveyor with trolleys that are able to engage and disengage from the powered chain thereby providing flexibility in the process. A downside is a non-continuous product flow, which results in an uneven workload for employees. Currently this system is controlled by the employees who change to different work stations if needed, however still a non-continuous flow is observed. It is this non-continuous flow which this thesis addresses by the research question: How can the flow continuity of a Power & Free conveyor system be controlled?

Found in literature were theories, methodologies and models on analyzing product flow in a production process. The development of Industry 4.0 or specifically Cyber-Physical Production Systems (CPPS) contributes to analyze the flow for example by creating a digital twin of the process. The Delft Systems Approach (DSA) was found to be a methodology to describe such a production process, specifically determining functions and the flow between them. The theory of Lean Manufacturing (LM) provides concepts to analyze and control this flow, for example the distinction between three types of waste resulting in non-value added time to a product. Another concept is takt time, which is used to structure the flow. Product flow can be simulated, various simulation models are made for Power & Free conveyor systems. Discrete-event simulation is a method which enables modelling production processes based on stochastic inputs. Tools are available with build-in elements like conveyors, queues and servers that are able to model a Power & Free conveyor.

The current state of this P&F conveyor system was analyzed by making a system description using DSA. The elements and attributes are discussed as well as the product flow between the functions and the tasks of the system. Three functions are identified: a quality control on the product, the application of one or more layers of paint and the preparation for dispatch. Variability in the system was assessed by the 3P model, which refers to 3 perspectives: product, process and production. The performance of the system or flow continuity was defined by the throughput and the average waiting time in the system per product. Based on LM a ratio was defined of the value added time and the total time in the system or lead time. Those performance metrics are also the output of the model that was made.

The product flow in the process was modelled using a discrete-event simulation tool JaamSim. This model simulates the product flow, the trolley flow and their interaction. The input of this model are probability distributions for the inter-arrival times of input products, the operating sequence of the spray booth interior conveyor and the inter-arrival time distribution of the packaging station. The output are the performance metrics previously discussed.

Various scenarios are explored using this model. The effect of the number of trolleys on the performance was analyzed, currently the system has 30 trolleys, a takt time was introduced at the location were products enter the system and a planning was made of the order of products over the course of a day. Finally a scenario was made that presumes continuous flow of the interior spray booth conveyor and a fixed service time at the packaging station. The latest scenario in combination with 22 trolleys shows an increase of the throughput of 21%, and a mean of the average waiting time per trolley of 5 minutes compared to 39 minutes in the current state.

The model enables estimating the flow continuity per day based on the mix of paint types. In order to come to real-time control, the model needs to be fed by measurement data performed in the physical system. In this way the model can be used and develop into a digital twin. Requirements for this digital twin are the possibility of real-time retrieving stopper and trolley queue data. Also the time at which trolleys pass at stoppers that are currently not measured, should be recorded and the data on the stoppers and the spray booth interior conveyor needs to be integrated.

Summary (in Dutch)

Dit onderzoek gaat over productstroomvariabiliteit in een assemblageproces van elektromotoren bij SEW Eurodrive Rotterdam. In het bijzonder de laatste werkstations van dat assemblageproces die met elkaar zijn verbonden door middel van een hangbaan (power & free conveyor). Een hangbaan is een type transportband die gebruik maakt van trolleys die zowel aan kunnen haken aan de ronddraaiende aangedreven ketting als hiervan los te koppelen, hierdoor biedt een hangbaan extra flexibiliteit in het proces. Een keerzijde echter is het niet-continue karakter van de productstroom die voor een ongelijke werkverdeling zorgt voor de werknemers. Op het moment wordt het systeem bestuurd door de werknemers zelf die wisselen naar andere werkstations als dat nodig is, toch wordt er nog steeds een niet-continue productstroom waargenomen. Deze productstroom wordt in deze scriptie behandeld door de onderzoeksvraag: Hoe kan de productstroomcontinuiteit van een hangbaan systeem worden bestuurd?

In de literatuur zijn theorieën, methodologieën en modellen gevonden die gaan over het analyseren van de productstroom in een productieproces. De ontwikkelingen binnen Industry 4.0 of specifieker Cyber-Physical Production Systems (CPPS) kunnen hiervoor gebruikt worden bijvoorbeeld door een digitale equivalent te maken van het proces. De Delft Systems Approach (DSA) is een methodologie om een productie systeem te beschrijven en is geschikt om de verschillende functies te onderscheiden met de productstroom daartussen. Concepten uit de theorie van Lean Manufacturing (LM) kunnen ook gebruikt worden om de productstroom te analyseren en te besturen. Bijvoorbeeld de drie vormen van waste die zorgen voor tijd waarin geen waarde wordt toegevoegd aan het product. Een ander concept om productstroom te structureren is takttijd. De productstroom kan ook gesimuleerd worden. Er zijn verschillende simulatie modellen van een hangbaan gemaakt. In het algemeen wordt hier discrete-event simulatie voor gebruikt, hierin is het mogelijk om te werken met stochastische inputs. Er zijn verschillende software pakketten beschikbaar met voorgeprogrammeerde elementen zoals transportbanden, wachtrijen en servers waarin een hangbaansysteem gesimuleerd kan worden.

Een systeembeschrijving met DSA is gebruikt om de huidige staat van het hangbaansysteem te analyseren. Er kunnen drie verschillende functies worden onderscheiden: een eindcontrole op de kwaliteit van het product, het aanbrengen van een of meerdere lagen verf en ten slotte het voorbereiden voor verzenden. De variabiliteit in dit systeem is onderzocht doormiddel van het 3P model, oftewel drie perspectieven: product, proces, productie. De prestatie van het systeem of de productstroomcontinuiteit is gedefinieerd door de doorvoer en de gemiddelde wachttijd in het systeem. Tenslotte is de verhouding bepaald tussen waarde toegevoegde tijd gebaseerd op LM en totale tijd in het systeem als maat voor de prestatie van het systeem. Deze drie maten voor de prestatie zijn ook de output voor het model die is gemaakt.

De productstroom in het proces is gemodelleerd door middel van de discrete-event simulatie software JaamSim. Dit model simuleert de stroom van trolleys, producten en de interactie tussen die twee. De inputs zijn kans verdelingen voor tijdsintervallen tussen producten die het systeem binnen gaan, de start-stop intervallen van de binnenbaan in de spuitcabine en de tijdsintervallen bij het inpakstation. De output zijn de drie prestatie maten zoals eerder genoemd.

Verschillende scenario's zijn met dit model onderzocht. Allereerst het effect van het aantal trolleys op de prestaties. Het systeem heeft op het moment 30 trolleys. Vervolgens is gekeken naar een

takttijd bij de invoer van producten in het systeem, en naar het plannen van de productinvoer per type. Ten slotte naar een scenario met continue doorstroom bij de binnenbaan van de spuitcabine en vaste werktijden bij het inpakstation. Dit laatste scenario met 22 trolleys verhoogt de doorvoer met 21% en zorgt voor een gemiddelde wachttijd per product van 5 minuten, vergeleken met de huidige 39 minuten.

Het model biedt de mogelijkheid om gebaseerd op de mix van verfsoorten een schatting te maken van de productstroomcontinuiteit. Om het systeem real-time te besturen, moet er input data beschikbaar zijn die direct in het model ingevoerd kan worden. Op deze manier kan het model ontwikkelen naar een digitale equivalent van het systeem. Hiervoor is het vereist dat stopper en wachtrij data real-time beschikbaar zijn. Daarnaast moet deze data worden gemeten voor iedere stopper, ook diegenen waar dat nu niet gebeurt. Tenslotte moet de data van de spuitcabine binnenbaan en de stoppers worden geïntegreerd zodat beiden gebruikt kunnen worden als input van het model.

List of abbreviations

AI	Artificial Intelligence
ATO	Assemble to Order
CPPS	Cyber-Physical Production Systems
DC	Dry cell
DES	Discrete-event Simulation
DMAIC	Define, Measure, Analyze, Improve, Control
DSA	Delft Systems Approach
GUI	Graphical User Interface
IQR	Inter-quartile range
JIT	Just-in-Time
KPI	Key Performance Indicator
LM	Lean Manufacturing
P & F	Power & Free (conveyor)
SEW	As part of company name SEW Eurodrive: Süddeutsche-Elektromotoren-Werke
TIMWOODS	Transport, Inventory, Motion, Waiting, Over-production, Over-processing, Defects, Skills (unused)
ToC	Theory of Constraints
TPS	Toyota Production System

Contents

Chapter 1

Introduction

This chapter introduces the company SEW Eurodrive, the concept of a power and free conveyor and the design of this research.

1.1 Company SEW Eurodrive

SEW Eurodrive is a German family-owned manufacturer of drive technology. It produces gearboxes, motors, geared motors and converter technology in various sizes based on a modular system with ca. 10^{28} variants. SEW Eurodrive operates globally with 77 assembly factories and 15 production factories. One of those assembly factories is located in Rotterdam and is supplied every day by a production factory in Germany.

In the Netherlands 100,000 end products are sold of which 40% is assembled in Rotterdam and 60% in Germany. All products are assembled to order (ATO) in a one piece flow, this means there are no finished products on stock. Products are assembled only after an order is placed by a customer. A standard delivery time in the Netherlands of 3 workdays was met, before material shortages appeared on the market since 2020.

In Rotterdam a wide range of geared motors are assembled. This includes the assembly of a motor and a gear box attached to it. The weight of the total end product is between 6 and 200 kg.

The products move through the factory in a one-piece flow. In this case this means that one employee assembles one product from beginning to end. The products are assembled on a dedicated plate. Assembled products enter the final stage of the production process on this plate (figure 1.1). This final stage of the of the assembly process before shipping involves the following steps: a final quality check on the functionality of the product, apply a desired paint layer, drying and packaging. Between those operations, the products are no longer transported on plates, but by a Power and Free (P&F) conveyor. This research focuses on those last steps of the assembly process.

Figure 1.1: Products are transported on dedicated plates in a one-piece flow

1.2 Power and Free conveyors

A power and free conveyor is a type of overhead conveyor. Mostly used in production environments that require more flexible transportation, than a conventional overhead conveyor could provide. A conventional overhead conveyor has trolleys that are fixed on the drive chain, whereas the power and free conveyor trolleys are able to mechanically engage and disengage from the drive chain enabling buffering before a specific operation (figure 1.2). It is used for operations like spraying, heating, cooling, drying, washing, dipping, etc. and transportation between those operations [4] [39]. Power and free conveyors could also be inverted and mounted on the floor [37].

Figure 1.2: Part of the Power and Free conveyor at SEW Eurodrive Rotterdam

A Power and Free conveyor consists of two tracks. An upper track that is powered by a chain and a lower free track that is unpowered. The load is carried via trolleys on the lower track. Mechanical devices on the powered track, referred to as pusher dogs engage with the trolleys to move them and disengage to stop them (figure 1.3). Once a trolley bumps into a free trolley the pusher dog will disengage by design. Furthermore, if required, pusher dogs could disengage on so called stoppers that are mounted on the track at designated positions.

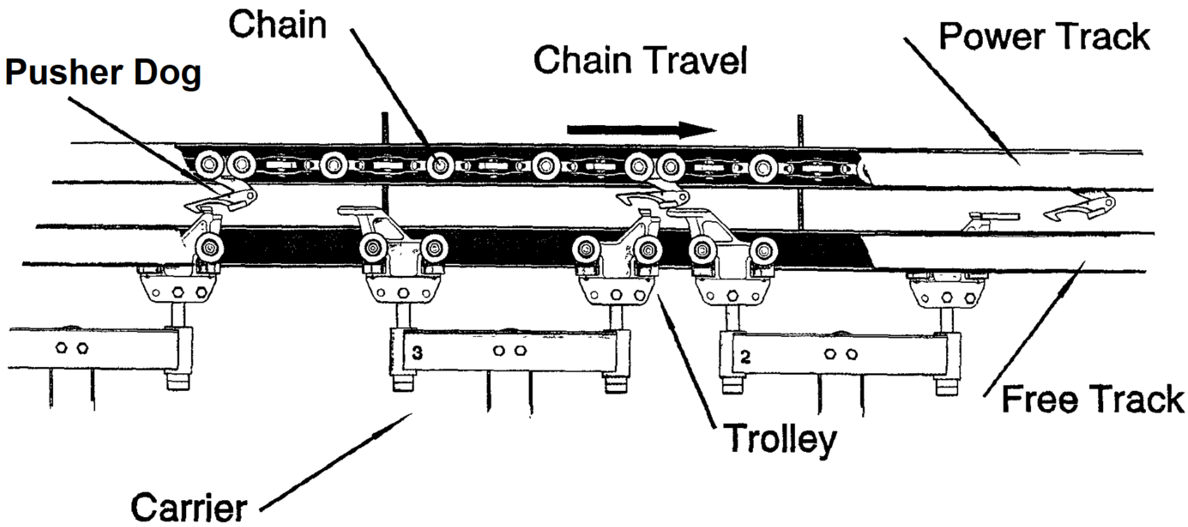


Figure 1.3: Working principle power & free conveyor [15]

1.3 Smart P&F conveyor lab

Figure 1.4 shows the layout of the P&F conveyor at SEW Eurodrive Rotterdam and the workstations that are connected by this conveyor. Products are attached at the final check station, transported through the spray and dry service and detached at the final assembly / dispatch, or packaging station. SEW Eurodrive cooperates with TU Delft for the development of a smart P&F conveyor lab. The idea is to turn the existing P&F conveyor system into a smart P&F conveyor lab. The data in the system can be analyzed and novel operational artificial intelligence (AI) algorithms can be implemented and tested. The focus lies on optimal design, optimal operation and finally the integration of those. To start this lab, deeper understanding of the system and variability's in the system is needed.
This exploratory research will act as a start for this development.

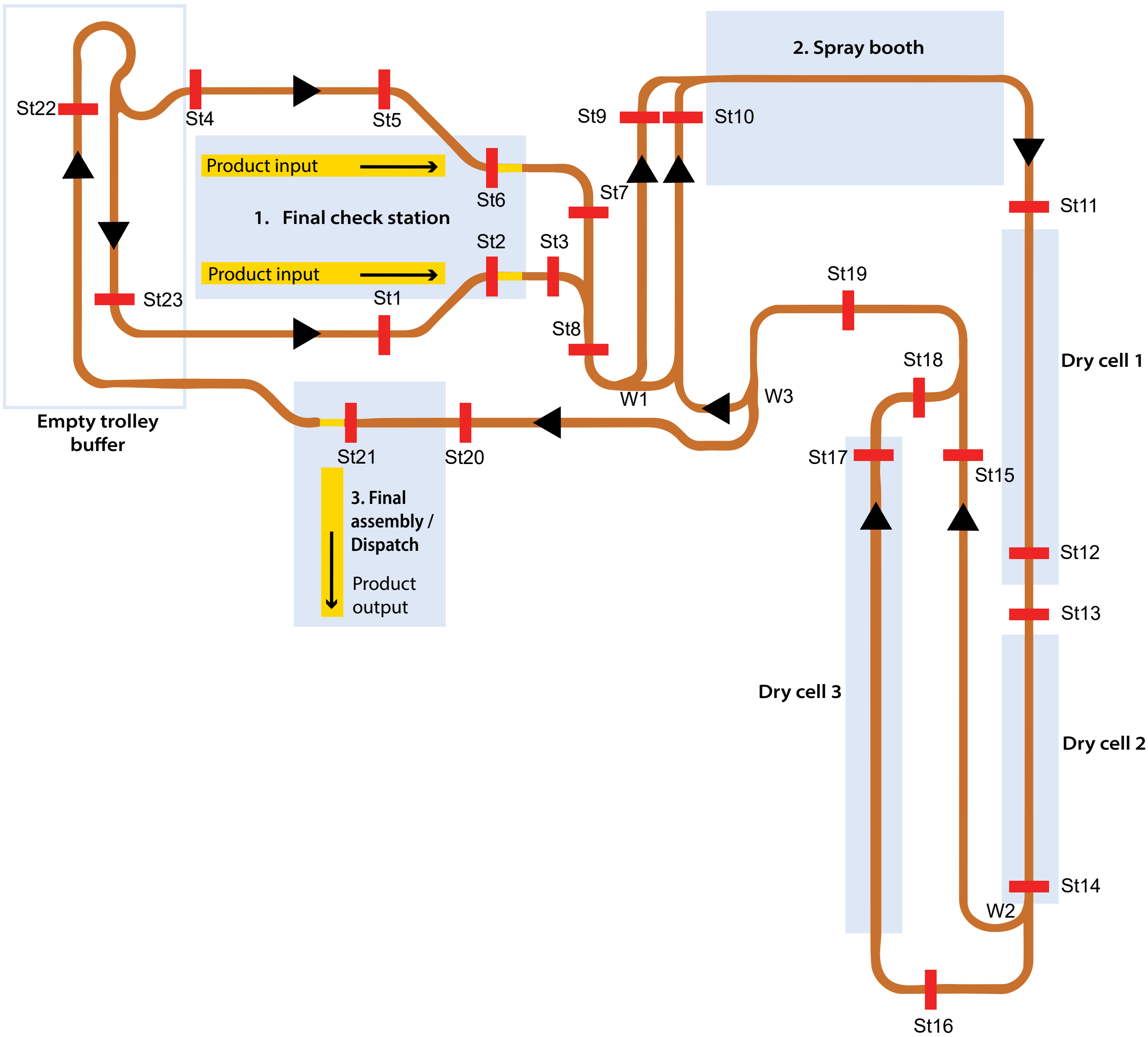


Figure 1.4: Layout of the P&F conveyor of SEW Eurodrive in Rotterdam with all the stoppers, marked as 'St', switches, marked as 'W', and working stations, marked as grey boxes. The locations at which products are attached or detached from trolleys are marked yellow as input or output. Products are attached at the final check station, transported through the spray and dry service and detached at the final assembly / dispatch, or packaging station. Arrows indicate the direction of the conveyor. Workstations are humanly operated, dry cells operate automatically.

1.4 Problem Statement

The different working stations interconnected by the Power & Free conveyor referred to as the Power & Free conveyor system, do not operate stable at the current implementation. Buffers are observed to appear and disappear over the course of a day before the final check station, the spray booth and packaging station. This results in an uneven workload for employees and non-value added time to the product, in other words non-optimal flow. Currently the employees control this flow by flexibly working at the working stations where work can be done. Figure 1.5 shows the length of the three buffers in the system over the course of an arbitrary day. Peaks can be observed as well as moments of 0 products in the buffer. Besides the visible variations in buffer lengths, the system contains various types of variability. This includes per product: size, routing and treatment. The system furthermore has multiple inputs, flexible employee occupation, both manual and automated processes, every day a start and stop phase including employee lunch break. The input of the system is random, based on which product first arrives on the plates from the upstream one-piece-flow process. Current understanding of the effects of variability on the flow, is not enough to control it.

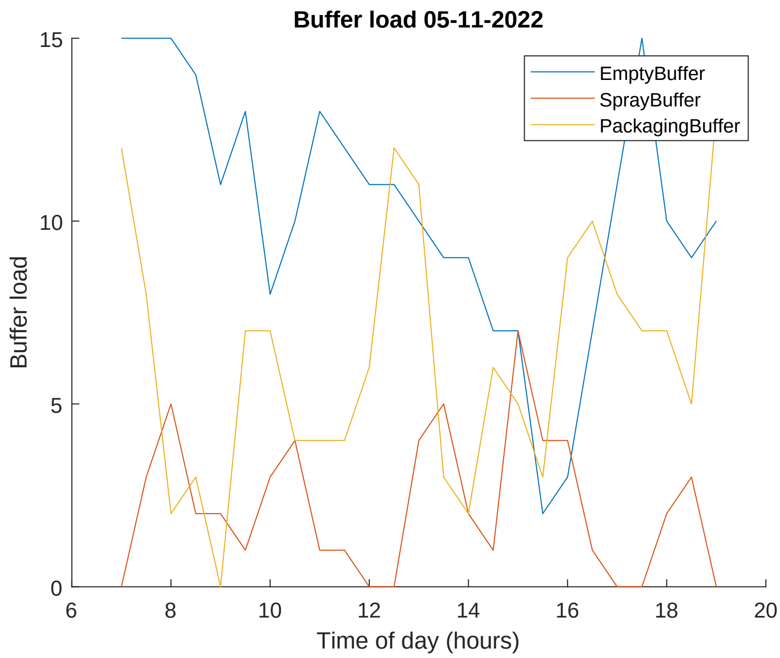


Figure 1.5: Buffer lengths of the P&F system for an arbitrary day in May 2022 with a resolution of 30 minutes. The empty trolley buffer refers to the sum of stopper 22,23,1,4 and 5. Spray buffer to the sum of stopper 9 and 10. Packaging buffer to the sum of stopper 20,19,18 and 15. This figure shows the problem of appearing, disappearing and varying buffer lengths.

1.5 Research goal

The goal of this research is to analyse the variabilities in the Power & Free conveyor of SEW Eurodrive Rotterdam, relate this to the performance and find measures that could control the flow in the system.

1.6 Research questions

A main research question is formulated as:

How can the flow continuity of a Power & Free conveyor system be controlled?

This research addresses this question by 5 subquestions that are linked per chapter in table 1.1.

Table 1.1: Subquestions and the chapters in which they are answered

	Subquestion	**Chapter**
1	What theories, methodologies and models are available on analyzing product flow in a production process?	2. Literature Review
2	What defines the Power & Free conveyor system, its performance and which part causes variability?	3. Current State
3	What model can be used to analyze and assess the flow continuity?	4. Model Design
4	Which scenarios can be used to control the flow continuity and what is the effect of those scenario's on the performance?	5. Scenarios and Results
5	What are the requirements for using the model as a digital twin in a cyber-physical production system and how could this contribute to control the flow continuity?	6. Discussion

Chapter 2

Literature Review

This chapter answers the first research sub-question:

What theories, methodologies and models are available on analyzing and controlling product flow in a production process?

Different theories are discussed on manufacturing and concepts are distilled from them that could contribute to the analysis of product flow. Methodologies are mentioned that could contribute defining a system and available models that are used to analyze product flow. Finally a matrix (table 2.1) was made which maps the literature with combination of research fields and shows a gap in the combination of subjects this research will develop.

2.1 Historical context

Production processes are not a new phenomenon; people have been manufacturing since the beginning of humankind [10]. Artefacts could be made without the help of others, however this limits the amount of complexity and takes relatively long to finish. By cooperating mankind has been able to specialise, a development that is related to the increase of wealth [10] [33]. This chapter will focus on the developments in production processes since the industrial revolution. Coming paragraphs will elaborate about the paradigms or theories in modern manufacturing, where they come from and what they could contribute to the analysis of product flow in a production process.

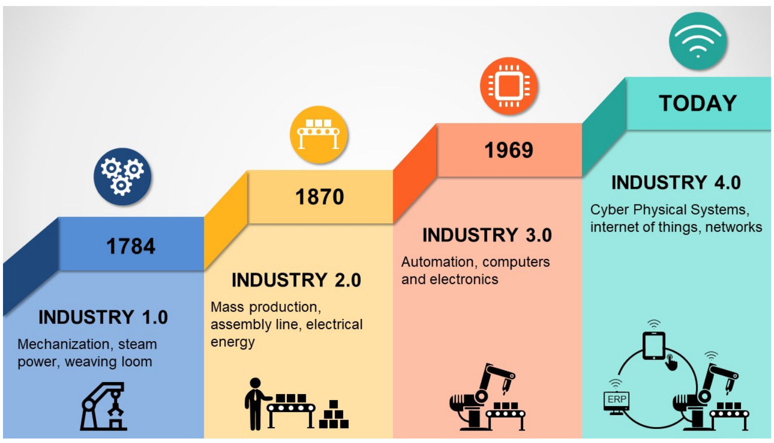


Figure 2.1: 4 industrial revolutions [50]

2.2 Industrialization in four revolutions

The development in modern manufacturing, referred to as industrialization can be described by four industrial revolutions (figure 2.1). The first started in the 18th century and is characterized by mechanisation. Examples are the entrance of the weaving loom in the textile industry and the application of steam engines enabling higher power and flexibility to produce [40]. A century later, the 19th century, Henry Ford made cars affordable to the masses by introducing the assembly line. With this assembly line he was able to increase the production rate of cars 8 times [26]. Hence the invention of electricity opened up a set of new possibilities [35]. This development is referred to as the second industrial revolution. In the 20th century the rise of computers and information technology enables a third industrial revolution, for production processes this means the introduction of automation. In this revolution the focus regarding energy sources is on renewable energy sources. Globalization was made possible by information technology and also resulted in massive global transport systems driven by efficiency [42]. In 2011 the World Economic Forum formulated the concept of Industry 4.0 [38]. It is presented as a new industrial revolution which takes place at the moment. Some directions in which this revolution could develop are: self-optimization and self-adaptation of cyber-physical (production) systems, human-machine symbiosis, intellectual networks (artificial intelligence) [9]. The coming sections will elaborate on these directions, considering flow in a production process.

2.2.1 Cyber-physical production systems

The concept of a cyber-physical production system is a conventional physical production system that is fully integrated in a cyber level. One part of this system is a digital equivalent, which is referred to as a digital twin [16]. A cyber-physical production system can be divided in 5 layers or 5C's: smart connection, data-to-information conversion, cyber, cognition, and configuration level [16]. Figure 2.2 shows the structure of such a system.

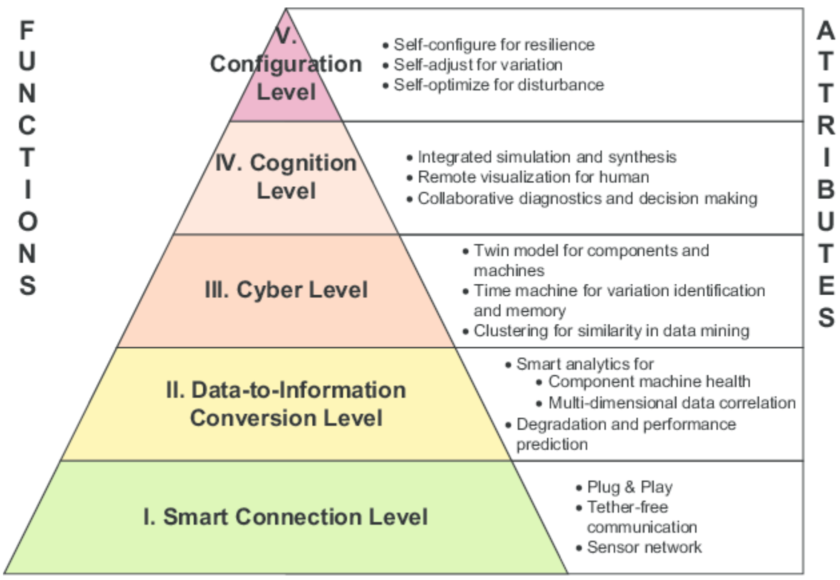


Figure 2.2: Architecture of a cyber-physical production system [51]

In the smart connection level devices are able to self-connect and self-sense. This is the bottom layer or starting point. One level up is the data-to-information conversion level, in this level data from these devices are measuring critical issues which will recognize for example component machine health or can do performance prediction. In the cyber level every machine uses this data to create its own digital twin. Those twins could compare themselves with other digital twins and could compare performance with historical data to detect variations. In the cognition level the outcome of the cyber level is presented to users and in the configuration level the configuration of the production system can be adapted based on given risk criteria and priorities to achieve resilient operation. [51]

The critical issues on the conveyor can be sensed and used for the creation of a digital twin [24]. What the critical issues are is dependant on the application.

2.2.2 Human-machine symbiosis

The next subject in Industry 4.0 is human-machine symbiosis. The idea is to leverage both the strength of humans and machines. Intuitively human control is only possible to a certain amount of complexity in a system, it is here that machines could contribute. [9]. Humans will be needed in the role of strategic decision-makers and flexible problem-solvers [14]. An example is the rise of collaborative robots or cobots [52]. This type of robot is designed to work in an environment together with humans, including the associated safety requirements [28].

Some ethical risks are discussed regarding human-machine symbiosis by Pacaux-Lemoine & Trentesaux [31]. In unexpected situations humans are able to experience a bad conscience and could rely on common sense to limit the impact of their decisions. If machines do not have a programmed common sense, they might make unethical decisions in unexpected situations. Also, humans could learn bad habits to machines, which might amplify bad decisions. There is also the responsibility question if something goes wrong and humans and machines cooperated in the process. Finally there could develop a master-slave or emotional dependency between the machine and humans that might result in loss of human skill or overconfidence in the ability of the machine [31].

2.2.3 Intellectual networks (artificial intelligence)

Artificial Intelligence (AI) has been defined as a system's ability to learn from external data correctly and apply the learnt learnings for achieving specific goals and tasks [17]. This could be used in the optimization of both the design and the operation of a production process. AI solves the problems that "consist of reasoning based on knowledge, learning using experimental observations, and reasoning with uncertain, partial, or incomplete information through various types of perception and learning algorithms" [29]

2.2.4 Product flow in a Industry 4.0 context

The Industry 4.0 paradigm gives a vision in which industry could develop. Ultimately latest technology is implemented to integrate both physical processes with possibilities in cyberspace. Thereby promising an higher global optimum for production systems. The optimization of flow in a production process therefore could be an outcome of this development. Ethical risks however should be considered. The status of this development for current systems could be rated according to the 5C's of cyber-physical production system. Requirements could be set that are needed to move a step higher in the pyramid (figure 2.2).

Another paradigm that influenced modern manufacturing are production management theories like Theory of contstraints and lean manufacturing, those will be discussed in the following paragraphs.

2.3 Theory of Constraints (ToC)

The Theory of Constraints (ToC) was introduced by the physicist, author and philosopher Eliyahu Goldratt in his book *The Goal* [12] in 1984. The core idea of this theory is that a chain is as strong as its weakest link. Therefore in order to improve a complete system one has to improve the weakest link or constraint. For a production systems this means finding the bottleneck. This is not always trivial, it starts by determining the overall goal of the process and remove everything that is not related to this goal. [12]. Different ToC measures are developed: Thinking Process, Five Focussing Steps, Critical Project Management [43].

From this theory one could learn that the flow in a production process is dependant on the weakest link. This is illustrated in *The Goal* [12] by an example of a group of people making a hike. Variability is observed in the environment involving hills, valleys and also in the group of participants involving sporty people and less sporty people, people with heavy bags and light bags. Without control this group spreads over time, resulting in waiting times for the fast and stress for the slow. At a certain moment a control measure was made; the slow guy will walk on first position and everyone else will follow him. Now the group stays together and the attention focuses on measures that could help the slow guy. It appears that his bag was heavy, so after giving his heavy luggage to a sporty person, the complete group was able to hike in a faster pace and arrive at the destination on time.

Examples like this could be used as a thought experiment for existing industrial processes [8]. Concepts of this theory are closely related to the management philosophy lean manufacturing that will be discussed in the next paragraph.

2.4 Lean Manufacturing

Lean manufactering is a production philosophy, originated in Japan, that focuses on maximizing resource utilization and thereby minimizing waste [45]. Minimizing waste means focus on value creation for the customer and eliminate everything that is not related to this focus. The later is referred to as waste. Lean manufacturing was introduced in western production plants via the Toyota Production System (TPS) [54] [25]. Some theories are closely related to lean manufactering for example the theory of swift even flow [30]. Taiichi Ohno (1912-1990) is known to be the founder of the TPS, he summarizes it as follows:

"*All we are doing is looking at the time line from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that time line by removing the non-value-added wastes*" [25]

2.4.1 Types of waste

According to the TPS, those non-value-added wastes could be divided in 3 categories. Commonly referred to by their Japanese names: Mura, Muda and Muri.

Muda
Every activity in a production plant could be divided in value added and non-value added activities. Every step that adds something to the product, a screw, a layer of paint, etc. is a value-added activity. Everything else is a non-value added activity. Those non-value added activities could be summarized by the abbreviation TIMWOODS, which stands for: Transport, Inventory, Motion, Waiting, Over-production, Over-processing, Defects, Skills (unused).

A result of specifically reducing inventory - and thereby also transport, motion and waiting - is the concept of Just-in-Time (JIT). Materials are ordered such that they arrive at the moment they are needed.

Companies try to reduce muda as much as possible, sometimes forgetting the other types of wastes. An optimal result is achieved by balancing the three [44].

Muri
Muri means overburdening of people or processes. According to the TPS this will ultimately lead to

muda [44]. Overburdening of people will decrease safety, quality and probabily the health of employees. Overburdening of equipment will cause defects [25].

Mura

Mura means unevenness or inconsistency. In other words an high variability in the process, which will create muda as well. Mura happens for example when the right combination of people, products and material are not present at the right time.

Related to this is the concept of heijunka (load levelling) Strictly focussing on Just-in-time could result in high variations. Heijunka is a way of planning the products for example over the time period of a week and thereby levelling the work load.

Figure 2.3 shows an illustrative example of those types of wastes.

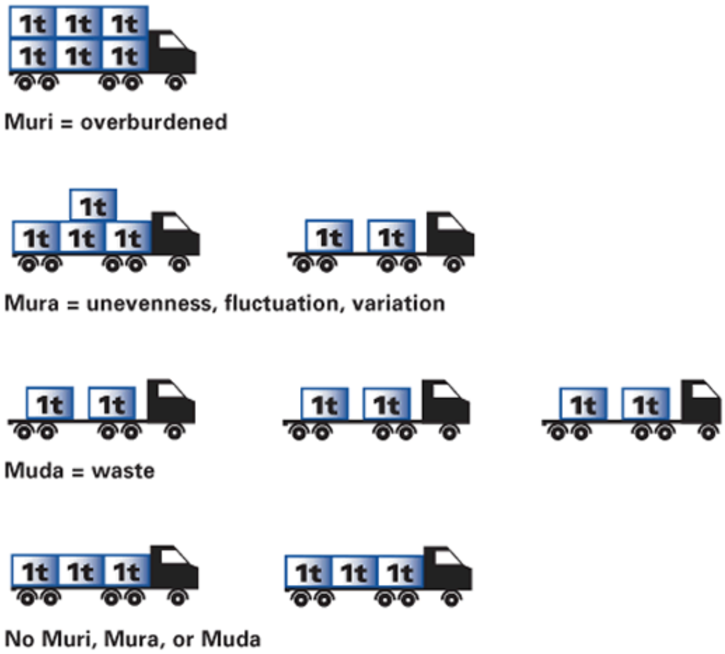


Figure 2.3: Illustrative example of the 3 types of waste or 3M's by the Lean Enterprise Institute [20]

One type of waste results in the other wastes as well, therefore the relationship between those wastes can be described by a triangle in which every waste effects the other two (figure 2.4) [3].

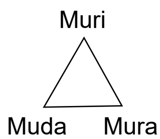


Figure 2.4: The three types of waste in lean manufacturing are all related to each other [3]

2.4.2 Takt time

An important concept in the Toyota Production System to reach a constant flow is the takt time. The takt time is determined by the demand of the customer, expressed by the amount of products per time unit. A production system should be organized in such a way that at the end this production rate is met. The concept of takt time means that the process is divided in parts that all require the same time. In a one-piece-flow context, this means that the product is passed to the next work station in a fixed pace. For this reason the takt time is also referred to as the heart beat of a production process [25]. In this research a takt time is implemented in the simulation model described in chapter 3.

2.4.3 Performance metrics

The time value is added to a product could be compared with the time no value is added. A method to visualize this distinction together with the flow of a production process is a value stream map [36], which shows the flow of a raw material to the end product for the customer. A sketch of such a value stream map is attached in Appendix B. The time value is added to a product and the total time in the system or lead time could be used as a measure of the performance [2].

2.4.4 Lean-Six Sigma

Lean Manufacturing is often combined with Six Sigma. Six Sigma is a methodology to remove defects from a production process and the name refers to a normal distribution where the product specifications are met in a range of six times the standard deviation. In Six Sigma five phases are defined, referred to as the DMAIC cycle. Define, Measure, Analyze, Improve, Control. Six Sigma is used to measure variability in a process, specifically by measuring the output products [18] .

2.5 A systems approach

To apply theories like previously discussed, methodologies are needed that are able to translate a real life situation into a defined system. One such a methodology is referred to as the Delft Systems Approach. Initiated by J. in 't Veld [1] and translated and further developed by Veeke et al. [49], the Delft systems approach is a fundamental approach for describing industrial systems. It defines the following fundamental building blocks: a system, elements, content, attributes, relationships, structure, universe, environment, emergence. It also defines the concepts subsystem, aspect system, state, process, behaviour, goal, function and task. All of which one might regard as commonly known, however could be considered with a higher level of abstraction by using the definitions of this methodology.

2.5.1 Variability analysis

The Delft Systems Approach could be extended with a variability analysis on the flow between the functions and tasks. Dekking et al. [6] mentions various ways to quantify variability in a data set. This includes the variance, median of absolute deviations (MAD) and inter-quartile range (IQR). The first two are further discussed in appendix B. For the computation of the IQR, the data is divided into four quartiles of equal number of data points. The interquartile range is defined as the middle datapoint of the third quartile minus the middle datapoint of the first quartile (figure 2.5), in this way the effect of outliers is small which makes the IQR a robust method to quantify the spread of a data set. For this reason the IQR is used to quantify variability in the observed data.

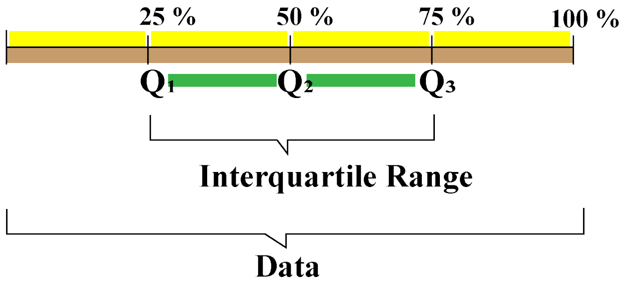


Figure 2.5: The interquartile range [21]

2.5.2 3P model

A model which can be used to analyze and improve a production system, is the 3P model which stands for Product, Production and Process. Those 3Ps are related to each other in a triangular relationship, meaning that all are related to the other two [3]. For example, changing the product means that also the production and the process needs to be adjusted to come to an optimal operation.

2.6 Simulation methods

In order to analyze the product flow in a production process, a simulation of a described system could be made. The layout of a plant which partly facilitates this flow could be optimized by approaches like for example parametric modelling [46]. Product flow itself should be modelled over time. Continuous simulation could be used and due to the discrete nature of events also discrete-event simulation [34].

2.6.1 Continuous simulation

Continuous simulation is based on differential equations and models a set of state variables over time [32]. Continious simulation therefore could be used for every problem that can be written in a set of differential equations like for example vehicle dynamics, electrical power systems and fluid dynamics.

2.6.2 Discrete-event simulation

Discrete-event simulation is a method to simulate processes that are characterized by discrete events and not by continuous differential equations; this includes a wide variety of instances. Examples are queueing systems, such as a supermarket checkout, where customers arrive randomly and wait in queues for service; manufacturing systems, like production lines; and inventory systems, where random quantities of certain products are bought by customers at a store each day [13].

For manufacturing, different tools can be found in literature that are used to build a discrete-event simulation model. Simul8 [7] and Tecnomatrix plant simulation by Siemens [41] are professional simulation environments. SimPy [27] and Salabim [19] are two open source Python based discrete-event simulation tools. JaamSim is a Java based discrete-event simulation environment that offers a drag and drop user interface including visual simulations. The software is open-source, although there is also a paid extension specifically for modelling complex transportation systems like ports, bulk terminals, shipping, rail networks [23] [22]. A manufactering process could be modelled in the free version of this software.

2.6.3 Discrete-event power & free conveyor simulation models

Specific simulation models for a power & free conveyor can be found in literature and are discussed below:

Research has been done by Graehl [15]. The effects of adding an extra product type in a current state of a single product type are visualised by a simulation model. P&F systems are also widely used in car manufacturing industry, Devikar et al. [7] models a power & free conveyor for an automotive manufacturing plant. The software Simul8 was used for simulation. The variability in this system comes from 6 different body types.

Research on the ideal number of carriers on a power & free conveyor in a paint shop was done by Williams and Sadakane [53]. In this case an higher performance was shown by less carriers. A discrete event simulation was made using the software WITNESS [48].

Berg [4] describes a Power & Free system for painting of steel container parts and Seeger [39] describes a Power & Free system of a radiator manufacturer that connects various operation stations. It describes the possibility of buffer zones where radiators could be sorted out per size. Bukchin [5] and Tavakoli and Fattahi [47] describes a comparable system using the mixed model assembly line balancing problem.

2.7 Conclusion

This chapter started with the question: What theories, methodologies and models are available on analyzing and controlling product flow in a production process?

The Industry 4.0 framework gives an outline for further developments. The concepts discussed can contribute to the control of product flow. Performance prediction can be made based on the data from a sensor network, thereby going from level I to level II in the cyber-physical production system architecture. A digital twin can be made to reach level III.

A start in the design of a digital twin can be a simulation model based on discrete-event simulation. Various tools are discussed that can be used for that. JaamSim is a open source tool that enables the use of pre-build elements in a drag and drop interface.

Theories like Theory of Constraints and lean manufacturing can help focus on an ultimate goal and take measures accordingly. From lean manufacturing the concepts of muri, mura and muda contribute to a better understanding of the problem. Variability in the process can be seen as mura (unevenness). This unevenness can result in muri (overburdening of people) and both result in non-value added activities like waiting.

Production processes can be described by methods like the Delft Systems Approach. Variability in the system can be quantified in a data set for example by the interquartile range. A focus on the product, production and process (3P model) can be used to analyze a production system. A simulation model can be made of the process. Discrete-event simulation is used to model power & free conveyor systems and various tools are available in which such a model can be implemented.

The following table gives an overview of literature with corresponding research fields. Focus lies on the combination of: power & free conveyors, lean manufacturing, discrete-event simulation, Cyber-Physical Production Systems and the Delft Systems Approach. Publications in literature are listed chronologically and the marked with the subjects they address.

Table 2.1: Literature review that shows a chronological order of publications and the combination of subjects those publications address

Reference	Title	Power & Free conveyor	Lean - Six Sigma	Discrete-event simulation	Cyber-Physical Production System	Delft Systems Approach	Variability analysis
(Veld, 1983)	*Analyse van organisatieproblemen: een toepassing van denken in systemen en processen*					x	
(Graehl, 1992)	*Insights into carrier control: A simulation of a power and free conveyor through an automotive paint shop*	x		x			
(Williams & Sadakane, 1997)	*Simulation of a paint shop power and free line*	x		x			
(Bukchin, 1998)	*A comparative study of performance measures for throughput of a mixed model assembly line in a JIT environment*		x	x			x
(Liker, 2004)	*Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*		x				
(Veeke et al., 2008)	*The Delft Systems Approach*					x	
(Devikar et al., 2010)	*Evaluating the performance of a complex power and free conveyor system in a flexible manufacturing environment*	x		x			
(Tavakoli & Fattahi, 2011)	*Sequencing Mixed-Model Assembly Line under a JIT-Approach*		x				x
(Manavizadeh et al., 2012)	*Mixed-Model Assembly Line Balancing in the Make-to-Order and Stochastic Environment Using Multi-Objective Evolutionary Algorithms*		x				x
(Grieves, 2015)	*Digital Twin: Manufacturing Excellence through Virtual Factory Replication*				x		
(Ciano et al., 2021)	*One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study*		x		x		
(Kosacka-Olejnik et al., 2021)	*How Digital Twin Concept Supports Internal Transport Systems?—Literature Review*		x	x	x		

A research gap can be observed in the combination of these subjects. This research therefore contributes to the literature by analyzing the operation of the power & free conveyor system with the 3P model in a variability context. Thereby combining Lean Manufacturing with the Delft Systems Approach and discrete-event simulation to analyze the system in a Cyber-Physical Production System perspective.

Chapter 3

Current state

System description and data analysis

3.1 Introduction

The goal of this chapter is to give a system description of the Power & Free conveyor and quantify the variability and the performance in the system. The research subquestion is adressed: 'What defines the Power & Free conveyor system, its performance and which parts causes variability?' In order to do so, the available data is introduced, the 3P model is used to analyze variability and the variability for different working stations is visualized. A definition for the performance is given and the performance is quantified for the current state.

3.2 System description

This section focusses on the first part of the research subquestion: What defines the Power & Free conveyor system? The Delft Systems Approach [49] is used to come to a system description for the Power & Free conveyor system at SEW Eurodrive. The system can be described by the following black box based on material flow with an average throughput of 150 products per day. The material flow is based on the data from May and June 2022. The data from these months will be referred to as the dataset. Products enter unfinished and leave finished, the function of the complete system is to finish the assembly process.

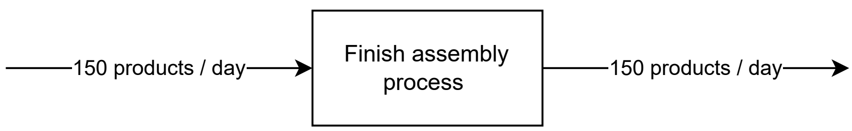


Figure 3.1: Black box model of complete system

Table 3.1 gives the extreme values per painttype of the dataset.

Table 3.1: Flow rate per day for the months May and June 2022 per paint type and corresponding dry cell route

		Flow rate		
Paint type	**Dry cell route**	**Min.**	**Max.**	**Avarage**
513	Single layer DC1,DC2	69	161	121
529	Double layer DC1, DC2	0	16	5
551+552	One layer DC1,DC2 + one layer DC1,DC2,DC3	10	36	24
All	-	104	202	150

The system could be divided in the following three functions:

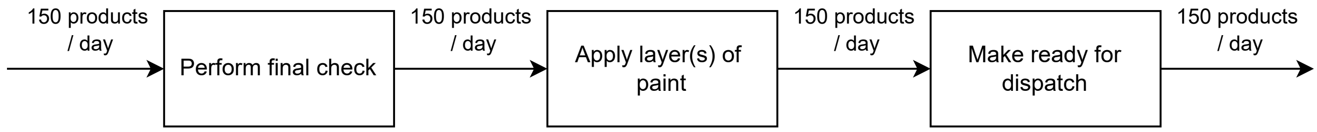


Figure 3.2: The system divided in three functions

The middle function 'Apply layer(s) of paint' involves both the application of paint on the surface as well as the drying afterwards. This function could imply one or multiple layers, multiple layers require more capacity of the system, so a higher local throughput value for this part of the system. Figure 3.3 shows the average throughput values for the time period that is observed, when this function has split up.

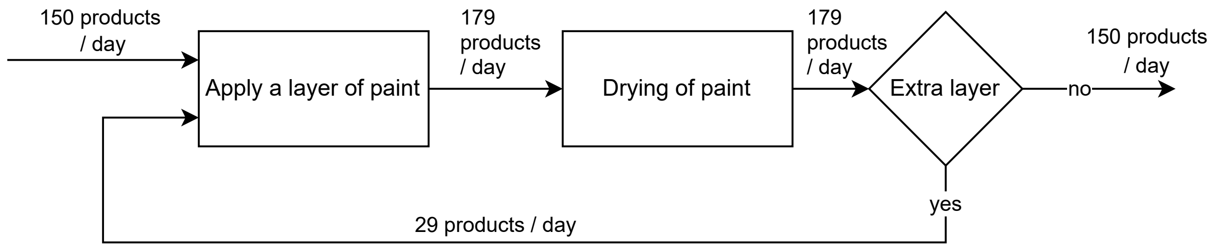


Figure 3.3: Painting and drying process

3.3 Elements and attributes

Within the system the following elements and corresponding attributes can be distinguished. Table 3.2 gives an overview.

Table 3.2: Elements and corresponding attributes of the Power & Free conveyor system at SEW Eurodrive

Elements	Attributes
Final check station	Product inputs, product service time, employee occupation, check equipment, screw tool, conveyor
Spray cabin	Interior conveyor speed, employee occupation, service time, paint, spray equipment
Dry cells	Location, length, temperature
Packaging station	Name plate press, label printer, overhead crane, employee occupation
Conveyor rail subsystem	Length, segments, speed, drives, controller, sensors
Trolleys	Number, location, product order number
Stoppers	Number, location, maximal buffer load
Sensors	Location
Lift platforms	Location

The purpose of the system is to finish the assembly of products. Note that the products themselves are not regarded as part of the system for this reason. The elements will be discussed in the next paragraphs.

3.3.1 Final check station

The final check station consist of two lines at which the following operations are performed: check on electrical circuit, check on nominal rotational speed, close electrical circuit housing with 4 screws, apply protective grease on shaft, lift and attach the drive to a trolley. Drives are attached at stopper 2 and 6. The final check station is supplied by AGV's at one side (stopper 6) and by a conveyor belt at the other side (stopper 2).

The final check station depends on trolleys that are present in the empty trolley buffer before stopper 22 and 23. If there are no trolleys available, no more drives could be attached to trolleys, which means ultimately the final check station will stagnate.

3.3.2 Spray booth

The spray booth consists of one line that is powered by a dedicated chain driving at a lower speed than the rest of the conveyor. This enables spraying while continuing product flow and the possibility of stopping the interior chain while the rest of the conveyor keeps running. The operator is able to switch off the interior conveyor if more time is needed, this is done manually with a switch.

There is a buffer for the spray booth, before stopper 9 and 10.

3.3.3 Dry cells

Every product has a pre-defined dry time per dry cell which is controlled by a stopper. Dry cell 1 blows relative cold dry air, dry cell 2 warm air, and dry cell 3 hot air. The type of paint determines whether the product needs to pass all 3 dry cells or only dry cell 1 and 2 and if an extra layer is needed or not.

The 'Drying of paint' function in figure 3.3 needs some more detailed flow information for the specific use case of SEW Eurodrive. This function is performed by the 3 different dry cells (see also figure 1.4). The flow between the specific tasks at this case is visualized in figure 3.4.

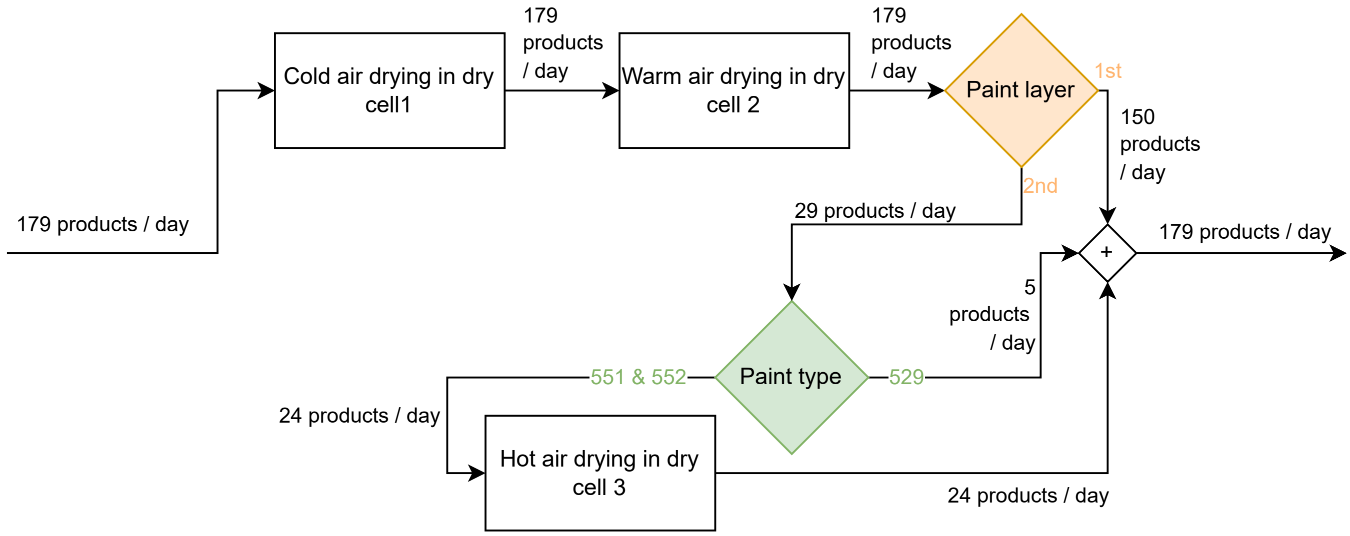


Figure 3.4: The drying tasks performed by 3 dry cells based on latest paint layer and paint type.

3.3.4 Final assembly / Dispatch or packaging station

At this station the drive is detached from the trolley, the empty trolley is sent to the empty buffer and the drive is finished with a name plate and prepared for dispatch.

3.3.5 Conveyor rail subsystem

The conveyor rail subsystem connects all working stations and consists of the track segments, drives, speed controllers and sensors that provide data about products and trolleys. The conveyor operates at a constant speed on which the travel times for line segments could be related.

3.3.6 Trolleys

The system currently consists of 30 trolleys, each one having a hook on which the products could be attached.

3.3.7 Stoppers

The 23 stoppers in the system could stop or pass trolleys at their location. Every stopper has a maximum amount of trolleys that could be idling before the stopper, referred to as the buffer load. For a lot of stoppers this number is one. Table 3.3 gives the buffer load per stopper for the stoppers that have a non-one buffer load. Stoppers that are not mentioned in this table have a buffer load of 1.

Table 3.3: Bufferload per stopper

Stopper	3	9	10	11	12	14	15	16	17	20	22	23
Buffer load	2	6	5	6	7	4	12	2	10	7	8	4

3.3.8 Sensors

Sensors signal if a trolley enters a stopper or a queue before a stopper. At the following instances data is saved :

- A trolley enters a stopper
- A trolley enters a queue

Currently only data is saved if a trolley carries a product. Empty trolleys are not tracked. For trolleys carrying a product, the following data is saved:

- Trolley number
- Stopper number
- Position in queue
- Order number details
- Paint type
- Scan time

Based on the order number details, more data like the weight of the product can be retrieved. Data is saved since May the 2^{nd} 2022. The plots in this report are taken from the combined data of May and June. Comparison of the data with those two months does not result in significant differences.

3.3.9 Lift platforms

The system consists of three lift platforms that are used to attach or detach products on or from trolleys. Two lift platforms are used for attaching at the final check station and one for detaching at the packaging station. Lift platforms are marked yellow in figure 1.4.

3.4 Variability in the system

Now that the basic structure of the system is discussed, the operation of this system can be analysed, in particular the variability that can be observed. Variability can be observed in three levels: the product, the process and the production. All of which have specific types of variability, as well as are related to each other (figure 3.5) [3] and will be discussed in this section. The method that is used to quantify variability in the data set is the inter-quartile range (IQR) that was mentioned in chapter 2.

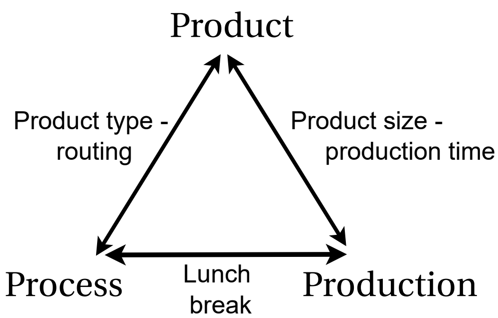


Figure 3.5: Three perspectives on variability in the system, each one influencing the other two [3]

3.4.1 Product

On the product level variability can be observed in the range of motor or gearbox types that are assembled, resulting in different sizes for the complete product and thus different surface areas to be sprayed. An available measure is the weight of every product. For the months May and June the histogram of the weight data is presented in figure 3.6. The weight is regarded a measure for the surface area.

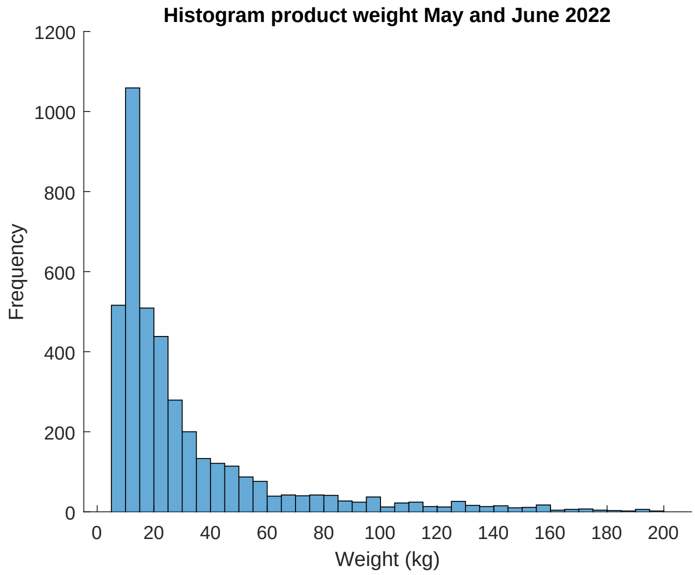


Figure 3.6: Histogram of product weight in the data set

Table 3.4: Statistical data product weight for the data set

	Number of products	Mean (kg)	Median (kg)	IQR (kg)
Weight	4104	34	19	25

Another variability in the product is the specific type of paint that needs to be sprayed. The types of paint can be separated in three categories which correspond to three different routes through the system. Table 3.5 shows the various paint types that are used by the company per category and the corresponding route through the dry cells.

Table 3.5: Paint type categories with the route they correspond with through the system, the paint type number used by SEW Eurodrive and the fraction of this category in the data set.

Paint category	Route	Paint type (SEW Eurodrive)	Fraction
1	1 layer DC1-DC2	100,101,102,200,511,512,513, 516,517,518,541,574	0.81
2	2 layers DC1-DC2	526,527,529	0.03
3	1 layer DC1-DC2 + 1 layer DC1-DC2-DC3	521,522,523,524,531,534,551, 552,587,588,589	0.16

3.4.2 Production

Variability in the production can be divided into two parts. First there is the assignment of employees for the different work places. This includes variable start times of a work day between 6:45am and 9 am and corresponding end of work day times. To guarantee minimal occupation, people are assigned for an early and late shift. Also there is lunch break between 12pm and 1pm. At that time the manual work stations stop, but the automatic parts of the system continue. Manual work stations are the final check station, spray booth and packaging station. The dry cells and conveyor segments operate automatically. Secondly there is variation in how employees perform the tasks, some little in-between jobs could be done somewhere else in the process or little breaks could influence the flow at the P&F system.

3.4.3 Process

Variability in the process involves different paint types, routing per paint type and different throughput per day. Different paint types result in different actions that needs to be performed by the spray cabin employee(s). The routing through the system depends on the paint type and is described in figure 3.4. Table 3.1 shows the extreme values of the throughput per day for the data set that is used in this analysis. Furthermore a variability in speed of the conveyor can be observed, the speed of the conveyor is slower inside the spray cabin. Without stopping a trolley in the spray cabin needs approximately 6:20 minutes.

The variability in the product, production and process could be observed in the data that is measured by the sensors at the stoppers. This data will be analyzed in the next paragraphs.

3.5 Data analysis

Variability can be observed in the system with the available sensor data. First the data from the sensors that are connected to the stoppers at the work stations are considered. The time interval between two trolleys is analyzed with respect to the size or paint type of the product. Secondly the product input is analyzed which is based on manual measurements.

3.5.1 Final check station

Data on time intervals between stoppers is available between stoppers 8 and 21 (figure 1.4). This means that the stoppers of the final check station do not record this data. Stopper 8 is located right after the point were the 2 conveyor segments of the final check station merge, therefore the effect of the final check station at the time intervals between trolleys is analyzed at this stopper.

The products are divided into 3 size categories. One half of the data points in the middle corresponding to size M, a quarter of the data below, size S and a quarter above, size L. For the data set, this results in the following weight categories (table 3.6).

Table 3.6: Product weight categories

S	**M**	**L**
6-11 kg	11-33 kg	33-200 kg

The time intervals per weight category are shown in figure 3.7. The mean and IQR are presented in table 3.7.

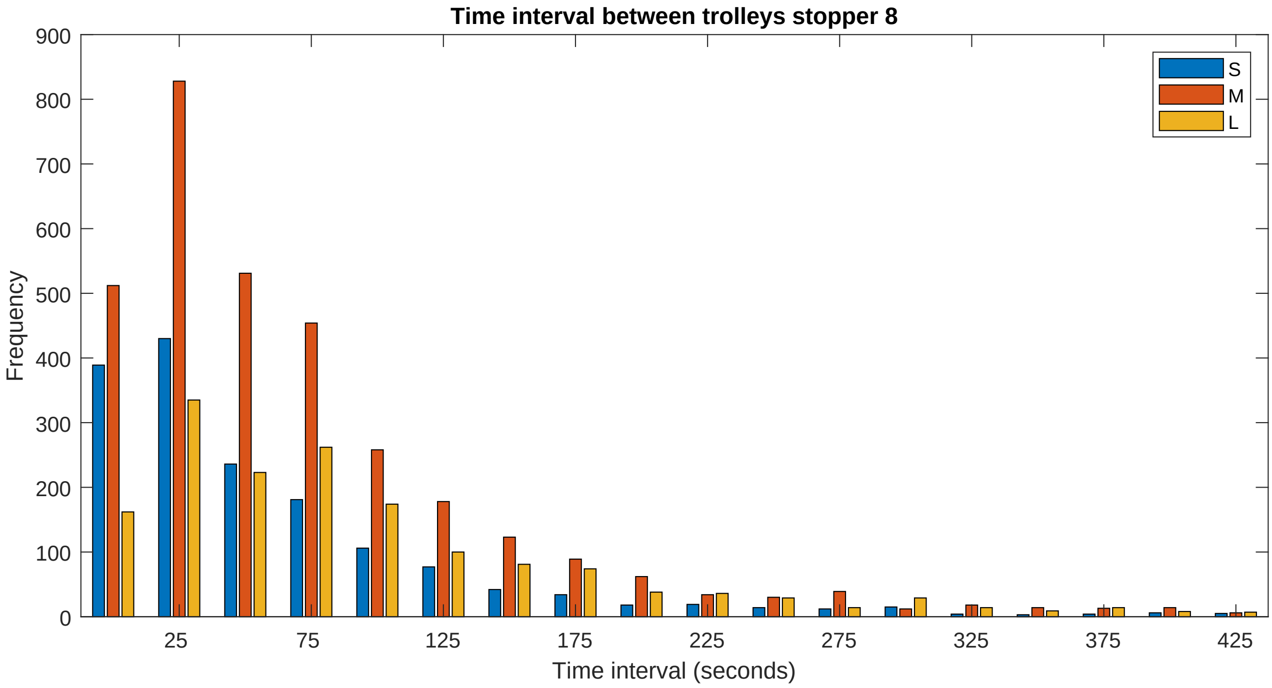


Figure 3.7: Time intervals between trolleys at stopper 8 for different size categories

It can be observed that for smaller products the time interval is shorter and also the IQR is smaller compared to heavier products.

Table 3.7: IQR and mean of trolley time intervals at stopper 8 per size category

Stopper	Size	Painttype	IQR	Mean
8	S	All	00:02:12	00:02:28
8	M	All	00:02:20	00:02:48
8	L	All	00:03:04	00:03:30

3.5.2 Spray cabin

The stoppers before and after the spray cabin record trolley data. Two options are considered for the analysis of variability at the spray cabin. The first one is to measure the time a trolley spends between the start and the end of the spray operation. This data could be retrieved from stoppers 9,10 and 11. Since the spray cabin contains about 4 trolleys during normal operation and the interior conveyor is stopped regularly, this value would be an average for those 4 trolleys.

Another option is to measure the time intervals for trolleys leaving the spray queue (stopper 9 or 10) Since the spray cabin employee start spraying once a trolley enters the spray cabin and stops the interior conveyor if more time is needed, this time interval would be a measure for the last departed trolley. This option was chosen because it gives a time interval per trolley and not the average of 4 trolleys.

Before using this method, some data was filtered out. In the scenario that the spray queue is empty before a trolley arrives, a (longer) time interval is recorded that does not relate to the spray booth operation. For this reason only time intervals are considered for trolleys that enter the queue if the queue length is higher or equal to 1.

The time intervals for different sizes and for different paint types are shown in figure 3.8 and figure 3.9. The mean and IQR are presented in table 3.8.

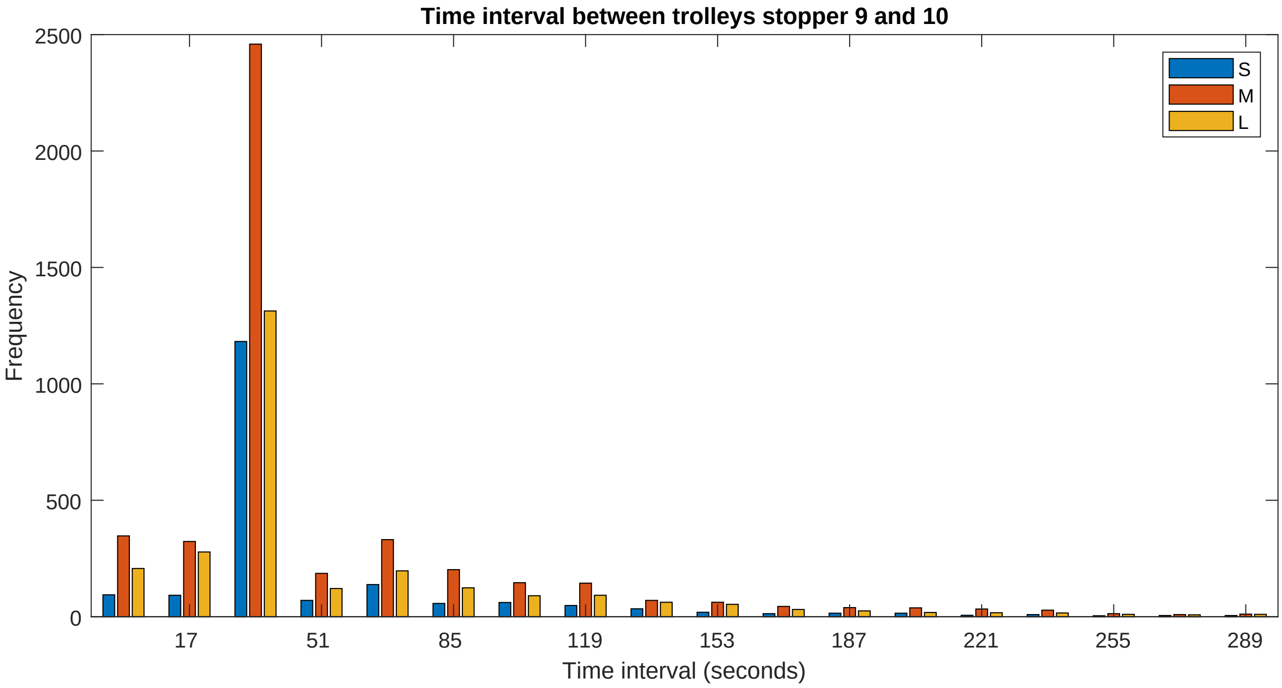


Figure 3.8: Time intervals between trolleys at stopper 9&10 for different size categories

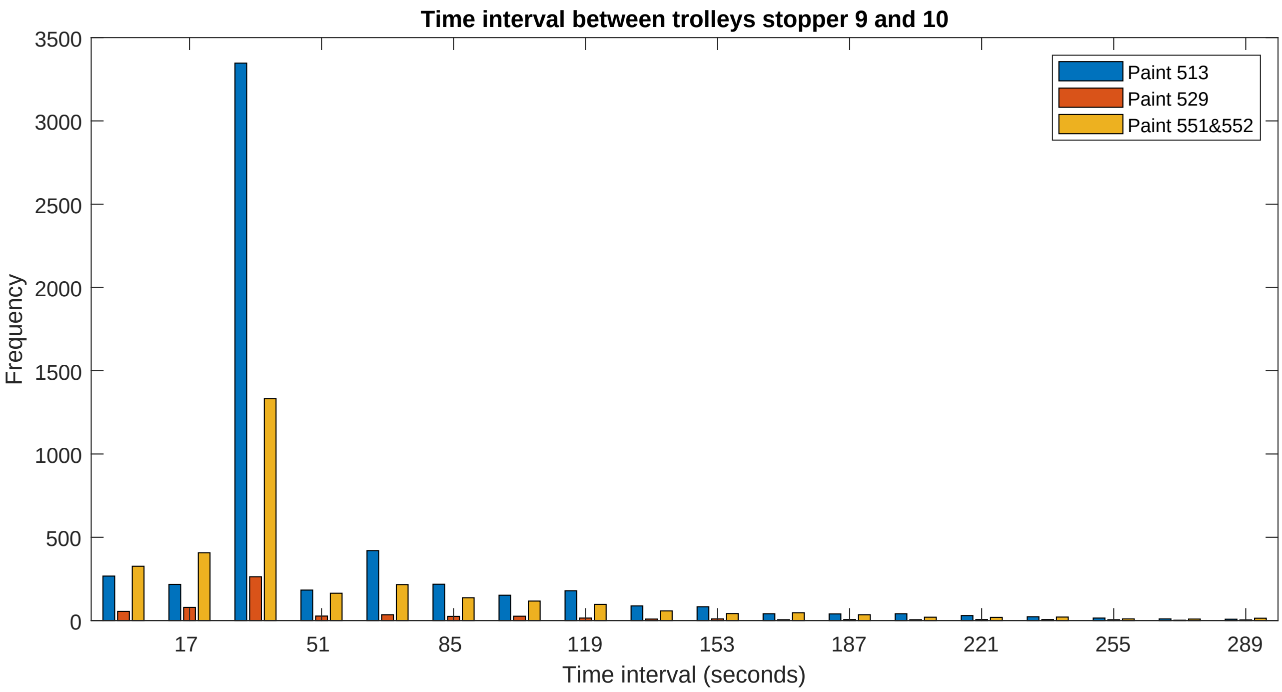


Figure 3.9: Time intervals between trolleys at stopper 9&10 for different paint types

Table 3.8: IQR and mean of trolley time intervals at stopper 9 and 10 per size category and paint type

Stopper	Size	Painttype	IQR	Mean
9&10	S	All	00:00:30	00:01:55
9&10	M	All	00:01:02	00:02:00
9&10	L	All	00:01:17	00:02:04
9&10	All	513	00:00:54	00:02:00
9&10	All	529	00:01:15	00:02:03
9&10	All	551-552	00:01:18	00:02:01

3.5.3 Packaging station

The packaging station consists of one stopper, variability in service times could be measured by taking the time interval between trolleys for stopper 21. For these measurements again a distinction was made per data point if there is a queue in front of the stopper or not. If not, the time intervals are not taken into account. This means that the time interval will be a representative measure for the service time.
The time interval between trolleys for different sizes is shown in figure 3.10. The mean an IQR are presented in table 3.9.

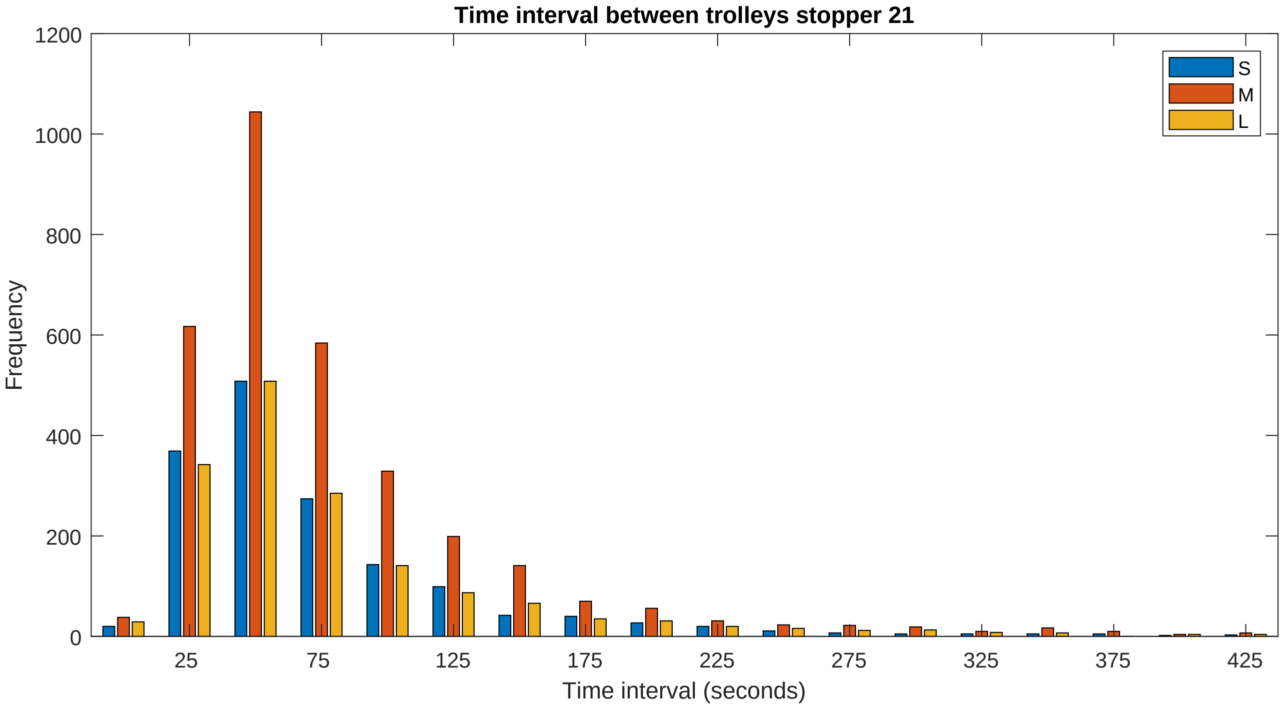


Figure 3.10: Time intervals between trolleys at stopper 21 for different size categories

Table 3.9: IQR and mean of trolley time intervals at stopper 21 per size category

Stopper	Size	Painttype	IQR	Mean
21	S	All	00:01:45	00:02:54
21	M	All	00:01:48	00:02:59
21	L	All	00:01:50	00:03:02

3.5.4 Product input

Since there is no sensor data available on the product input at the final check station, measurements were taken over a time period of 6 hours spread over the morning and afternoon. The product input inter-arrival time is shown in figure 3.11.

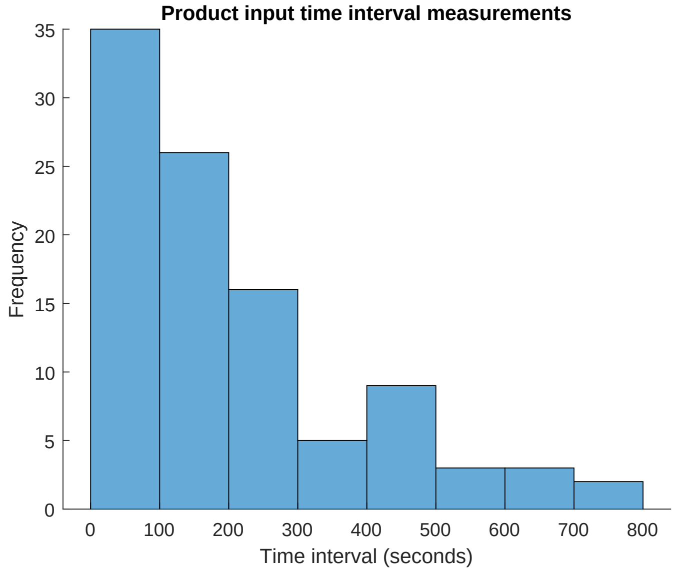


Figure 3.11: Product input time interval measurements

3.6 Performance metrics

The performance of the system depends on flow and on continuity. Flow is measured by the throughput in number of units per time unit and continuity is quantified by the average waiting time per time unit. Furthermore, based on the theory of waste in lean manufacturing, a ratio could be defined of value added time and the the total lead time of the product in the system.

3.6.1 Throughput

The throughput for the data set per day is in the interval 104-202 units per day. It is normally distributed with a mean of 150 unis / day and standard deviation of 20 units / day.

3.6.2 Average waiting time

The waiting time per product was determined by the time interval between the final check station and the packaging station minus the minimal observed time for this segment. This minimal observed time is regarded the continuous flow case. Hence the average is taken from all products to find the average waiting time, see table 3.10.

Table 3.10: Minimum transport times for trolleys from stopper 8 till 21 per paint type, the corresponding average waiting times and the weighted mean of the average waiting times with respect to the fraction this paint type is represented in the data set

Paint type	Description	Min. lead time st8-st21 (hh:mm:ss)	Avg. waiting time (hh:mm:ss)	Fraction
1	Single layer	00:29:00	00:28:41	0.81
2	Double layer	01:08:06	00:33:31	0.03
3	OS paint layer	01:45:08	00:50:04	0.16
	Weighted mean:		00:32:15	

3.6.3 Ratio of value added time and lead time

Based on the theory of Lean Manufacturing, activities could be divided in value added and non-value added activities. The value added time could be defined by the time where value is added to the product for the customer. This means, the times at the final check station, spray booth, dry cell and packaging station. Other contributions to the lead time are transport and waiting. Lean Manufacturing adds this perspective to the approach of the Delft Systems Approach that was chosen earlier. The ratio value added time and lead time therefore gives insight into the efficiency of the operation.

3.7 Conclusion

A system description of the power & free conveyor system was made using the Delft Systems Approach. This showed the flow between the different functions and tasks and the different routes through the system.

The variability was analyzed on the three levels of the 3P model: process, production and product; the relationship between them was included. The product size determines the production time and the product paint type determines the routing in the process, the relation between process and production is expressed among others by the lunch break.

The variability in the product and production are found in the analyzed data. A model is needed that further describes the process, which is elaborated in the next chapter.

On the product level a distinction was made between size and paint type. The trolley time intervals were analyzed for three stoppers corresponding to the three work stations. The inter quartile range was used as a measure for the variability. There were no significant changes observed in variability for the spray cabin and packaging station. For the final check station, however, an effect of size on the average time interval and variability was observed.

Two performance indicators were defined. Firstly the throughput in number of units per time unit and secondly the average waiting time per trolley. An extra performance indicator based on the waiting time could be defined by the ratio of the value added time and lead time. The first two performance metrics were quantified for the current state.

Chapter 4

Model Design

In order to quantify variability in the process a model was made and presented in this chapter. The goal of this chapter is to answer the research sub questions: 'What model can be used to analyze and assess the flow continuity?' First the requirements are set for this model and the corresponding methodology choices are explained. Afterwards a model description is given, the inputs and outputs are defined and the model is verified.

4.1 Requirements and simulation method

In order to model flow of a Power & Free conveyor a model needs to meet the following requirements:

- The model should be able to process the DSA system elements that are described in the system description in chapter 3.
- The system lay out needs to be visualized for verification.
- Different speeds per conveyor element should be possible to implement including a local temporary stop (for the spray booth).
- Transport times of the various conveyor sections needs to correspond to the physical system.
- Process variability in the product routing needs be made noticeable per paint type. The mix of product types should be an input.
- The three main routes through the system should be modelled.
- The model should process probability distributions as inputs.
- The output of the model should be the KPIs mentioned in chapter 3
- The model should be preferably implemented in software that is available as freeware.

A discrete-event simulation was chosen above continuous simulation, because of the discrete-event nature of a power and free conveyor system. Continuous simulation is based on a set of differential equations with state variables that change continuously over time. In a power & free conveyor however products enter the system according to a stochastic distribution and service times can be modelled as a stochastic process in the system with a queue in front of the server. It is desired to model the behaviour of single trolleys in the system and determine the flow on the basis of this behaviour. Discrete-event simulation in literature (Chapter 2) is found to simulate those type of processes. For this reason it was decided to model the system with discrete-event simulation.

Furthermore a tool has to be chosen to perform the discrete-event simulation and that is able to meet the requirements mentioned above. The python package Salabim was compared with the Java based software JaamSim. Both are free solutions that offer real time visualization of the simulation. Preference went to JaamSim due to the wide variety of pre-built elements like conveyors, queues, servers, downtime entities, branch and combine elements, combined with a drag and drop interface. In this way JaamSim is less prone to bugs compared to the interface of Salabim.

4.2 Model description

Figure 4.1 shows the visualization of the model, during a simulation run. The basic structure is made of 23 stoppers interconnected by conveyor elements. Every conveyor element has a fixed travel time. The stoppers are modelled by a sub model consisting of a queue, a server and a threshold and are represented by a big grey triangle. This figure could be compared with figure 1.4. In this section a description is given of the working principle of the model and its elements.

4.2.1 Product and trolley flow

The model simulates the product flow, the trolley flow and their interaction. The product elements are generated at the final check station at two different sides (stopper 2 and 6)). Every new product is generated after a so called inter-arrival time. This time interval is chosen according to the exponential distribution (figure 4.2) that is based on measurement data (figure 3.11). Every product that is generated gets the following attributes: paint type and spray layer. The paint type is assigned randomly according to the probability mentioned in table 4.1. The color of the product and trolley element is set accordingly in the model. The spray layer attribute acts as a counter for the amount of sprayed layers and is set 0 initially. Products and trolleys meet at the stoppers 6 and 2. Here trolley departure is based on the following conditions: product availability, conveyor segment availability and downstream stopper availability. If there is no product available, the trolley will wait. (Also the other way around, if there is no trolley available, the product will wait.) The conveyor segment is set available if there is no trolley riding on it. For stopper 6 for example, this means the the segment availability of *ConveyorElement8* will be checked. This is implemented in the model at every stopper as an expression threshold which checks the segment availability for the downstream segment as well as the stopper availability for the downstream stopper. Those two criteria are based on the maximum queue length at each stopper (table 3.3)

Switches are modelled by so called branch elements, they use logic based on paint type and amount of paint layers to decide which route to choose per trolley. For *Branch1* at the empty buffer in the case that both stopper 23 and 4 do not have trolley, priority is given to stopper 23, in the case that one side does not have a trolley, it is send to this side. Combine elements combine the flow. For stopper 9 and 10, priority is given to the trolley with the greatest waiting time. For stopper 19 priority is given to trolleys leaving dry cell 3 (stopper 18).

The spray booth interior conveyor between the element *Combine2* and *SC_end* operates at a slower speed, a travel time of 386 s. Besides that a downtime entity is used to model the stop intervals of this conveyor that are visible in the data.

4.2.2 Paint types and product routing

The paint type of the product attached to the trolley determines the route it will make through the system. Table 4.1 shows how the various paint types are referred to by the company with the corresponding routes through the system. In the model this was simplified by three paint types: 1,2 and 3. Referred by yellow, blue and green respectively. The first one needs a single layer and will go through dry cell 1 and 2 (figure 1.4). The second needs two layers and will pass after both through

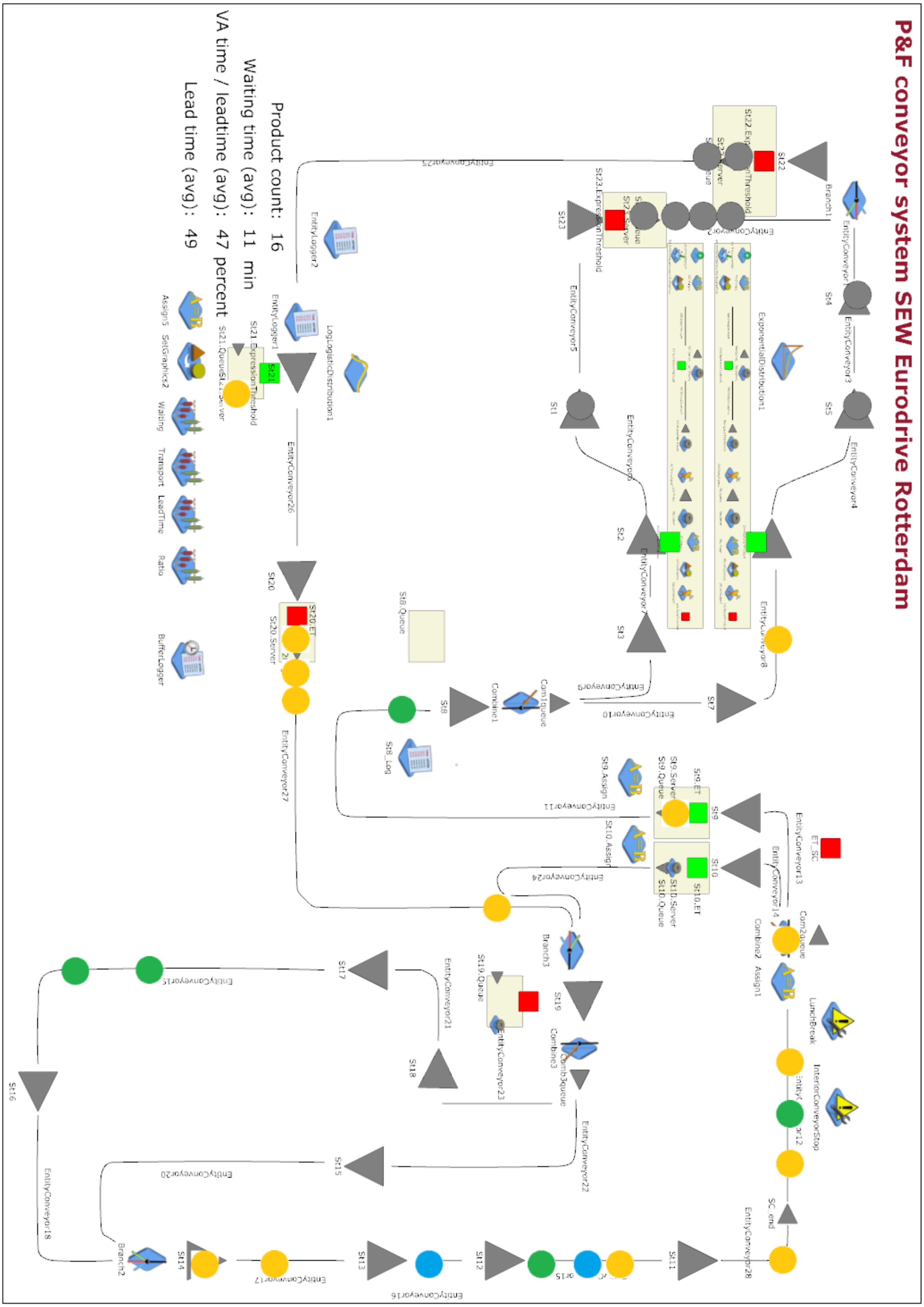


Figure 4.1: JaamSim discrete-event simulation model of P&F system

Table 4.1: Legend of product and trolley elements with the following columns: The number they are referred to in the model, the route they correspond with through the system, the paint type number used by SEW Eurodrive and the probability this paint type chosen based on the data set. The amount of layers mentioned in the route column refer to the times the product will go through the spray booth, the dry cell (DC) numbers correspond to the ones of figure 1.4

Paint type model	Elements	Route	Paint type (SEW Eurodrive)	Probability
1	yellow	1 layer DC1-DC2	100,101,102,200,511,512,513, 516,517,518,541,574	0.81
2	blue	2 layers DC1-DC2	526,527,529	0.03
3	green	1 layer DC1-DC2 + 1 layer DC1-DC2-DC3	521,522,523,524,531,534,551, 552,587,588,589	0.16

dry cell 1 and 2. The third needs two layers, after the first through dry cell 1 and 2 and after the second dry cell 1, 2 and 3.

4.2.3 Model initialization

The start of a workday in the morning is simplified in the model. The situation in reality is as follows: the capacity of the empty buffer is limited, therefore not all empty trolleys fit in this buffer at the end of a day. In order to finish the last products, empty trolleys are fed into the system. Sometimes also products that needs to be ready the next day are already fed into the system. At the end of a workday there is therefore a mix of empty and full trolleys in the system.

In the model the decision was made to neglect the effects of this start phase. An initialization phase is introduced in which all the trolleys are generated at the empty buffer with 40 s time between each trolley. In this way every trolley gets a product and the empty buffer capacity is not exceeded. The effects of empty trolleys in the system as well as a few products in the system is thereby assumed to be small.

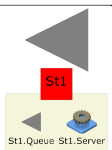
4.2.4 Simulation parameters

The simulation was run for one day, this means a time period of 9 hours with a lunch break of 1 hour after 4 hours. During this lunch break manual processes stop, which includes the final check, spray booth and packaging station. Automatic processes which are the dry cells and conveyor segments continue.

4.2.5 Model elements

The main elements this model is made of are listed and explained in table 4.2. All elements can be found in the JaamSim software, except the stopper sub model which is made up out of multiple elements.

Table 4.2: Legend of model elements

Elements	Name	Description
	Conveyor	Has a fixed travel time and is used for transport sections, dry cells, spray cabin.
	Queue	Elements enter a queue after a conveyor section, it is followed by a server and passes elements to the server if available.
	Server	Processes an element for a deterministic or stochastic period of time, is used in the stopper sub-assembly, final check and packaging station.
	Branch	Conveyor elements are attached to a branch. Is used to model a switch, uses logic to decide which side to choose.
	Combine	Combines two conveyor elements to one.
	EntitlementSelector	Is used to assign the mix of paint types.
	Assign	Assigns attributes to trolley elements, like spray layer.
	ExponentialDistribution	Is used to model the product input time intervals
	LogLogisticDistribution	Is used to model the service time interval for the packaging station
	DowntimeEntity	Could stop the operation of one or more elements, is used to model the stop intervals of the spray cabin interior conveyor, the lunch break and the night.
	EntityGenerator	Generates trolleys in the initial phase and generates products at the final check station
	EntitySink	When products enter trolleys the product entity is removed from the model in the EntitySink
	EntityLogger	Is used to log lead times, waiting times, etc.
	ExpressionThreshold	Is used to decide whether or not trolleys need to stop or to pass at stoppers.
	SetGraphics	Graphics of trolley elements change when a product is mounted and unmounted.
	Statistics	Collects KPI's per trolley.
	ValueSequence	In the scenario of product planning, the order of product types is implemented with a value sequence.
	Stopper sub model	Sub model that is used for every stopper, consists of ExpressionThreshold, Queue and Server.

4.3 Inputs

The inputs for the model are the probability distribution of time intervals that products enter the system and the probability distribution of time intervals in which they are processed at the spray booth and packaging station.

4.3.1 Product input

A exponential probability distribution was fit on the product input histogram (figure 3.11) and shown in figure 4.2. The mean is 220 seconds. Product input happens at two different sides, like discussed in the previous chapter. Since the measurements were conducted in a time period that only one side was operational, an estimate needs to be made how the flow is divided over the two sides. It was assumed that the amount of products remain the same and that therefore both sides could be modelled with an exponential distribution with a mean two times larger.

The product input is modelled with two exponential distributions with a mean of 440 s, a minimal value of 30 s and a maximum value of 800 s.

The paint type of the products is defined by the fraction this paint type occurs (table 4.1).

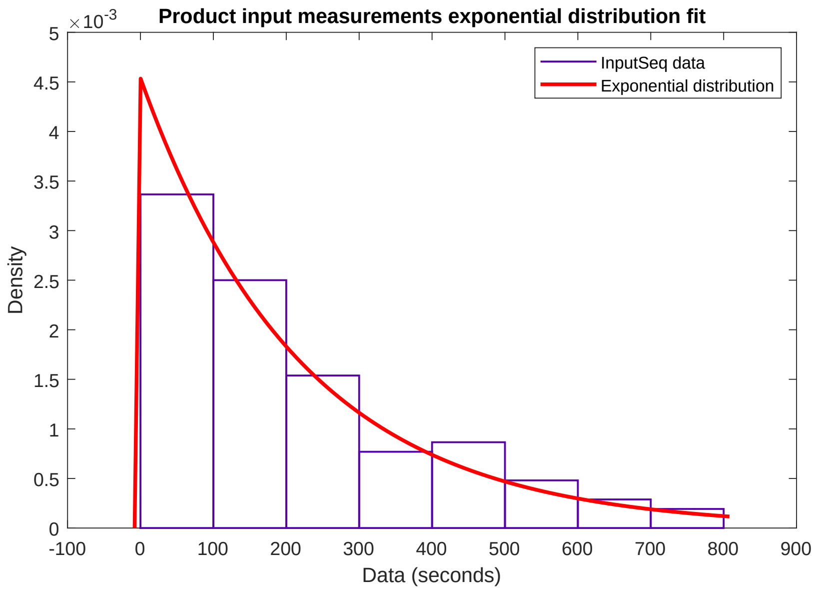


Figure 4.2: Product input time interval measurements with a exponential distribution fit

4.3.2 Spray booth

The spray cabin interior conveyor start stop data was evaluated. This data was retrieved between December 12th, 2021 and May 5th, 2022, without the time between January 28th 2022 and April 20th 2022, so a two month time period. When the lunch break was filtered out from this data, it can be concluded that during working hours, the interior conveyor operates 66% of the time and stands still for the remaining 33%. This is implemented in the model as a downtime every 300 s of 100 s.

4.3.3 Packaging station

The service time of the packaging station was approximated with a log-logistic distribution (figure 4.3) with a scale of 145 s and a shape factor of 3. The maximum value was set to 800 s.

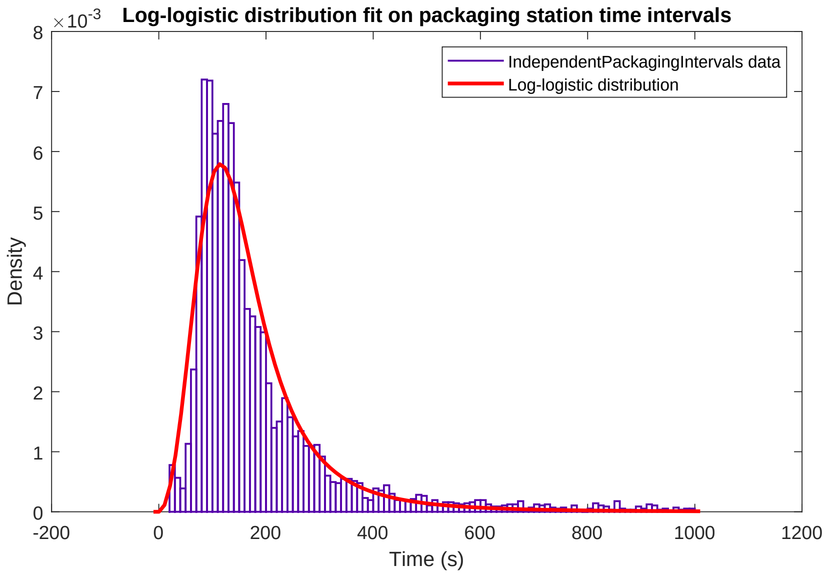


Figure 4.3: Distribution fit on independent packaging service intervals

4.4 Output

The key performance indicators (KPI's) are the output of the model:

1. Throughput (number of units / day)
2. Average waiting time (minutes)
3. Ratio of value added time and lead time (%)

4.5 Verification and validation

During simulation the model picks a sample from the stochastic inputs. This sample is based on a random seed number which is set constant. This means that running the model multiple times gives the same output each time. In order to see the effects of other input samples, the model was run 500 times with a different random seed. This number of replications was needed to observe a clear normal distribution in the output. The output of the KPI's is normally distributed and visualized in Appendix B.

The following aspects of the simulation model were verified visually using the visualization (figure 4.1) during a simulation run: product routing per paint type, the operation of the spray cabin interior conveyor, product input, maximum queue lengths, product priority when flow merges. Also the throughput, waiting time and lead time are made visible during the simulation. Afterwards the model is compared with the sensor data by the following validation steps:

4.5.1 Throughput

The throughput for the data set per day is in the interval 104-202 units per day, with an average of 150 unis / day and standard deviation of 22 units / day. So a 95% confidence interval of 150±36 units / day.

The outcome of the model for one day results in 146±9 units. Clearly the amount of units per day varies more in reality, however the model is in the range of the data set.

4.5.2 Minimal lead time

In order to find the fastest possible way for a trolley to move through the system, the model was ran with 1 trolley. For this scenario the time to finish one segment from stopper 8 until stopper 21 was measured; this is referred to as the minimal lead time. The 95% confidence intervals are shown in the third column of table 4.3. Those lead times are compared with the trolley intervals between stopper 8 and 21 of the current state sensor data. The histograms of this data is presented in Appendix B. After the outliers are removed the minimal lead times per paint type can be found in the fourth column of table 4.3.

It can be noted that for paint type 1 the model is at least 2 minutes slower, for paint type 2 it is in range and for paint type 3 the model is at least 5 minutes slower. One possible explanation for the last one could be the practice of manually removing trolleys from dry cell 3 before the dry time is over. This is done in the case that all trolleys are in use and new ones are needed. The model does not take this manual behaviour into account. Furthermore it could be discussed which data points are outliers and which not.

Table 4.3: Single trolley laps for different paint types

Paint type	Description	Model lead time (minutes)	Sensor data lead time (minutes)
1	Single layer	33±2	29
2	Double layer	67±2	68
3	OS layer	111±1	105

4.5.3 Trolley time interval at stopper 8

Sensor data of the power and free system is saved between stopper 8 and stopper 21. This means that the trolley activity before stopper 8 is not measured in the real system. To verify the model at this point, the trolley time intervals of the model and the sensor data are visualized in a histogram to compare them visually. Both follow a negative exponential distribution, however a difference can be observed in the model output around 100 and 200 seconds, where the model has a peak in the amount of trolleys. In the discussion (chapter 5) differences in these plots are further discussed.

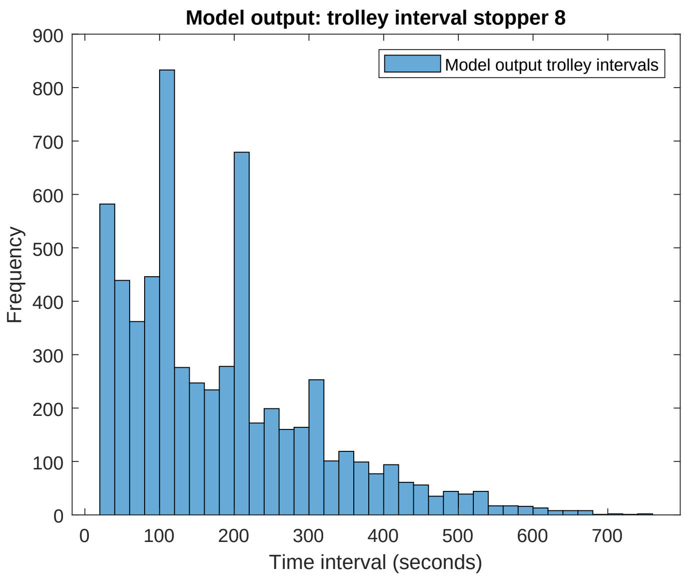


Figure 4.4: Stopper 8 intervals in the model for the current state scenario

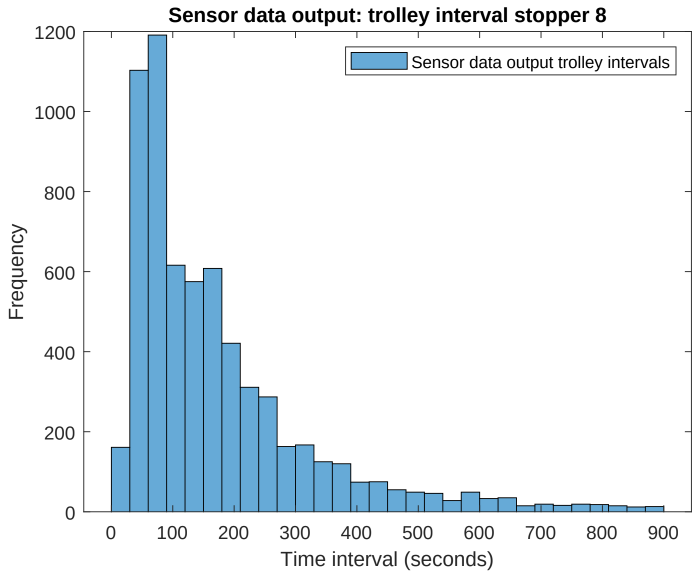


Figure 4.5: Sensor data of the stopper 8 time intervals for all paint types and sizes

4.5.4 KPI's in sensor data and model

The model was ran for the current state scenario. The KPI's from the model are compared with the KPI's retrieved from the sensor data.

Table 4.4: Model compared with sensor data KPI's showing the 95% confidence intervals

KPI	**Model current state**	**Sensor data current state**
Throughput (units/day)	146± 9	150±36
Average waiting time / unit (minutes)	39 ± 9	32

4.6 Conclusion

In this chapter a discrete-event simulation model is presented in which the flow continuity could be analyzed and assessed. The inputs of this model are probability distributions for the product input, including the mix of paint types and the service times for the spray and packaging station. The output is the estimated throughput in units per day, the average waiting time per product and the ratio of value added time and lead time. The model was verified using the visualization and validated by the following steps; the throughput, minimal lead time and average waiting time per product are compared with sensor data from the current state and the trolley time interval between the model and the sensor data is compared at the location of stopper 8. It was concluded that regarding the throughput the model takes less variability into account compared to the sensor data. The average waiting time is in range and for the minimal lead time, the model slightly varies from the measurements for paint type 1 and 3 and corresponds for paint type 2.

Chapter 5

Scenarios and Results

With the simulation model various scenarios were evaluated; the results are presented in this chapter. An answer is formulated to the sub question: 'Which scenario's can be used to control the flow continuity and what is the effect of those scenarios on the performance?' First the different scenarios are discussed. Scenario A1 is the current state, for the other scenarios control measures were taken. The results of those control measures are shown afterwards.

For every result 500 days were simulated with the model. The output is normally distributed and shown in Appendix B per scenario, in this chapter the results are presented as a 95% confidence intervals

5.1 Scenarios

First of all the scenario could be modelled that corresponds to the current state (scenario A). This means the inputs described in chapter 4 are used. For this scenario the number of trolleys could be taken as a variable and the performance could be evaluated.

The concept of takt time as can be found in literature (Chapter 2), structures the product flow. For this reason the effects of a takt time on the performance are evaluated in scenario B.

As described in chapter 3, the system consists of manual and automated processes. During the lunch break manual processes stop while automated processes continue. In order to optimally make use of the automated processes during the lunch break scenario C was developed that performs a planning of the order of product types at the input.

In the final scenario D the amount of variability in the production is minimized meaning that the interior conveyor of the spray cabin operates non-stop and the packaging station has a fixed service time. For this scenario the number of trolleys is analyzed as well.

So the following scenario's are simulated:

- Scenario A1: The current state (with 30 trolleys)
- Scenario A2: The current state with 22 trolleys
- Scenario B: A fixed takt time for the arrival of trolleys at the final check station
- Scenario C: A planning of the order of products at the input.
- Scenario D1: Continuous flow with 30 trolleys
- Scenario D2: Continuous flow with 22 trolleys

5.2 Scenario A: Number of trolley analysis for current state

First the effect on the KPI's of the number of trolleys are simulated with the model. For the current state, scenario A, the KPI's per number of trolleys are visualized in the following figures 5.1, 5.2 and 5.3.

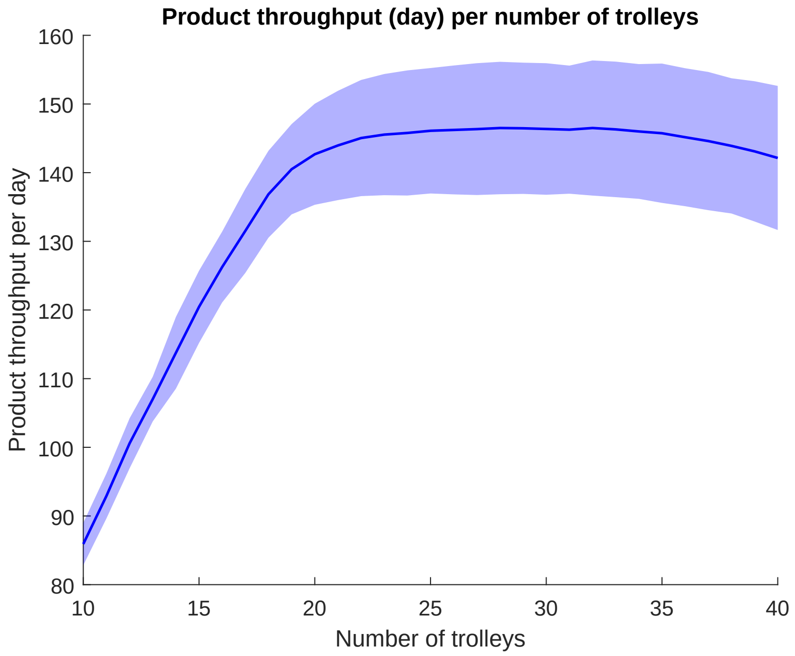


Figure 5.1: Throughput per number of trolleys for the current state scenario

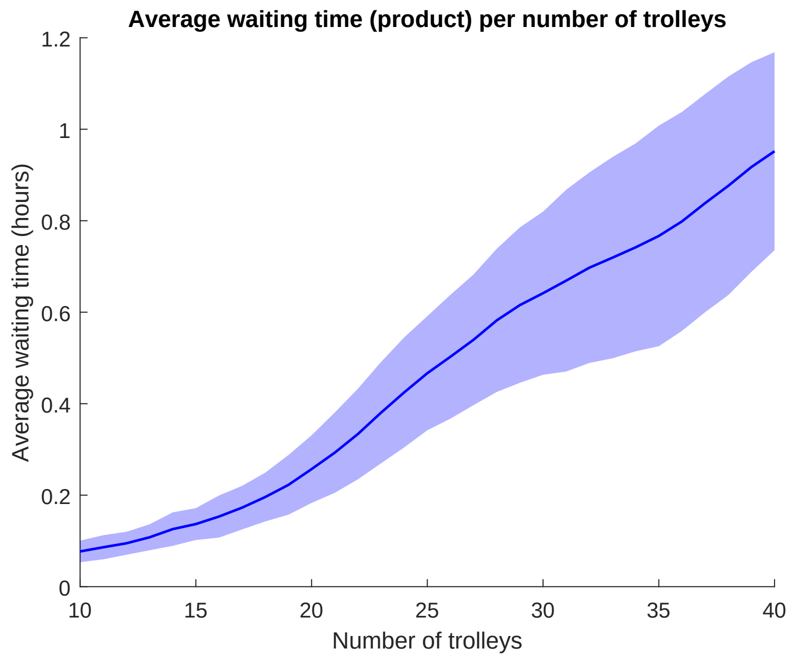


Figure 5.2: Average waiting time per number of trolleys for the current state scenario

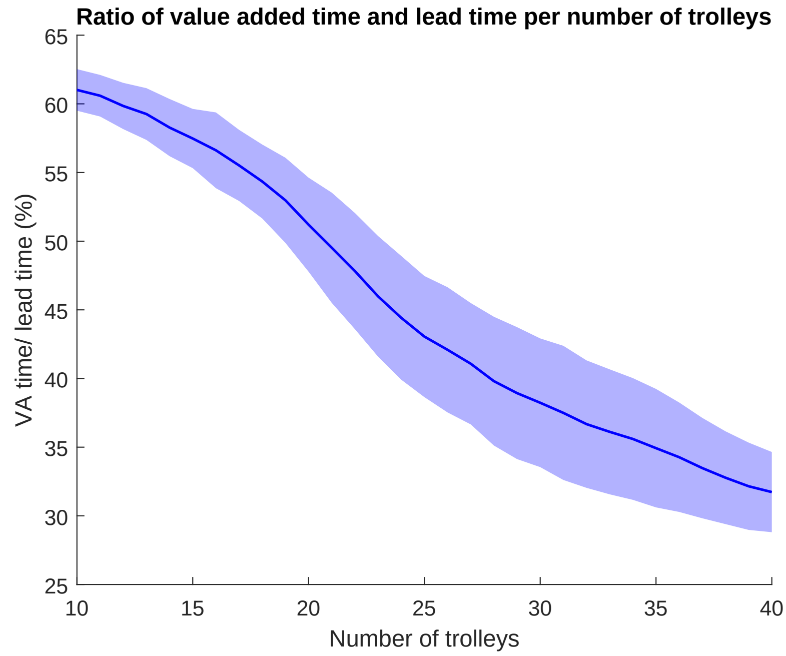


Figure 5.3: Ratio of value added time and lead time per number of trolleys for the current state scenario

5.3 Scenario B: Fixed takt time

The throughput and average waiting time are analyzed for various takt times as well as the ratio of value added time and lead time. In the current state the takt time could be regarded 0. For this scenario 30 trolleys were implemented. It can be observed that both the throughput and average waiting time slowly decrease with increasing takt times. The KPI's for a takt time of 30 s are listed in table 5.1

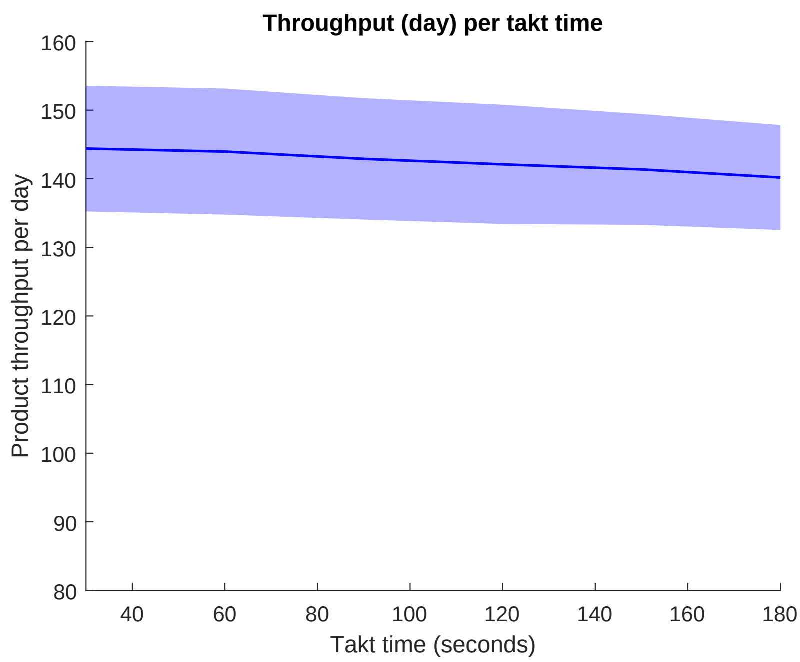


Figure 5.4: Throughput for different takt times at the final check station

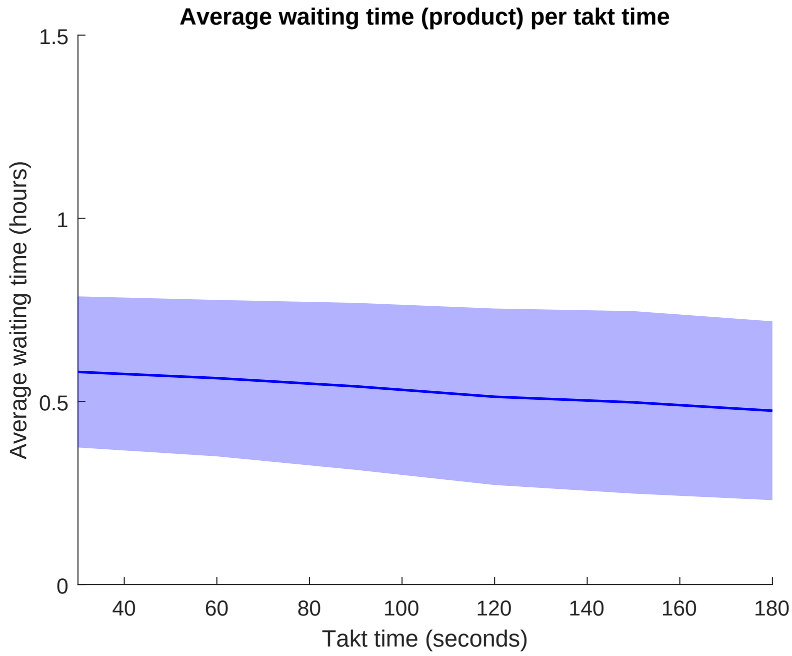


Figure 5.5: Average waiting time for different takt times at the final check station

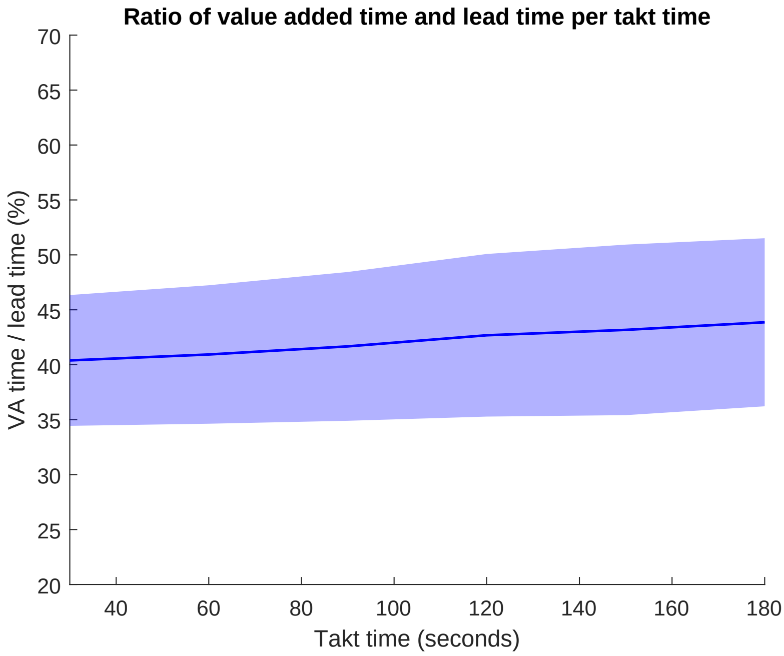


Figure 5.6: Ratio of value added time and lead time for different takt times at the final check station

5.4 Scenario C: Product input planning

A custom order of input product types was made in order to optimally use the dry cells in the lunch break, while keeping the product type probability of table 4.1.The lunch break is modelled with a 1 hour time period in which the final check, spray booth, packaging station and product input do not operate. The goal was to use dry cell 3 maximally during the lunch break, which services products with paint type 3 for a duration of 45 minutes. The order of paint types is included in Appendix B. For this scenario 30 trolleys were implemented.

The KPI's of this scenario are listed in table 5.1.

5.5 Scenario D: Continuous flow

In this scenario the spray cabin interior conveyor operates non-stop and the packaging station has a service time of 30 s. This could be achieved with two extra employees, at the spray booth and at the packaging station. The number of trolleys was analyzed for the KPI's. In this case the throughput has a maximum of 178 units/day at 24 trolleys, with an average waiting time of 5 minutes.

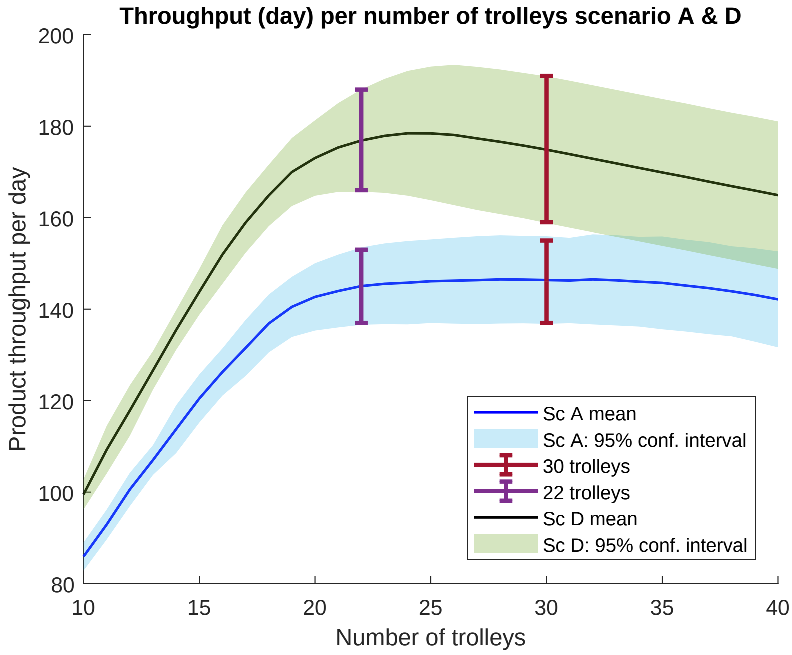


Figure 5.7: Throughput per number of trolleys for scenario A and D

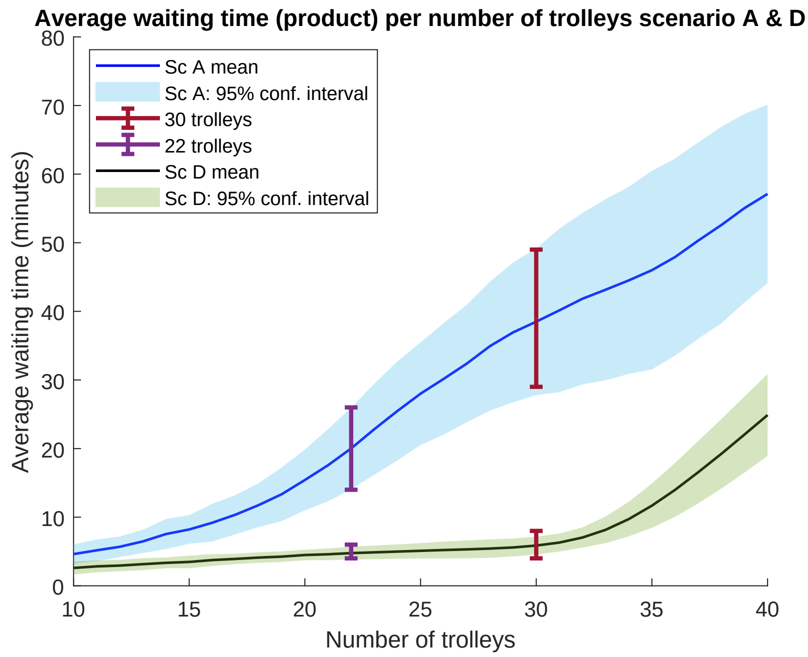


Figure 5.8: Average waiting time per number of trolleys for scenario A and D

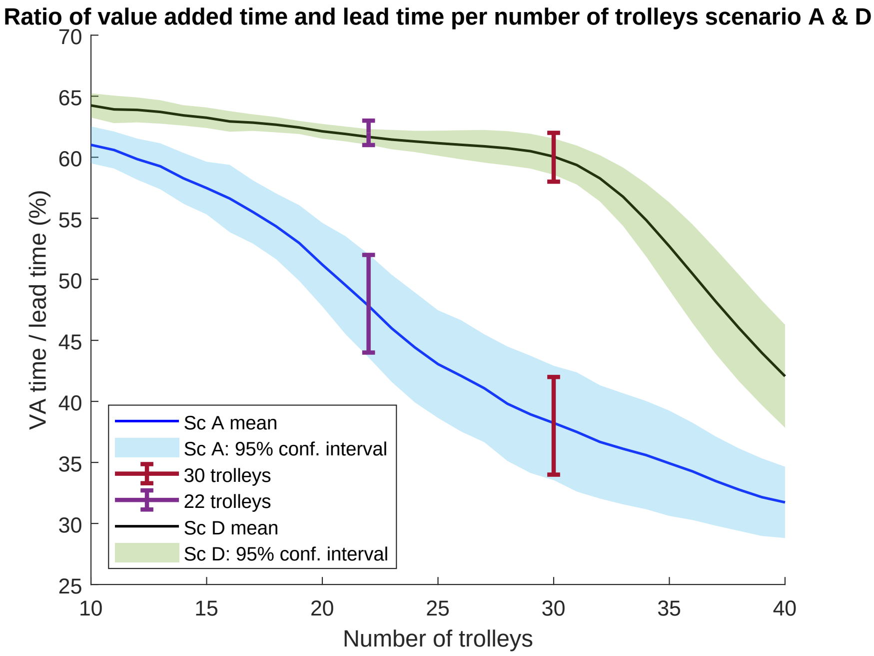


Figure 5.9: Ratio of value added time and lead time per number of trolleys for scenario A and D

Table 5.1: KPI's for different scenarios with the 95% confidence interval results

KPI \Scenario	**A1**	**A2**	**B**	**C**	**D1**	**D2**
Throughput (units/day)	146 ± 9	145 ± 8	142 ± 8	141 ± 8	175 ± 16	177 ± 11
Average waiting time / unit (minutes)	39 ± 9	20 ± 5	32 ± 13	44 ± 6	6 ± 2	5 ± 1
Value added time / lead time per unit (%)	38 ± 4	48 ± 4	42 ± 7	37 ± 2	60 ± 2	62 ± 1

5.6 Conclusion

For every scenario different control measures were taken. This includes, changing the number of trolleys, introducing a fixed trolley departure time or takt time, change the order of products at the input and finally adjust the operation of the spray cabin and the packaging station. The results per scenario are shown in table 5.1. For every scenario a plot was made comparable to figure 3.3 in the problem statement of chapter 1. Those plots are listed in Appendix B.

The takt time and input planning did not result in a performance increase and therefore those are not control measures to control the flow continuity. Changing the number of trolleys did have effect on the performance. Also the operation of the spray cabin interior conveyor and the service time of the packaging station have effect on the performance. Those could be controlled by the amount of employees that work per workstation.

The control method in this chapter needs to be further developed towards real-time control, which is done in the next chapter. In the next chapter the results presented in this chapter will be further discussed and also requirements will be set in which the current control measures can be developed into real-time control.

Chapter 6

Discussion

Now that different scenarios are implemented in the model and the effect on the performance of those scenarios were shown, first a discussion is held on the combination of theories this research addresses or theoretical framework, secondly a discussion is held on the results presented in Chapter 5, thirdly this model is placed in a control perspective and finally requirements are discussed that are needed for using the model as a digital twin in a cyber-physical production system in order to come to a higher level of control of the flow continuity.

6.1 Theoretical framework

Chapter 2 on the current state started with a system description using the Delft Systems Approach (DSA). This contributed to a clearer understanding of the system including the different elements and attributes, their function and the tasks they perform. DSA enabled to describe the average local product flow per function and task. Variations in this flow are considered to be part of the problem statement and therefore Lean Manufactering (LM) was used to further understand variations in this flow. In order to come to an analysis on the amount of variability in the system a method other than DSA was needed. The 3P model was introduced because it gives insight into more aspects of the system that contribute to the flow. or lack of flow, enabling to analyze more types of variability. With DSA it is possible to describe variability in the product flow, however the relationship between different types of variability defined by the 3P model gives a deeper understanding. The variability in the process, referred to as Mura in LM was further analyzed using discrete-event simulation. The discrete-event simulation model enables the possibility of testing various scenarios to control the flow continuity. The effects of those scenarios are further discussed in the coming section. The theory of Cyber-physical production systems will be used to define requirements to come to real time control.

6.2 Results of scenarios in simulation model

For scenario A (current state) and scenario D (continious flow) a number of trolley analysis was performed. The results of this analysis are discussed in the coming paragraph. Also the results from scenario B (takt time) and scenario C (input planning) are discussed afterwards.

6.2.1 Number of trolley analysis

The number of trolleys were analyzed for the current state, scenario A and compared with scenario D. Specifically the throughput and average waiting time will be further discussed.

Throughput

At scenario A, the throughput increases until at stabilizes between approximately 22 and 35 trolleys, after which the throughput slightly decreases. This can be compared with scenario D (figure 5.7) in which the average throughput is higher for every number of trolleys. Whereas the curve stabilizes at scenario A, a real optimal point can be found in scenario D around 24 trolleys.

It can be noted that in the case of less variability for the throughput there is a real optimal point, but when there is more variability it is harder to mark one specific point.

The 95% confidence interval for scenario A is generally smaller at this plot, than for scenario D. This was not expected, since scenario D decreases the amount variability in the system. An explanation could be that because higher throughput values also means more products over the course of a day and therefore a higher spread in the data.

Average waiting time

Due to the non-continuous flow in the spray cabin and the variable service time at the packaging station, an higher waiting time is expected in scenario A compared to scenario D. This can be observed in the results as well. An increasing waiting time for more trolleys is also expected, since inherently less trolleys means shorter queues. For scenario A this is the case. For scenario D, the curve rises slightly between 10 and 30 trolleys, however is almost constant.

Based on the results, a capacity of the power & free system could be observed that depends on the amount of variability in the production and the amount of trolleys. This capacity can be expressed in throughput per amount of variability. In this research the varibility in time intervals is quantified for a data set as the interquartile range (IQR) (Chapter 3). For this specific type of production variability also a measure is needed that quantifies this specific type of variability in order to further describe this relation.

6.2.2 Takt time

Since a takt time structures the product flow, an improvement in performance was expected at this scenario. This was not observed, every takt time even decreased the performance a bit. Takt times in a one piece flow are used for production processes in which the product passes from one employee or work station to the other [25]. The P&F conveyor system is more complex than that. It consists of working stations, but also of very product specific actions that need to be performed with corresponding time and routing through the system. A takt time does not take this into account by setting a fixed time for every product, without taking into account any further information.

6.2.3 Input planning

The input planning with the objective to optimally make use of the automatic dry cells in the lunch break did not improve the performance. In the hindsight, this can be related to an aspect of the Theory of Constraints (ToC), namely the human behaviour of optimizing one single machine in a process, which does often not improve the flow [11]. Based on the results it can be concluded that it does not solve a bottleneck by letting the dry cells perform maximally during the lunch break.

6.2.4 Continuous flow scenario

The continuous flow scenario shows that by decreasing variability at the spray booth and the packaging station, the performance increases. Specifically the average waiting time per product. This research quantifies this increase in performance and thereby helps decision makers of this system to control the flow.

6.3 Control perspective

The approach that was chosen in this research to come to a control of the flow continuity was to make a model of this flow and test various scenarios. Every scenario has a number of control measures and the expected performance per scenario is a measure whether or not those control measures would increase the performance. The function defined by DSA of figure 3.1 could be extended with a control loop (figure 6.1). The control measures about the spray cabin interior conveyor and packaging station service time are process control. Function control deals with the boundaries of the process, so the takt time and product input planning control measures are function control.

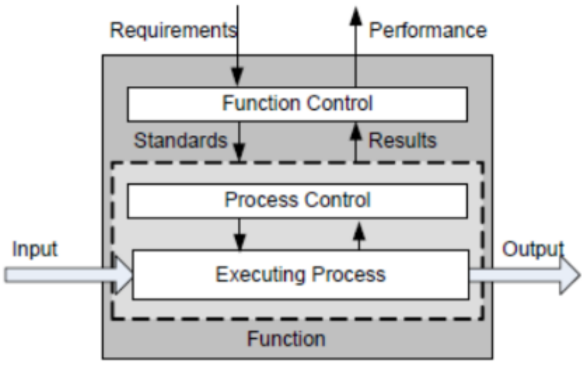


Figure 6.1: Control loop in the Delft Systems Approach [49]

The model furthermore does also give insight into the process itself. Something that is also possible with a DMAIC cycle from Lean - Six Sigma, which stands for Define, Measure, Analyze, Improve, Control. This is a process to come to improvements in the process rather than control a current process. After those improvements are made control is needed to maintain them. The discrete-event simulation model can be used specifically in the analyze phase of this DMAIC cycle, since it enables to test various scenarios.

By only using the scenarios discussed, the flow continuity could be controlled to some extend. The model could be used to make a prediction for a work day and a decision could be made on the amount of employees per work station. In order to come to real-time control, the theory of cyber-physical production systems (CPPS) can contribute. The coming section will discuss the requirements for using this model as a digital twin in a CPPS and how the model could be implemented in the smart P&F conveyor lab.

6.4 Implementation in a smart P&F conveyor lab

The model is a base for a digital twin of the P&F conveyor system. In the development of a smart P&F conveyor lab, one necesarry step is the design of such a digital twin. The model previously discussed is a simulation model. This means that the system is simulated based on the relations in the model and the inputs that are provided. Currently there is no active connection between the physical system and the simulation model. In a digital twin, as mentioned in literature as part of a cyber-physical production system, the physical system and the digital twin are mutually interconnected. The digital twin learns from the physical system and vice versa. [16]

6.4.1 Communication between model and physical system

Currently the model is not able to learn from the physical system, the physical system however could learn from the simulation model (figure 6.2). The product input for example can be measured real time and immediately fed into the model. The model can predict the behaviour of those products on the system. The effects of continuous or non-continuous spray cabin interior conveyor operation can be simulated and measures can be taken before a buffer is growing and flow stagnates. The same can be done with the packaging station. A communication tool can be implemented that shows employees what the expectation of the model is for the work load. Employees could adjust the moment to take a break based on this expectation. When the desired throughput for a day is known, management can plan the amount of employees that are needed for the specific work stations based on this expectation, or a self-managed production team can adopt this.

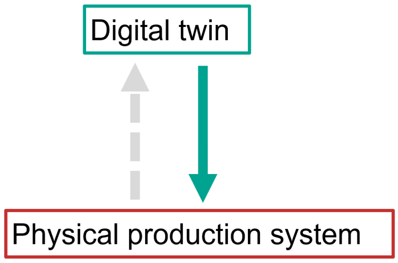


Figure 6.2: Currently communication is only possible from the digital twin towards the physical production system, not the other way around.

A next step is to implement the connection from the physical system to the simulation model. During operation the sensor measurements needs to adjust the model if needed. Requirements are set below to integrate the simulation model in a digital twin.

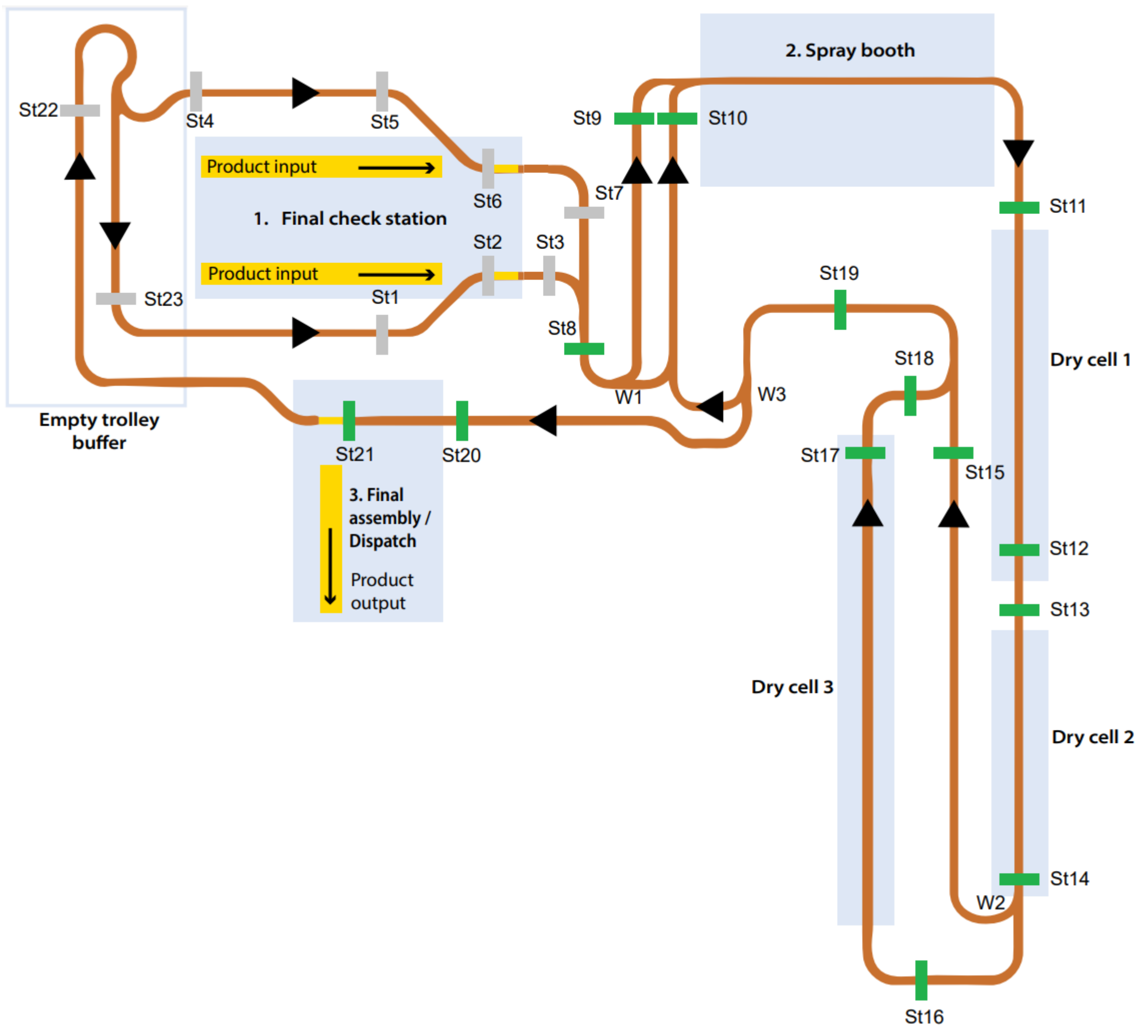


Figure 6.3: Locations of the current sensors at stoppers that record data in green. The same sensor data is required for stoppers marked grey for the development of a digital twin.

6.4.2 Requirements for the development of a digital twin

Both the physical system and the model needs to capable of this two way communication. Currently sensors are mounted at the stoppers which detect the trolley number that passes or enters the queue. Currently not all stoppers have those sensors or they are not being recorded. For the physical system therefore the following requirements should be met:

- Per stopper data on which trolleys are waiting at which position should be real-time available.
- The measurements that are already performed per stopper needs to be extended with stoppers 1,2,3,5,6,7,22 and 23
- Data per stoppers and start-stop data on the spray booth interior conveyor needs to be integrated
- To further improve the model, also empty trolleys should be detected by the sensors
- Control measures calculated by the model regarding amount of people per work station needs to be communicated.

In order to create a digital twin, in which the simulation model is a part, requirements needs to be set for this digital twin also. The current model assumes service times at the working stations based on a probability distribution. In order to develop into a digital twin, stochastic variables needs to be replaced by real-time measurements. This means that there needs to be a shell around the simulation model that is able to process real-time measurement data and translate that into input for the model.

- A translation of real-time measurements to input of the model needs to be made.
- The JaamSim model should be made capable of running without the graphical user interface, but as a function that give the output based on a set of inputs.
- The control measures should be an output of the model.

6.5 Conclusion

In this chapter a discussion is held on the theoretical framework of this research and on the control of the flow continuity enabled by the presented model. The control measures performed by the different scenarios were discussed. Since this control is based on a number of control measures that are based on an estimate over a longer period of time, requirements are made to come to real-time control. The discrete-event simulation model is placed in a cyber-physical production system perspective and the model could be used as part of a digital twin of the process. The requirements were set for the physical system and the model after which the model can be developed into a digital twin.

Chapter 7

Conclusion

This research started with an observation of non-continuous flow in the production process of SEW Eurodrive, therefore the following main research question was formulated: How can the flow continuity of a Power & Free conveyor system be controlled?

In literature Cyber-Physical Production Systems (CPPS) enable real-time control of production processes, a digital twin is part of this development. Also the Delft Systems Approach (DSA) and Lean Manufacturing (LM) are considered to be respectively a methodology to describe a system and a theory to minimize waste in a production process. Those theories could be combined with a variability analysis. This research uses a 3P model to relate different types of variability in the product flow.

The system was defined by three functions and a product flow between them. Variability in the system was assessed by the 3P model, which refers to 3 perspectives: product, process and production. The effect of variability in the product on the production was analyzed and found to be small. A discrete-event simulation model was made to analyze and assess the flow continuity and observe the effect of variability between the product and the process and the production and the process.

Various scenarios were simulated with this model, corresponding to different control measures. For the current state an ideal number of trolleys was found to be 22. The scenario in which a takt time was introduced between every trolley departure did not result in an performance increase. A planning of product types at the input did neither. A scenario with 22 trolleys at which the spray booth interior conveyor operates continuously and the packaging station service time as a constant time, the throughput increases by 21%, the mean of the average waiting time was 5 minutes compared to 39 minutes for the current state. A ratio of the value added time and the lead time was found to be 62% compared to a current state of 38%.

The Power & Free conveyor system could be controlled by using the model to make an estimate of the performance per day based on the mix of paint types. Hence the model could be used as a base for a digital twin to come to real-time control. Requirements for this digital twin are the possibility of real-time retrieving stopper and trolley queue data, also the time at which trolleys pass at stoppers should be recorded for all stoppers and the data on the stoppers and the spray booth interior conveyor needs to be integrated.

Chapter 8

Recommendations

The following recommendations can be made for further research:

- The requirements of chapter 7 for the development of a digital twin, mentions a shell in which the real-time measurement data is translated into input for the model. Research needs to be done on how to implement this at the JaamSim discrete-event simulation model. The model is currently only accessible in a graphical user interface (GUI), so research needs to be done on on how to execute this model outside this GUI.
- Other scenario's could be investigated using the model. In the current model the mix of paint types is set constant based on the average value of the data set. New results could be obtained by varying this mix of paint types.
- The human factor in the model is taken into account since real data is used as an input for the model. However some relations are not taken into account, for example, it can be assumed that human effort is related to the queue length in front to the work station. The model does not take that into account.
- The operation of the spray cabin interior conveyor was modelled as a downtime of 100 s every 300 s, this is a simplification. The on and off time intervals could be analyzed and implemented in the model with a stochastic distribution.
- The scenario of product input planning could be optimized. With an objective of high throughput and low average waiting time and the order of inputs as variable. An optimization algorithm could be made that optimizes this order.
- The fixed takt time scenario could be extended with a number of trolley analysis, this might give an optimum for both a takt time and number of trolleys.
- In addition to the system description using the Delft Systems Approach, a more mathematical description of the system can be made. For example queuing theory or Multi Model Assembly Line Balancing Problem (MMALBP) theory can contribute to this system description.

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Power & Free conveyor operation at the SEW Eurodrive Assembly plant in a Cyber-Physical production system perspective

R.A. Slingerland[a], Dr. W.W.A Beelaerts van Blokland[b], Dr. Ir. D.L. Schott[b]

[a] *Candidate of MSc ME-MME, Delft University of Technology, Netherlands,*
[b] *Department of Maritime and Transport Technology, Delft University of Technology, Netherlands,*

Abstract

This paper focuses on the effect of variabilities in a Power & Free conveyor system on the flow continuity by an analysis on the product, process and production level (3P), a discrete-event simulation model and the theory of Cyber-Physical Production systems (CPPS) to control the product flow. Scenarios were evaluated with this model and the results show the effect of performance increase when variability decreases. Requirements are set to come to real-time control by developing this model into a digital twin as part of a CPPS. It can be concluded that the discrete-event model can be used to predict the performance and take control measures accordingly, subsequently real-time control is possible by implementing real-time sensor measurements in the model, thereby developing the model into a digital twin.

Keywords: Power & Free conveyor, Discrete-event simulation, Digital twin, Cyber-physical production system

Contents

1. Introduction

A Power & Free (P&F) conveyor is a type of overhead conveyor with trolleys that are able to engage and disengage from the powered chain and thereby providing flexibility in the process. SEW Eurodrive Rotterdam assembles electrical geared motors and uses this type of conveyor in the assembly process. A downside of this conveyor is a non-continuous product flow, which results in an uneven workload at the work stations this conveyor passes. Those work stations are a final quality check, a spray booth, dry cells and a packaging station. All of which, except the dry cells, are manually operated. Currently this system is controlled by the employees who change to different work stations if a growing queue is observed somewhere in the system. Nevertheless still a non-continuous flow is observed. Figure 1 shows the varying product buffers over the course of a day. It is this non-continuous flow which this paper addresses by the research question:

How can the flow continuity of a Power & Free conveyor system be controlled?

This question is answered by the following sub questions:

1. What theories, methodologies and models are available on analyzing product flow in a production process?
2. What defines the Power & Free conveyor system, its performance and which part causes variability?
3. What model can be used to analyze and assess the flow continuity?
4. Which scenarios can be used to control the flow continuity and what is the effect of those scenario's on the performance?
5. What are the requirements for using the model as a digital twin in a cyber-physical production system and how could this contribute to control the flow continuity?

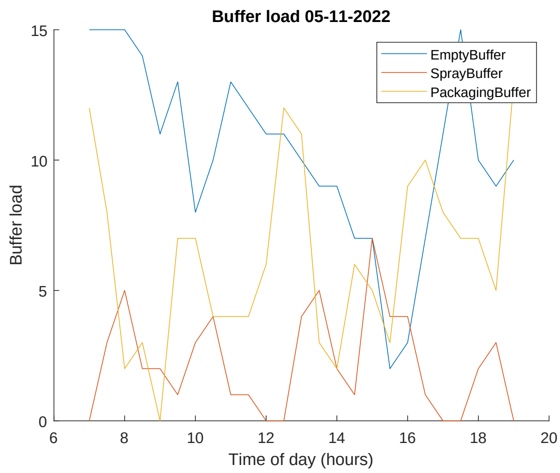

Figure 1: Buffer load before the three work stations for an arbitrary day

2. Literature background

A literature review was used to find theories, methodologies and models on analyzing product flow in a production process. The development of Industry 4.0 or specifically Cyber-Physical Production Systems (CPPS) contributes to analyze the flow [2]. Figure 2 shows the levels in which a production system could be scaled according to this theory. The current P&F system is in the Data-to-Information Conversion Level (Level II). There is a sensor network, data from these sensors are being analyzed. A next step towards level III is the development of a digital twin model of the process [4].

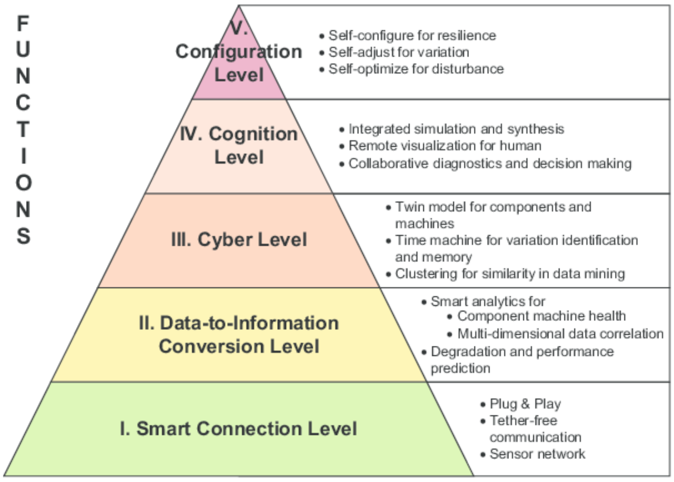

Figure 2: Architecture of a cyber-physical production system [8]

The Delft Systems Approach (DSA) was found to be a methodology to describe functions and the flow between them for a production process [7]. The theory of Lean Manufacturing (LM) provides concepts to analyze and control this flow, for example the distinction between three types of waste resulting in non-value added time to a product [6]. LM refers to this waste by the Japanese words muda, muri and mura. Muda are all activities that do not add value to the product. Those are often summarized by TIMWOODS which stands for Transport, Inventory, Motion, Waiting, Over-production, Over-processing, Defects and Skills (unused). Muri means overburdening of people or processes and muda unevenness in the process, variability therefore is muda. According to LM those types of waste are related to each other by a triangular relationship. One of those will result in the other two (figure 3). Variability will therefore also result in overburdening of people or processes and non-value added activities.

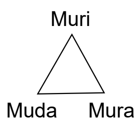

Figure 3: Three types of waste in Lean Manufacturing which relate to each other according to a triangular relationship: one of them results in the other two.

Another concept from LM is takt time, which is used to structure the flow. In a one-piece flow process, ideally every work station needs the same time to finish the task, the takt time. Consequently this is also the sequence at which end products leave the process, therefore the takt time is chosen based on the demand of the customer [6].

Product flow can be simulated, various simulation models are made for Power & Free conveyor systems. Discrete-event simulation is a method which enables modelling production processes based on stochastic inputs [3]. Tools are available with build-in elements like conveyors, queues and servers that are able to model a Power & Free conveyor. In this paper a model is presented using JaamSim [5]

3. Current State

The current state of this P&F conveyor system was analyzed by making a system description using DSA.Three functions are identified: a quality control on the product, the application of one or more layers of paint and the preparation for dispatch.

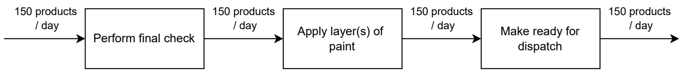

Figure 4: Three functions and average product flow between them in units per day performed by the P&F conveyor.

Three perspectives on a production system are used, considering the 3P model: product, production and process [1]. Variability in the system is evaluated by this 3P model (figure 5). Data recorded by sensors at the stoppers was used for the months May and June 2022. These sensors record the following data if a trolley enters a stopper or a queue before a stopper:

- Trolley number
- Stopper number
- Position in queue
- Order number details
- Paint type
- Scan time

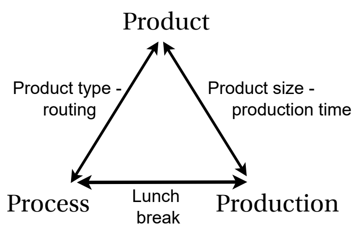

Figure 5: 3P model, three perspectives on a production system, each one influencing the other two [1], in this research used to assess variability.

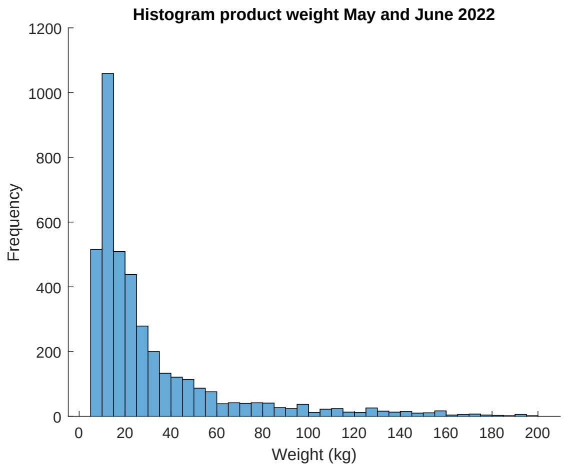

Figure 6: Histogram of product weights

Product

Variability in the product includes the size and corresponding spray area. This was made visible in an histogram showing the weight of all products in two months time (figure 6).

Variability also includes the different paint types per product. Those paint types could be divided in 3 categories, corresponding to 3 different routes through the system. The fraction per paint type is shown in table 1.

Production

Variability in the production can be divided into two parts. First there is the assignment of employees for the different work places. This includes variable start times of a work day between 6:45am and 9 am and corresponding end of work day times. Also there is lunch break between 12pm and 1pm. At that time the manual work stations stop, but the automatic parts of the system continue. Manual work stations are the final check station, spray booth and packaging station. The dry cells and conveyor segments operate automatically. Secondly there is variation in how employees perform the tasks, some little in-between jobs could be done somewhere else in the process or little breaks could influence the flow at the P&F system. Also variability is observed in the operation of the spray booth. This spray booth has an own dedicated interior conveyor that can be switched on and off. Sensor data show that this conveyor is switched of for 33% of the time.

Process

Variability in the process involves different routes through the system per paint type. It also involves the effect of the lunch break. A model is needed in which the effect of variability in this process can be analyzed. This model will be discussed in the next chapter.

Performance

The performance of the system or flow continuity was defined by the throughput and the average waiting time in the system per product. Based on LM a ratio was defined of the value added time and the total time in the system or lead time. The throughput for the current state per day is in the interval 104-202 units per day. It is normally distributed with a mean of 150 unis / day and standard deviation of 20 units / day. The average waiting time per product is shown in table 1 per paint type. This waiting time is determined as follows: first the minimum lead time is found in the data set. The assumption is made that this number corresponds to a waiting time of zero. Secondly this value is subtracted from all lead times of a paint type and the average is regarded the average waiting time. A weighted mean of those values based on the paint type fraction was determined to come to an average waiting time for the whole system. Those performance metrics are also the output of the model that was made.

Table 1: Minimum transport times for products in the system per paint type, the corresponding average waiting times and the weighted mean of the average waiting times with respect to the fraction this paint type is represented in the data set

Paint type	**Min. lead time (hh:mm:ss)**	**Avg. waiting time (hh:mm:ss)**	**Fraction**
1	00:29:00	00:28:41	0.81
2	01:08:06	00:33:31	0.03
3	01:45:08	00:50:04	0.16
Weighted mean:		00:32:15	

4. Model

The product flow in the process was modelled using a discrete-event simulation tool JaamSim. This model simulates the product flow, the trolley flow and their interaction by combining elements that are available in this software package. This includes among others product entities, conveyor elements, queues, servers, thresholds, switches and downtime entities. The paint type dependent routing is visualized and also the effect of the lunch break on the product flow. The input of this model are probability distributions for the inter-arrival times of input products (figure 7), the operating sequence of the spray booth interior conveyor and the inter-arrival time distribution of the packaging station (figure 8). Also the paint type fractions of table 1 are input for the model. The output are the throughput in units per day, the average waiting time per product and the ratio of value added time and lead time. The product flow could be analyzed and assessed with this model by implementing various scenarios. The next chapter discusses different scenarios that are simulated with this model.

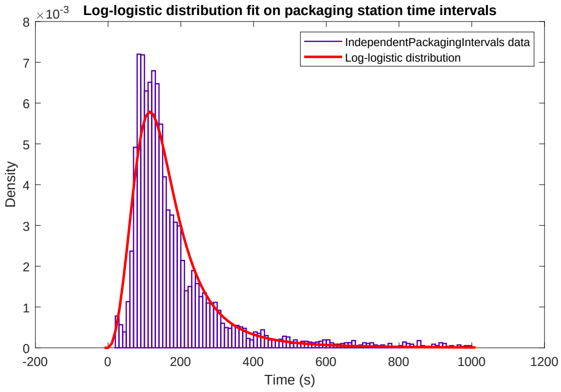

Figure 8: Service time packaging distribution fit

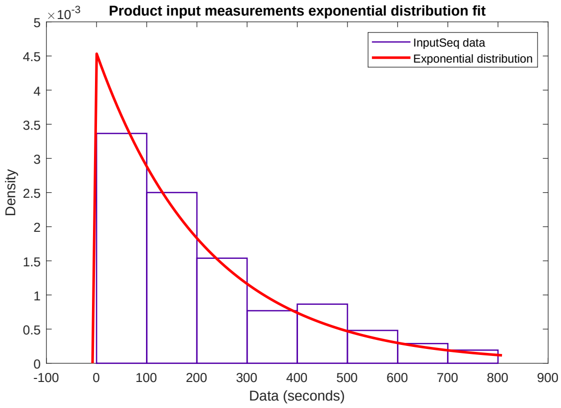

Figure 7: Product input exponential distribution fit

5. Results

Various scenarios are explored using this model. The effect of the number of trolleys on the performance was analyzed, currently the system has 30 trolleys, a takt time was introduced at the location were products enter the system and a planning was made of the order of products over the course of a day. Finally a scenario was made that presumes continuous flow of the interior spray booth conveyor and a fixed service time at the packaging station. The scenarios are referred to as:

- Scenario A1: The current state with 30 trolleys
- Scenario A2: The current state with 22 trolleys
- Scenario B: A fixed takt time for the arrival of trolleys at the final check station
- Scenario C: A planning of the order of products at the input.
- Scenario D1: Continuous flow with 30 trolleys
- Scenario D2: Continuous flow with 22 trolleys

The results of those scenarios are presented in table 2

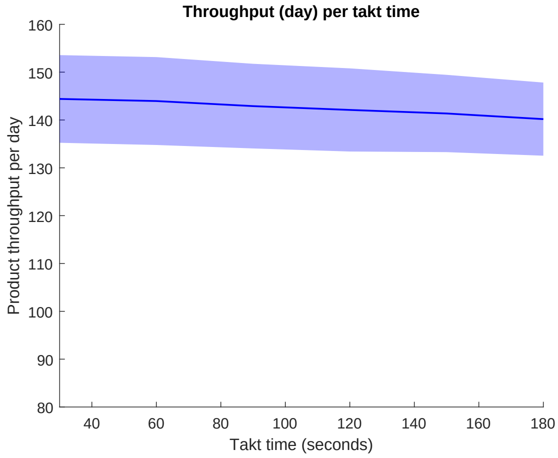

Figure 9: Throughput for different takt times

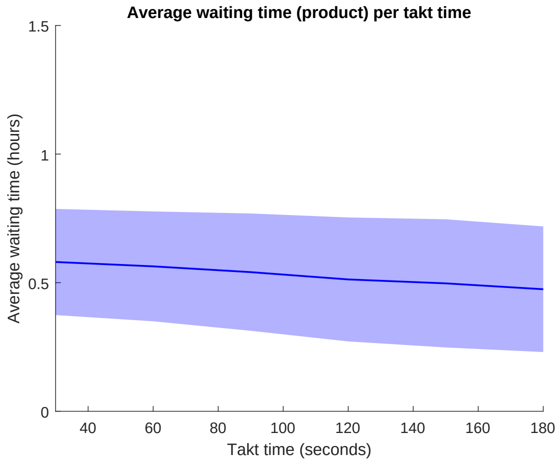

Figure 10: Average waiting time for different takt times

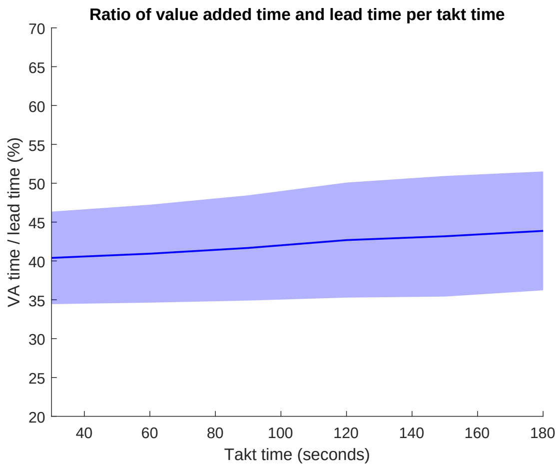

Figure 11: Ratio of value added time and lead time for different takt times

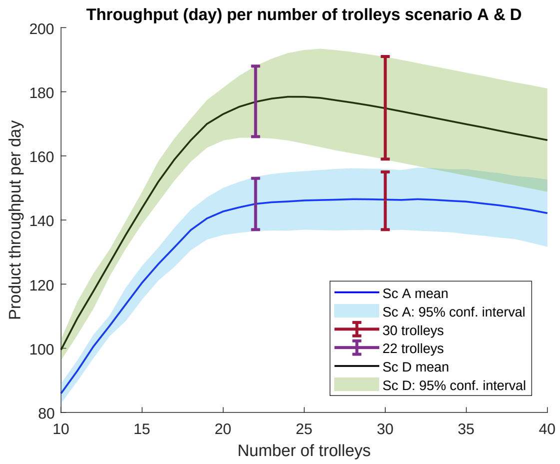

Figure 12: Throughput per number of trolleys for scenario A and D

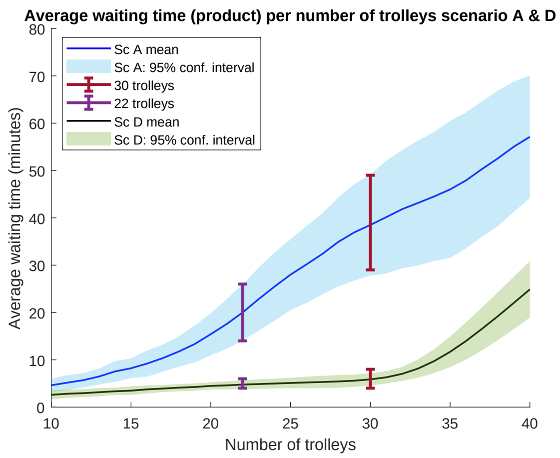

Figure 13: Average waiting time per number of trolleys for scenario A and D

The results of scenario B for different takt times are shown in figures 9, 10 and 11. The line represents the average value and the area the 95% confidence interval based on 500 samples. It can be noted that introducing a takt time does not result in an performance increase.

Figure 12, 13 and 14 show the three performance metrics for scenario A and D where the line represents the mean and the colored area the 95% confidence interval based on 500 different input samples.

6. Discussion

The model enables estimating the flow continuity per day based on the product input and the operation of the work stations, also the mix of paint types could be adjusted in the model. This model therefore could be used to decide what control measures are needed. In order to come to real-time control, the model needs to be fed by measurement data performed in the physical system. In this way the model can be used and develop into a digital twin. Communication between the digital twin and the physical production system is required.

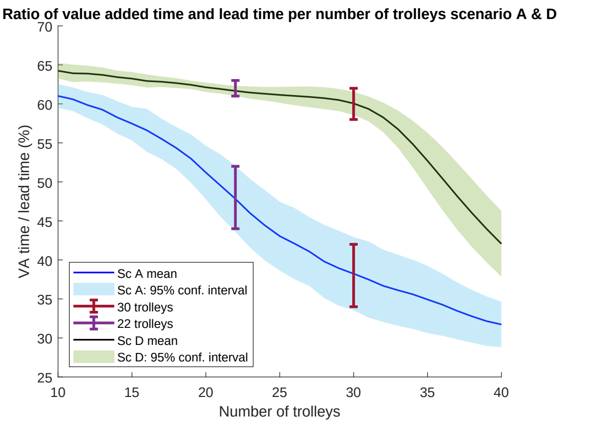

Figure 14: Ratio of value added time and lead time per number of trolleys for scenario A and D

Table 2: KPI's for different scenarios with the 95% confidence interval results

Scenario	Throughput (units/day)	Average waiting time / unit (minutes)	Value added time / lead time per unit (%)
A1	146 ± 9	39 ± 9	38 ± 4
A2	145 ± 8	20 ± 5	48 ± 4
B	142 ± 8	32 ± 13	42 ± 7
C	141 ± 8	44 ± 6	37 ± 2
D1	175 ± 16	6 ± 2	60 ± 2
D2	177 ± 11	5 ± 1	62 ± 1

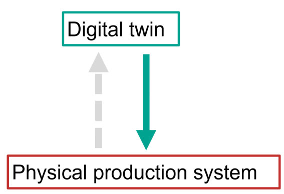

Figure 15: Communication between model and physical system

Both the physical system and the model needs to capable of this two way communication. Currently sensors are mounted at the stoppers which detect the trolley number that passes or enters the queue. Currently not all stoppers have those sensors or they are not being recorded. For the physical system therefore the following requirements should be met:

- Per stopper data on which trolleys are waiting at which position should be real-time available.
- The measurements that are already performed per stopper needs to be extended to all stoppers
- Data per stoppers and start-stop data on the spray booth interior conveyor needs to be integrated
- To further improve the model, also empty trolleys should be detected by the sensors

- Control measures calculated by the model regarding amount of people per work station needs to be communicated.

In order to create a digital twin, in which the simulation model is a part, requirements needs to be set for this digital twin also. The current model assumes service times at the working stations based on a probability distribution. In order to develop into a digital twin, stochastic variables needs to be replaced by real-time measurements. This means that there needs to be a shell around the simulation model that is able to process real-time measurement data and translate that into input for the model.

- A translation of real-time measurements to input of the model needs to be made.
- The JaamSim model should be made capable of running without the graphical user interface, but as a function that give the output based on a set of inputs.
- The control measures should be an output of the model.

7. Conclusion

The latest developments of Cyber-Physical Production Systems (CPPS) enables real-time control of production processes, a digital twin is part of this development. Also the Delft Systems Approach (DSA) and Lean Manufacturing (LM) are considered to be respectively a methodology to describe a system and a theory to minimize waste in a production process. Those theories could be combined with a variability analysis. This research uses a 3P model to relate different types of variability in the product flow.

The system was defined by three functions and a product flow between them. Variability in the system was assessed by the 3P model, which refers to 3 perspectives: product, process and production. The effect of variability in the product on the production was analyzed and found to be small. A discrete-event simulation model was made to analyze and assess the flow continuity and observe the effect of variability between the product and the process and the production and the process.

Various scenarios were simulated with this model, corresponding to different control measures. For the current state an ideal number of trolleys was found to be 22. The scenario in which a takt time was introduced between every trolley departure did not result in an performance increase. A planning of product types at the input did neither. A scenario with 22 trolleys at which the spray booth interior conveyor operates continuously and the packaging station service time as a constant time, the throughput increases by 21%, the mean of the average waiting time was 5 minutes compared to 39 minutes for the current state. A ratio of the value added time and the lead time was found to be 62% compared to a current state of 38%.

The Power & Free conveyor system could be controlled by using the model to make an estimate of the performance per day based on the mix of paint types. Hence the model could be used as a base for a digital twin to come to real-time control. Requirements for this digital twin are the possibility of real-time retrieving stopper and trolley queue data, also the time at which trolleys pass at stoppers should be recorded for all stoppers and the data on the stoppers and the spray booth interior conveyor needs to be integrated.

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Appendix B

8.1 Model input

The specific order of input products for scenario C is:

```
1 1 2 1 1 2 1 1 1 2 1 1 1 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 3 3 3 3 3 3 3 3 3 3 3
3 3 3 3 3 3 3 3 3 3 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1
```

8.2 Model output

The model was ran with 500 different input samples. The ouput KPI’s are normally distributed and displayed per scenario in this section.

8.2.1 Scenario A1

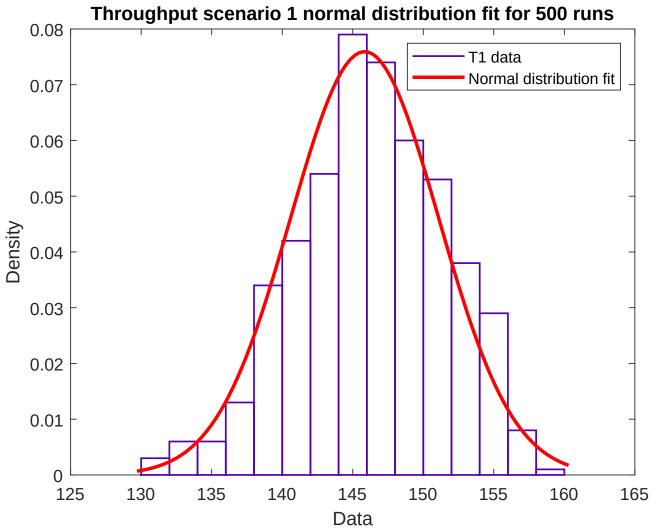

Figure 8.1: Histogram throughput normal distribution fit

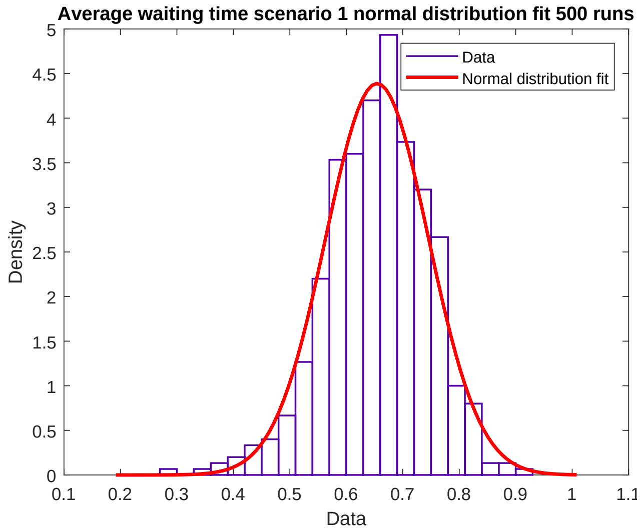

Figure 8.2: Histogram average waiting time normal distribution fit

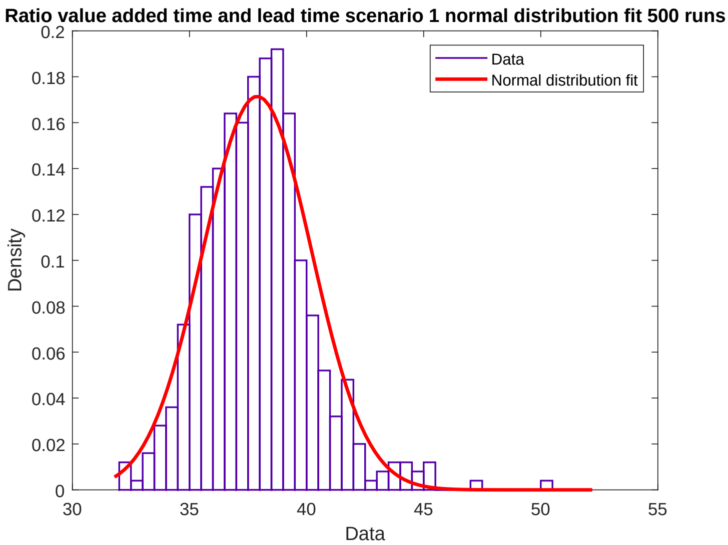

Figure 8.3: Histogram ratio value added time and lead time normal distribution fit

8.2.2 Scenario A2

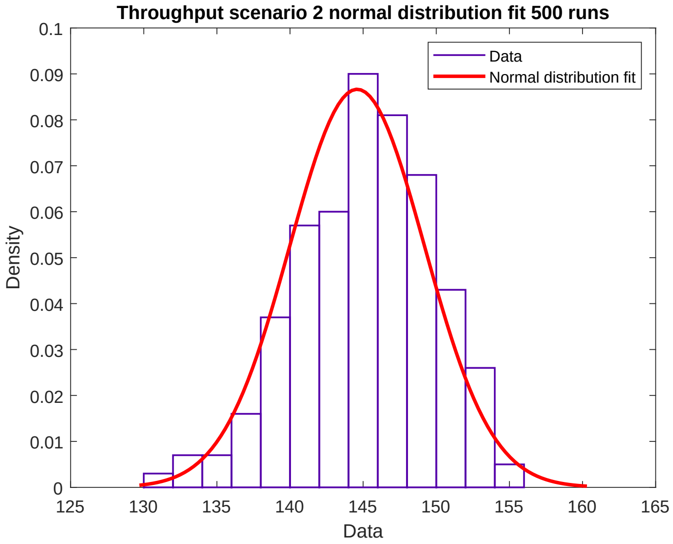

Figure 8.4: Histogram throughput normal distribution fit

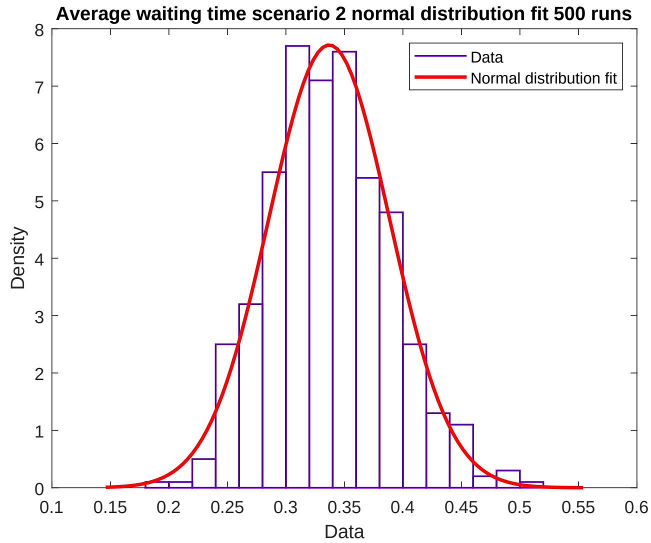

Figure 8.5: Histogram average waiting time normal distribution fit

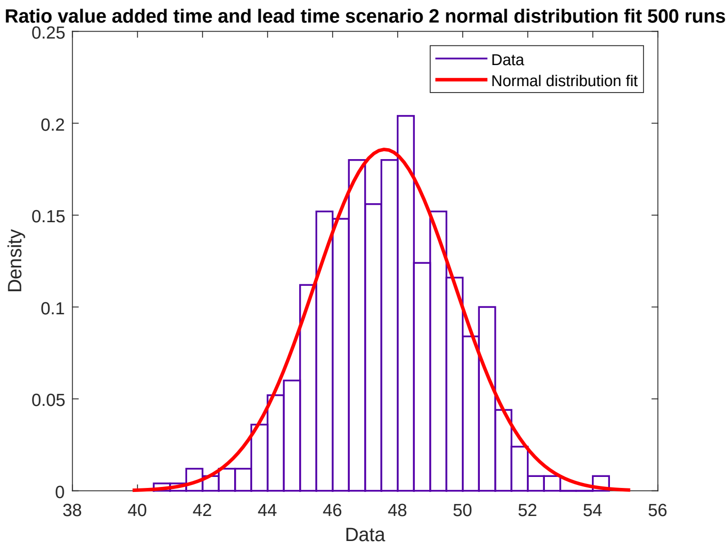

Figure 8.6: Histogram ratio value added time and lead time normal distribution fit

8.2.3 Scenario B

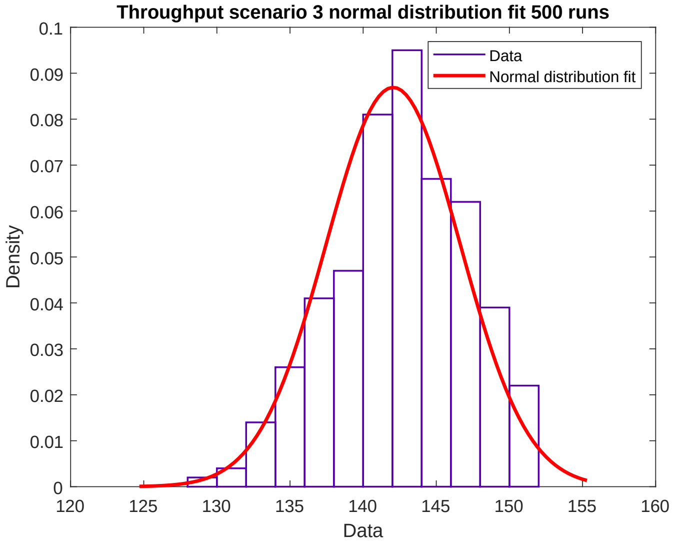

Figure 8.7: Histogram throughput normal distribution fit

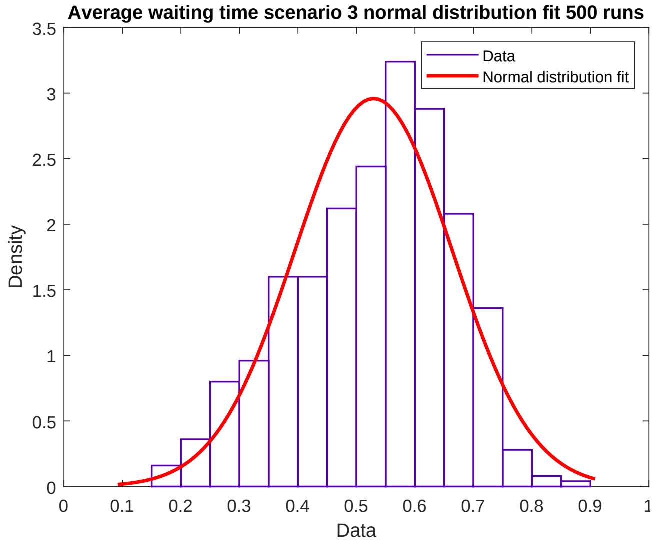

Figure 8.8: Histogram average waiting time normal distribution fit

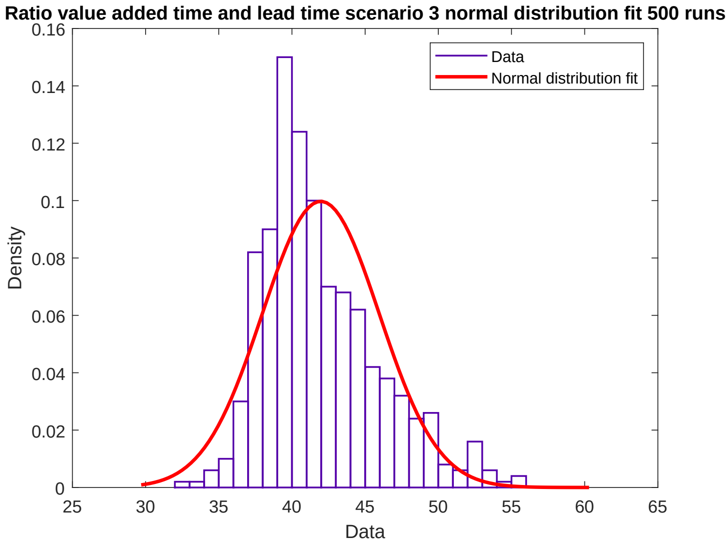

Figure 8.9: Histogram ratio value added time and lead time normal distribution fit

8.2.4 Scenario C

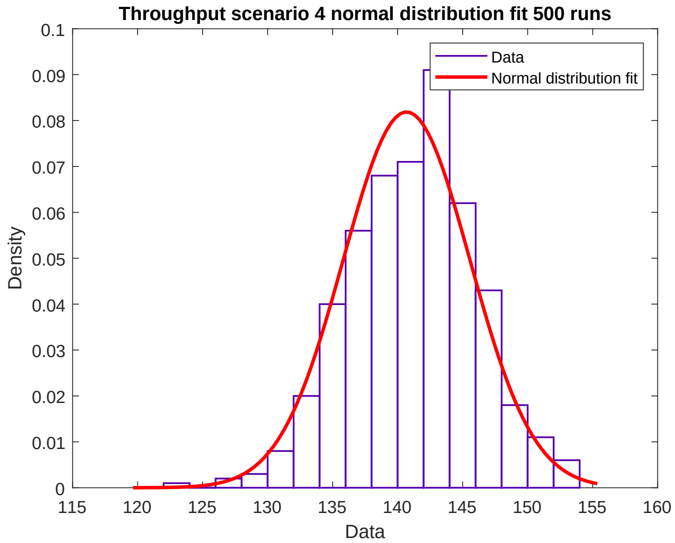

Figure 8.10: Histogram throughput normal distribution fit

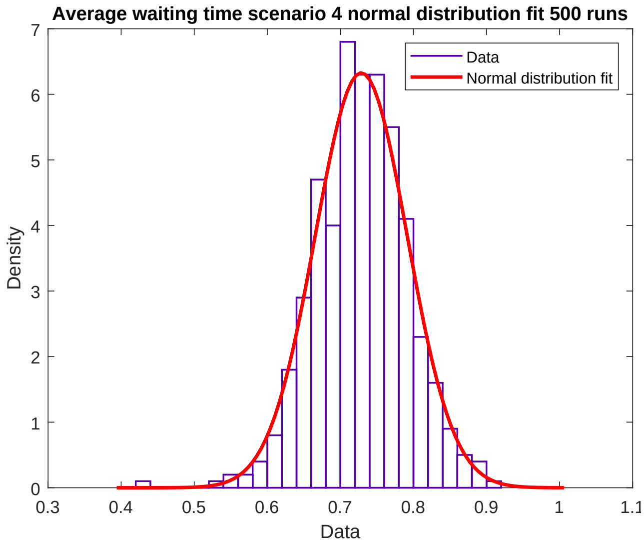

Figure 8.11: Histogram average waiting time normal distribution fit

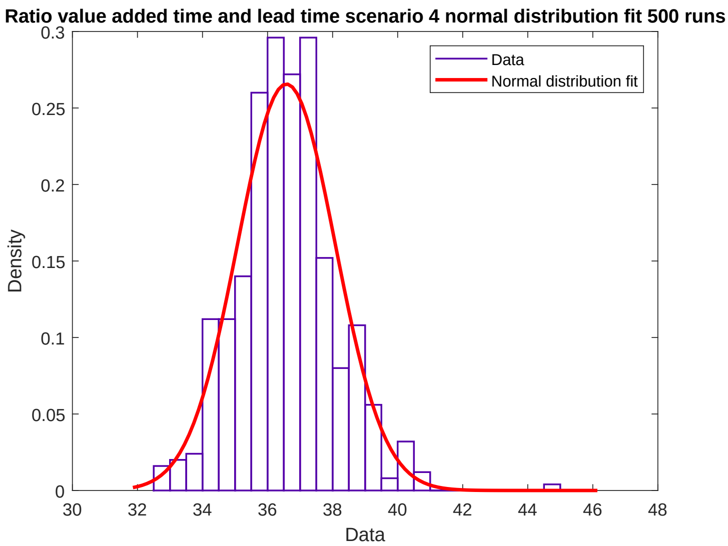

Figure 8.12: Histogram ratio value added time and lead time normal distribution fit

8.2.5 Scenario D1

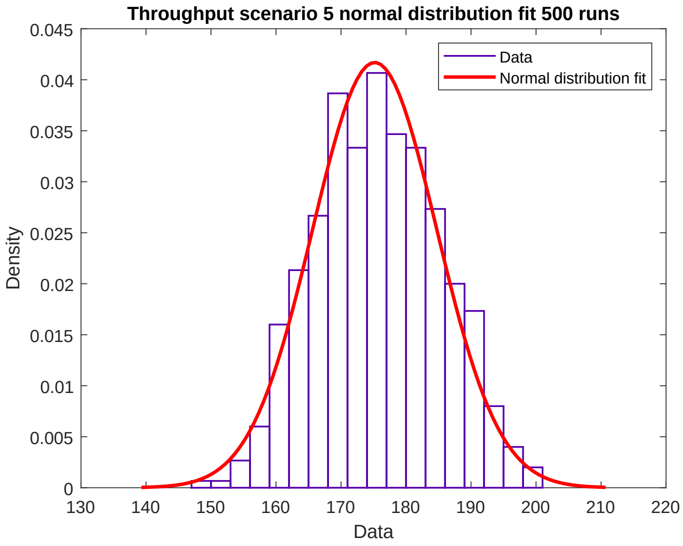

Figure 8.13: Histogram throughput normal distribution fit

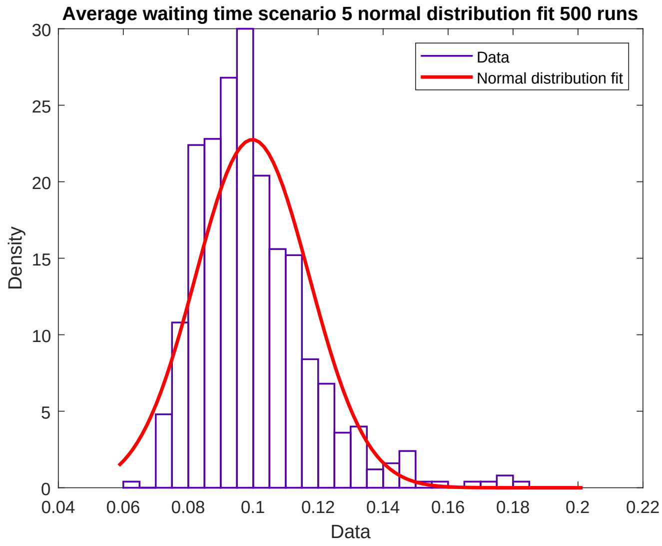

Figure 8.14: Histogram average waiting time normal distribution fit

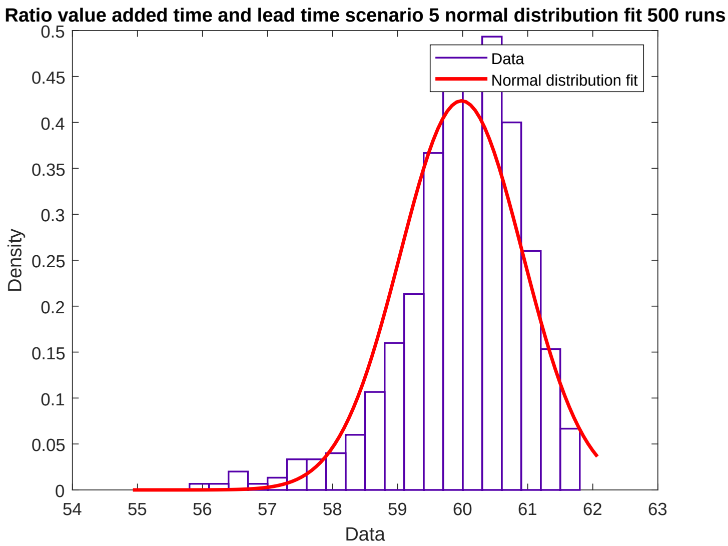

Figure 8.15: Histogram ratio value added time and lead time normal distribution fit

8.2.6 Scenario D2

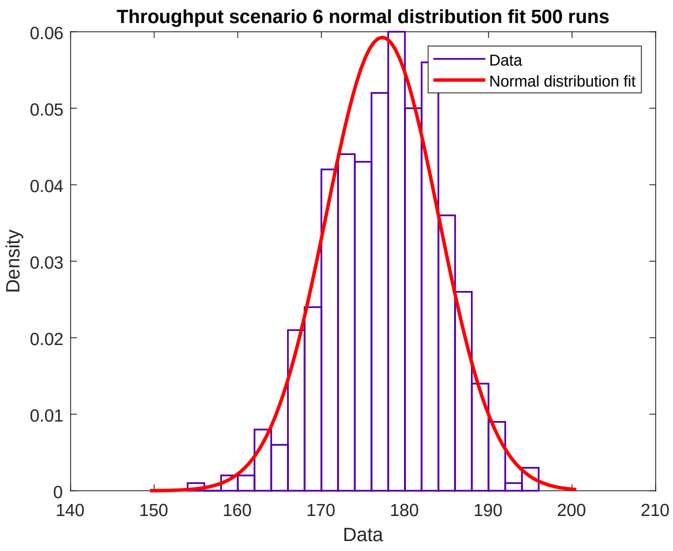

Figure 8.16: Histogram throughput normal distribution fit

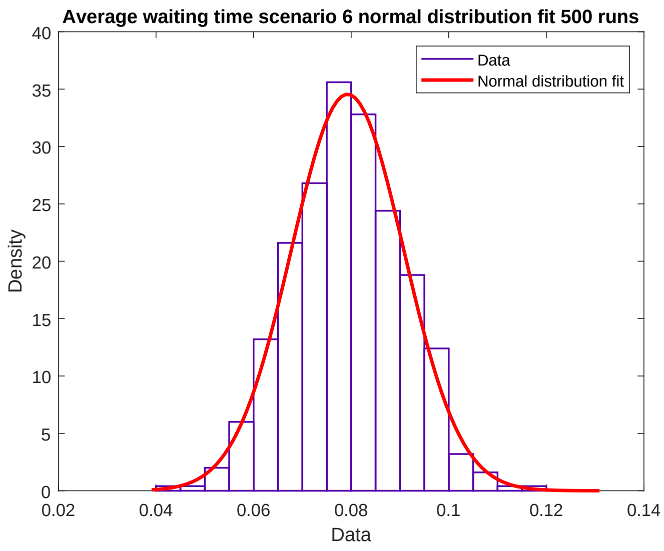

Figure 8.17: Histogram average waiting time normal distribution fit

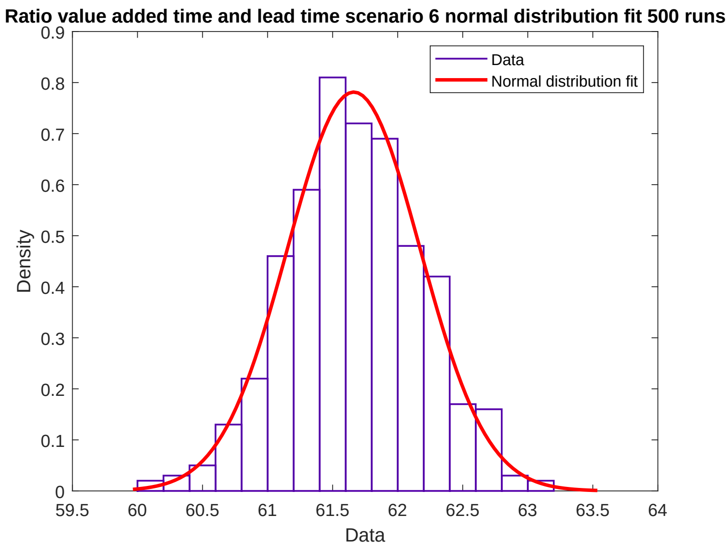

Figure 8.18: Histogram ratio value added time and lead time normal distribution fit

8.3 Lead time per paint type in sensor data

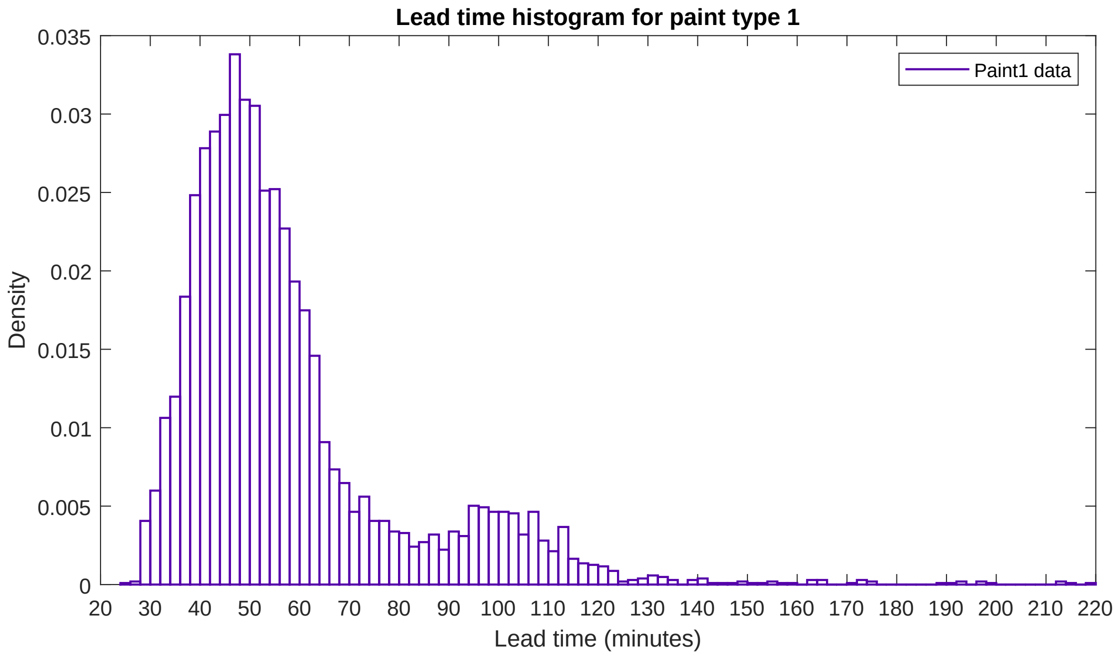

Figure 8.19: Histogram of lead time in sensor data for paint type 1

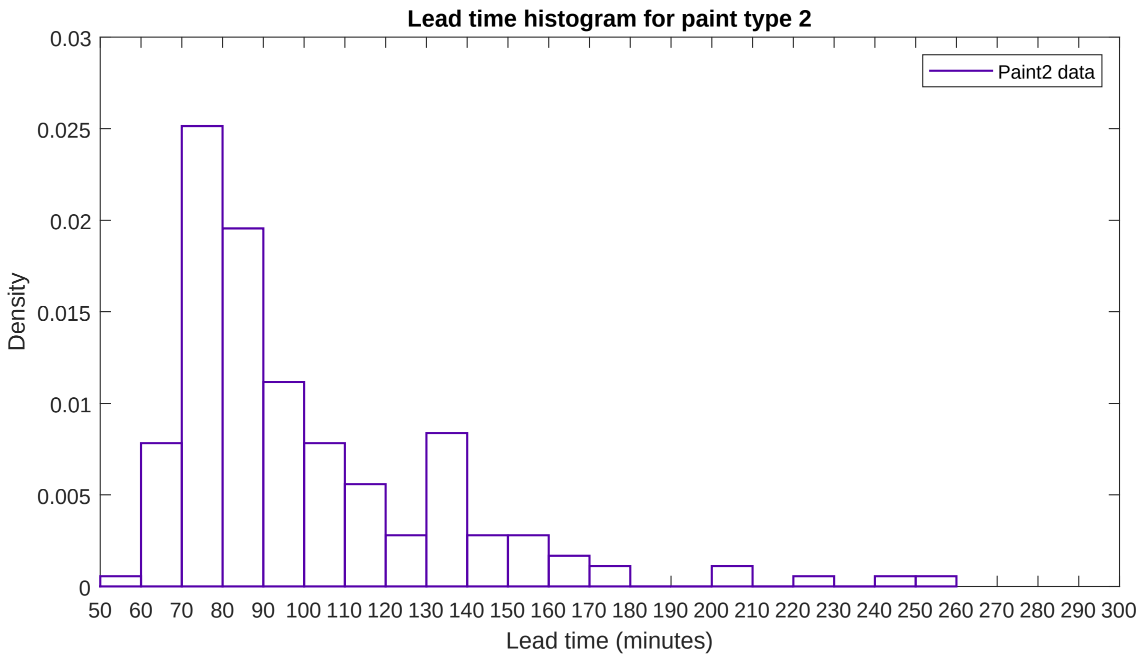

Figure 8.20: Histogram of lead time in sensor data for paint type 2

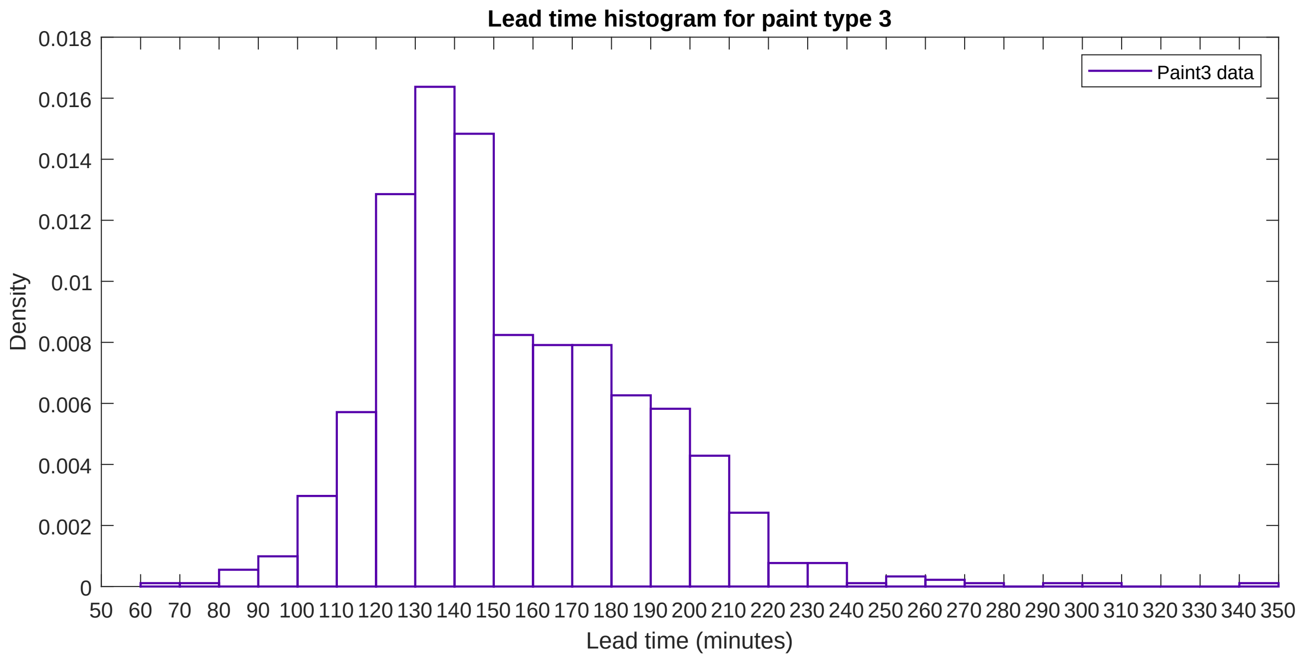

Figure 8.21: Histogram of lead time in sensor data for paint type 3

8.4 Buffer load plots

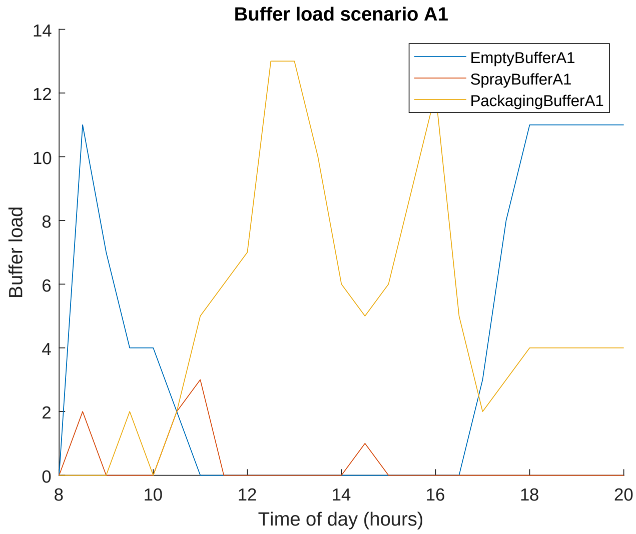

Figure 8.22: Model output buffer load scenario A1

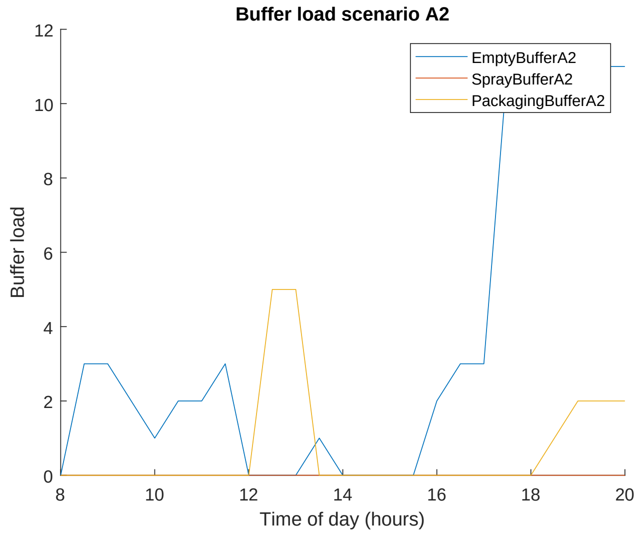

Figure 8.23: Model output buffer load scenario A2

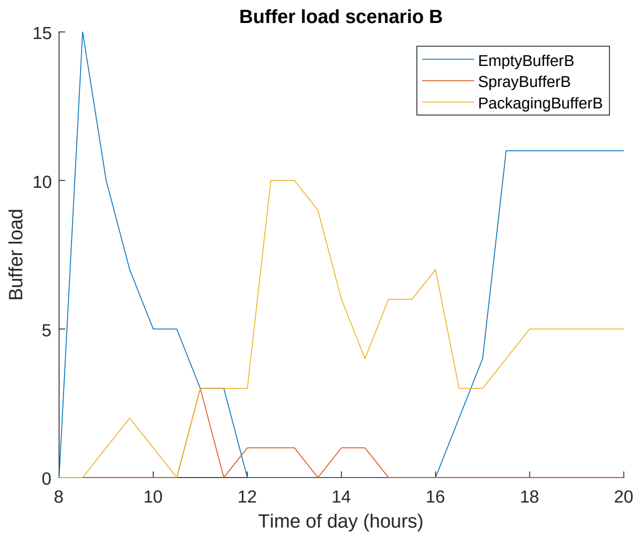

Figure 8.24: Model output buffer load scenario B

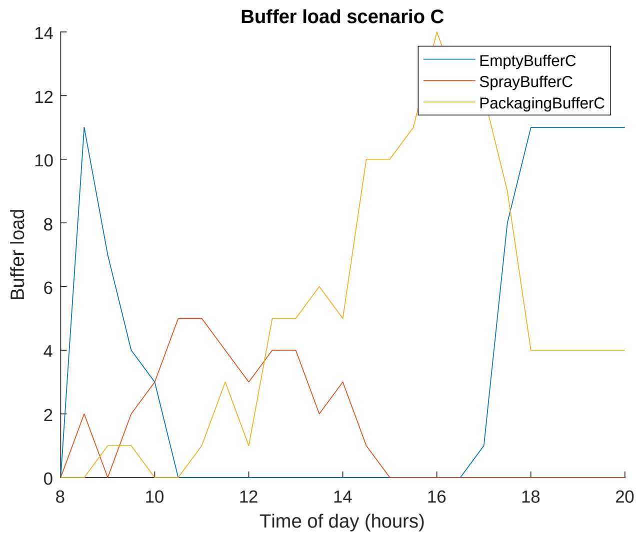

Figure 8.25: Model output buffer load scenario C

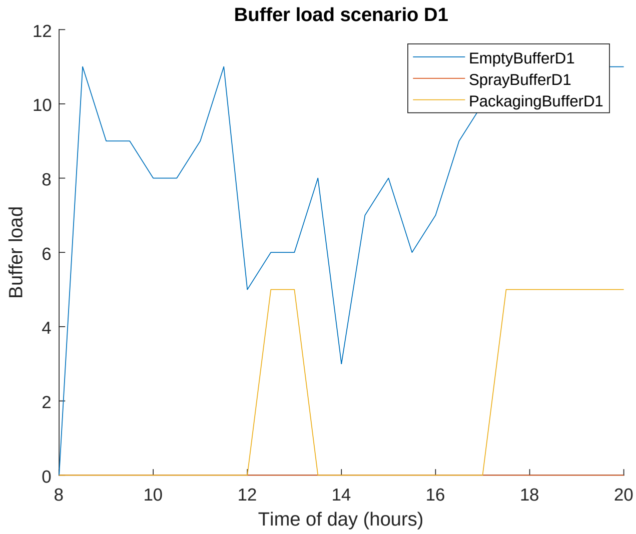

Figure 8.26: Model output buffer load scenario D1

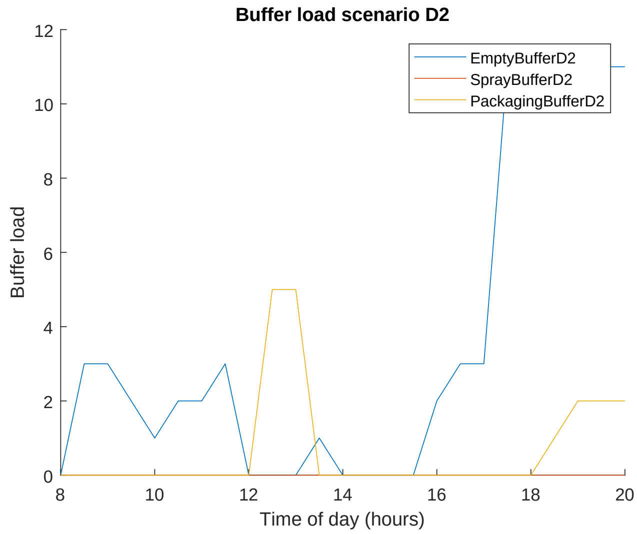

Figure 8.27: Model output buffer load scenario D2

8.5 Value stream map

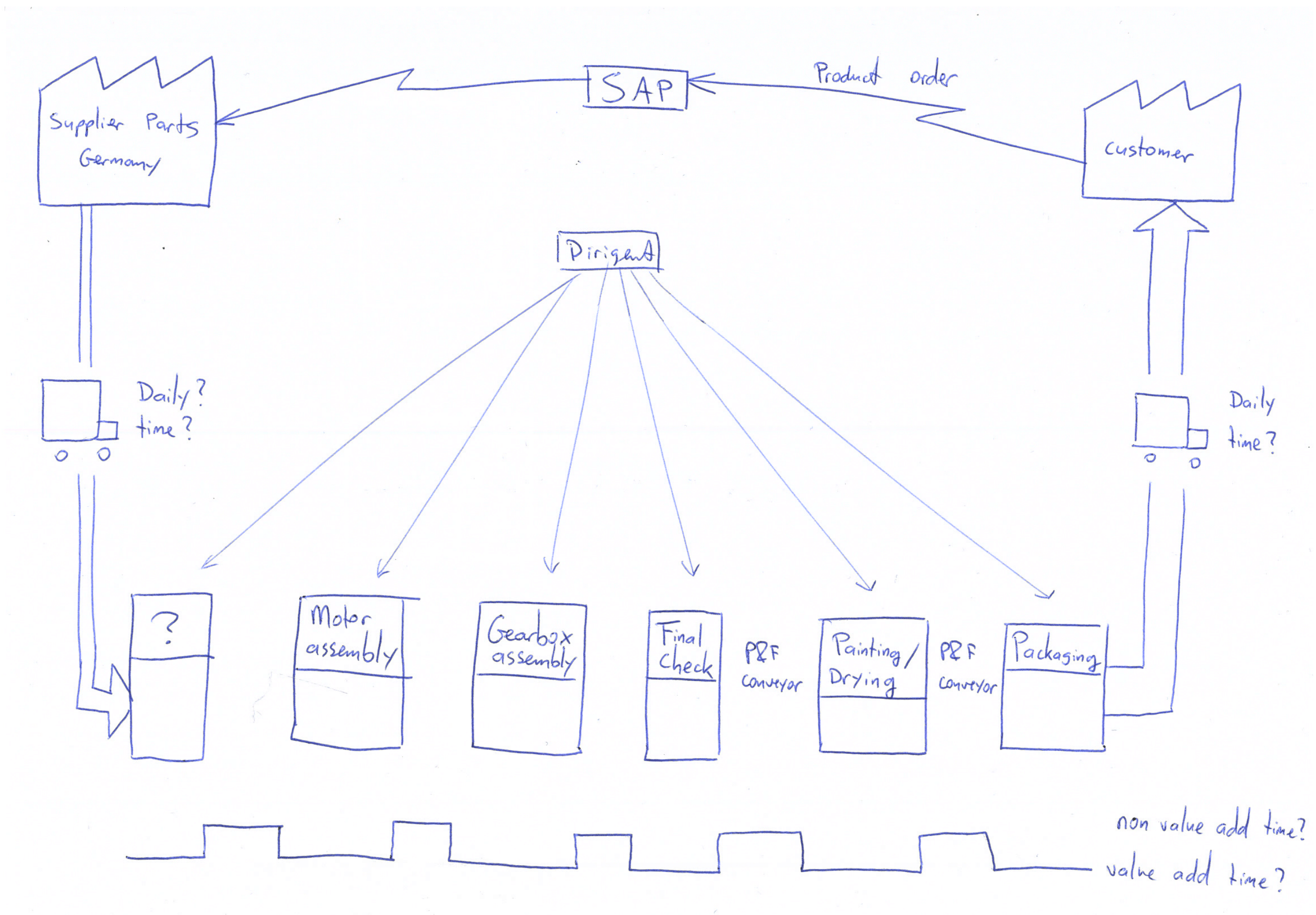

Figure 8.28: First sketch of a value stream map of the process. Question marks indicate this data is not known yet