2019

DEVELOPMENT OF AN RFID-ENABLED SERIAL KANBAN PRODUCTION SYSTEM WITH REAL TIME ORDER SCHEDULING

Kian M. Asgari
University of Rhode Island, kasgari@my.uri.edu

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DEVELOPMENT OF AN RFID-ENABLED SERIAL KANBAN
PRODUCTION SYSTEM WITH REAL TIME ORDER SCHEDULING

BY

KIAN M ASGARI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

SYSTEMS ENGINEERING

UNIVERSITY OF RHODE ISLAND

2019

MASTER OF SCIENCE
OF
KIAN M ASGARI

APPROVED:

Thesis Committee:

Major Professor Manbir S Sodhi

Valerie Maier-Speredelozzi

Paolo Stegagno

Nasser H. Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2019

ABSTRACT

Today's dilemma of realizing an efficient production schedule, minimizing downtime of a production system, and work overload for the production workers concerns almost every profit-oriented organization. Nowadays, manufacturers are faced with the challenge of providing a rich product variety at a low-cost level. Most companies have reacted to these disruptive changes by increasing internal flexibility and accelerating business processes. The growing penetration of advanced planning and scheduling systems, as well as the use of innovative and smart technology, promises synergy effects of combining physical and computational aspects of a manufacturing system.

This paper proposes a cyber-physical production system utilizing the communication technology of Radio Frequency Identification. Moreover, the philosophy of lean manufacturing is examined. The traditional Kanban concept, which is an essential part of a Just-in-time production, implies desirable characteristics enabling lean production. These assets are considered in the development of a flow shop production scenario. As a significant part of research in job scheduling, the particular problem of non-permutation flow shop scheduling is examined and applied to the scenario. With Radio Frequency Identification as an enabler of real-time information availability and the exploitation of valuable characteristics of a Kanban system, a mixed integer program is applied to use the bundled data and allow the generation of knowledge to install a production steering mechanism.

The efficient assignment of n jobs to m machines is a complex and widely discussed topic. As an essential part of a complete cyber-physical production system,

feedback loops improve the system's capacity to act in challenging situations such as machine delays or undesired machine idle time. At that, the technical enrichment through Radio Frequency Identification technology as well as the consideration of lean aspects deriving from the original Kanban philosophy, enable a flexible reschedule of the flow shop sequence in order to optimize the makespan of the production system proposed. This study conducts a simulation of several situation-based schemes and compares the efficiency between a reschedule with or without the integration of a flexible, real-time enabled feedback loop.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my Major Professor and advisor Prof. Dr. Manbir Sodhi for his tremendous support throughout my academic development at the University of Rhode Island. His strong dedication to our common research field and his academic guidance paved the way to reach my goal successfully.

Furthermore, I would like to acknowledge the Technical University Braunschweig and in specific Prof. Dr. Thomas Spengler who initially established the academic exchange and cooperation between the German and the American university and still contributes to this friendship with much effort.

Special thanks go to Prof. Dr. Valerie Maier-Speredelozzi and Prof. Dr. Paolo Stegagno who not only completed my Master's Committee but also contributed with their advice to my project.

My sincere thanks also go to my fellow researchers at the department, in particular Marwan Abdelatti and Mohsen Mosayebi, who supported me with their scientific knowledge and personal advice.

This project advances the idea and the technological apparatus developed by undergraduate students at the University of Rhode Island. Hence, I would like to thank Ryan Brown and Dallas Cottrell for their substantial design contributions.

Finally, I must express my profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. *Vielen Dank für Eure Liebe und Unterstützung.*

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LIST OF ABBREVIATIONS

CPS	Cyber-physical system
CPPS	Cyber-physical production system
CPU	Central processing unit
EPC	Electronic product code
EPCIS	Electronic product code information services
ERP	Enterprise Resource Planning
FCFS	First come first served
FSSP	Flow shop scheduling problem
GAMS	General Algebraic Modeling System
GPIO	General-purpose Input/ Output
GS1	Global Standards One
HF	High frequency
IEC	International Electrotechnical Commission
IMS	Intelligent manufacturing system
ISO	International Organization for Standardization
JIT	Just-in-time
LF	Low frequency
MES	Manufacturing Execution System
MIP	Mixed integer program
NFC	Near field communication
OR	Operations research
RF	Radio frequency

RFID	Radio frequency identification
SHF	Super-high frequency
TCP/IP	Transmission Control Protocol/Internet Protocol
TPS	Toyota Production System
UHF	Ultra-high frequency
VSWR	Voltage standing wave ratio
WIP	Work-in-progress

CHAPTER 1 - INTRODUCTION

1.1 Motivation

The highly competitive nature of today's business environment forces manufacturers to introduce smart technology to their production systems to enhance the overall efficiency and competitiveness. At the same time, customer requirements in terms of individualization and technical functionalities of products increase significantly and require flexible manufacturing systems in practice. Often, mixed-model assembly lines are employed to enable a highly diversified product portfolio without jeopardizing the benefit of an efficient flow-production (Boysen et al., 2009; Monostori, 2014). This mass-customized production concept leads to high complexity and uncertainty, especially on a shop floor level (Zhong et al., 2013).

In addition to implementing a strong customer orientation towards mass customization, today's production logistics also focus on diminishing costs by maintaining minimum inventory levels and highly utilizing given capacities (Nyhuis and Wiendahl, 2008). The degree of machine utilization, for example, ought to be maximized. Ruifeng and Subramaniam (2012) even consider the production rate of manufacturing companies (i.e., the ratio of produced units per given time) as a key performance indicator of competitiveness in the global marketplace. While products nowadays can barely be distinguished in price and quality, companies are advised to differentiate themselves from competitors through strong production logistics performance (Seitz and Nyhuis, 2015).

The lean management movement, initially driven by the development of the

Toyota Production System (TPS) in the 1960s by Japanese engineers, has contributed to a substantial shift towards highly efficient production systems. To accomplish a smooth operation of a sophisticated, efficient, and flexible production system, a thorough planning strategy is essential. An approach may be supported by smart technology brought up by the Fourth Industrial Revolution “Industry 4.0”. At this juncture, the traditional and still effective methods of realizing a Just-in-time (JIT) production through utilizing tools, such as the concept of Kanban, combined with highly innovative connected technology, appears to be promising (Monden, 2011).

McKinsey Digital (2016) found out that 90% of companies from the U.S., Germany, and Japan, who participated in a survey in 2016, believe that with Industry 4.0 their competitiveness will either increase or at least stay the same. About 89% expect Industry 4.0 to impact their operational effectiveness. The enormous potential of technological advancements in this area can certainly not be disclaimed and therefore justifies the research in this discipline. Seitz and Nyhuis (2015) claim that not only production planning but also production control needs to become more transparent and efficient through the use of technology. While the term Industry 4.0 has been around for more than a decade, assembled manufacturing lines still lack integration of smart and adaptable manufacturing execution systems (MESs). The emergence of Radio Frequency Identification (RFID) technology conveys a utilization with manufacturing systems to achieve a lean manufacturing environment along the lines of Ohno’s TPS.

The rise of cyber-physical systems (CPSs), as a general term for a system that combines computational and physical capabilities, suggests the application of such manufacturing environments to fulfill increasingly challenging requirements. The

configuration of these systems with smart and self-configurable control features through intelligent algorithm implementation advances manufacturing systems along with established concepts. The intelligent manufacturing system (IMS) is considered to be the next-generation manufacturing system and is obtained by adopting new models, forms, and methodologies to transform a traditional manufacturing system into a smart system (Zhong et al., 2017).

Several intricate Operations Research (OR) problems are related to flexible manufacturing systems on which researchers and practitioners must focus in order to exploit the potential of a manufacturing system fully. Stecke (1985) identifies planning, scheduling, and control problems in association with flexible manufacturing systems. While scheduling literature had been concerned with fixed schedule specifying, Stecke (1985) emphasizes the possible advantages of a real-time online scheduling policy.

In the research field of flow shop scheduling, the efficient arrangement of jobs on available machines within a production line lies in the focus of interest. The discipline of flow shop scheduling offers a broad range of different problems which have been thoroughly examined in the literature during the last seven decades. Most recently and related to Industry 4.0, the non-permutation flow shop scheduling problem (FSSP) has gained interest. In this problem scenario, the sequence of job assignments to machines can vary. At that, the deployment of supporting technology delivers an additional surplus for manufacturers to successfully overcome the challenge of dynamically balancing mass production and the maximization of profits by eliminating all kinds of waste in production.

1.2 Research objectives

The main objective of this research paper is to systematically develop an integrative CPS which builds upon the principles of the traditional production and inventory information system Kanban. RFID technology provides a technical fundament for advancing the original production philosophy. As a part of lean management and a strategic tool to accomplish JIT production, the concept of Kanban is aimed to be complemented by RFID technology. In so doing, major practices and principles of the original Kanban idea are enhanced by technology, which results in an improved electronic Kanban approach. The principles of the traditional Kanban system shall be considered to achieve a lean manufacturing setting. By applying an RFID-based tracking setup on a fictional production scenario, the developed system is supposed to generate meaningful information about the flow of objects.

The availability of real-time information about the status of work-in-progress (WIP) objects benefits the transparency of the production system and enables a highly flexible control opportunity for manufacturers. At that point, this study aims to integrate a third, cognitive dimension. The discipline of flow shop scheduling offers a range of different scenarios and mathematical programs to efficiently assign jobs to machines in a production system. This project aims to formulate an algorithm to continuously improve the job-machine assignment in a flow shop environment with the use of real-time data. The efficiency is to be proven in a scenario-based comparison. In an ultimate perspective on the developed system, three different dimensions shall contribute to an enhanced CPS. The technical dimension enables real-time information through RFID utilization, the lean dimension deploys some principles of Kanban as a production

management information system, and the scheduling dimension utilizes real-time data and increases the overall production system efficiency through the application of an iteratively operable scheduling algorithm.

1.3 Research structure

This study is structured as follows: Chapter 1 outlines the relevance and motivation to pursue this research project. The objectives of the study, as well as the structure, are briefly outlined.

Since the overall objective of this study has been formulated as the development of an integrative CPS, the research field of this discipline that has gained interest during Industry 4.0 is examined. Chapter 2 furthermore comprises a comprehensive literature review and state-of-the-art analysis of RFID technology. This review is followed by the exploration of the traditional Kanban concept as a major practice in lean manufacturing. The view on the Kanban philosophy includes a historical perspective, definitions as well as assets and drawbacks. The next subchapter introduces the general FSSP and classifies it within the discipline of scheduling problems in the field of OR. A generally standardized notation is briefly outlined, and the difference between a deterministic and stochastic approach is clarified.

Chapter 3 holds methodical references. A frequently cited, generic framework of how to design a CPS is introduced which shall structure the system design. This step-by-step guideline is supposed to be fundamental to the overall system development. The methodology furthermore includes remarks about the physical setup scenario that is considered in this study. This scenario brings forth several requirements which are

further described in Chapter 3.3. At this point the latest, it becomes clear that the CPS comprises three different dimensions which contribute to the integrative production system. The requirements concerning the technological, lean, and scheduling dimension are outlined.

The five different steps of the 5C architecture structure the main section of this study in Chapter 4. In the smart connection level, the technical specifications and the precise system layout are described. In the data-to-information conversion level, the needed software application is introduced; a technical data transfer technique is presented. The cyber level is the heart of a CPS and therefore linked to the Kanban practices which constitute the processual framework. The overall functionality related to the lean dimension lays in the focus of that section. In the cognition level, the scheduling algorithm is developed as well as simulated with a specific algorithmic software. The results are demonstrated. The configuration level creates a self-configuration dimension and aims to prove that the developed algorithm is capable of handling real-time data for optimization purposes.

In the final conclusion, implications for practice and research are drawn, the major limitations to this project are made and an outlook gives insight about future challenges and possible further research questions related to this topic.

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Cyber-physical systems

CPSs are expected to transform the operation and role of existing industrial systems (Lu, 2017). The main characteristic of a CPS is the integration of computation with physical processes (Lee, 2008). Baheti and Gill (2011) refer to the term as a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. Rajkumar et al. (2010) describe CPS as physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core.

Author(s), Year	Definition of CPS
Lee (2008)	“Cyber-physical systems are integrations of computation with physical processes.”
Baheti and Gill (2011)	“The term cyber-physical systems refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities.”
Rajkumar et al. (2010)	“Cyber-physical systems are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.”
Lee et al. (2015)	“Cyber-physical systems is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities.”

Table 1. Definitions of CPS

Table 1 lists definitions that have been frequently cited within the last eleven years. It can be noted that the main functionality of a CPS derives from the ability to

interact with and expand capabilities of the physical world through computation, communication, and control.

In practice, many companies consider making use of advanced technology in order to enhance either their product or production facilities' reliability. The potential is proven. Embedded systems have always been held to a higher reliability and predictability standard than general-purpose computing (Lee, 2008). Consumers expect their products to be highly reliable in terms of technological aspects. The same applies to manufacturers and their production systems. Above that, Lee (2008) assumes that within the transition towards CPSs, the reliability of such systems will only increase in the future.

Figure 1. Connected enterprise market revenues in the U.S. from 2014 to 2025 (Grand View Research, 2016)

Figure 1 emphasizes the enormous financial potential of connected technology for enterprises in the U.S. market. The revenues generated from connected technology sales for commercial purposes have increased steadily and are forecasted to grow exponentially in the next five years to come. The revenues from connected technology are anticipated to exceed the 400 billion U.S. dollar mark before the year 2025.

As a significant part of the Horizon 2020 program initiated by the U.S. and European research council, CPSs are a national research priority and expected to elevate the innovations in various sectors such as automotive, civil, medical and manufacturing (Gill, 2008). Especially in manufacturing terms, the systematic implementation of CPSs may bring intelligence into shop floors and provide factories with continuous production and almost non-existent downtime (Bagheri et al., 2015).

The term CPS is further narrowed down in terms of the application situation. A CPS that is applied in a production facility can generally be referred to as cyber-physical production system (CPPS). This sub-category of CPSs consists of autonomous and cooperative elements and sub-systems that get into connection with each other in situation-dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks (Monostori, 2014).

2.2 RFID technology

The examination of potential support technology to enrich a CPPS with the technical capabilities that are just right for the purpose of the system is of high relevance. When suitable information system architectures are provided with data on uniquely identified products, visibility of operations can be increased by associating products with their current location, condition, and history (Brintrup et al., 2010). RFID technology has been utilized in a variety of manufacturing-related applications in production automation and inventory management. The following section investigates the state-of-the-art RFID technology for industrial application and gives examples for specific technical devices that are commonly used in the industry. The issue of standardization is introduced, and several norms are briefly outlined. Lastly, the advantages and disadvantages concerning the manufactural use of RFID technology are described.

2.2.1 Definition and technical specifications

RFID technology can be defined as a wireless technology which utilizes radio waves to transfer data between active, passive, or semi-passive tags and readers without requiring direct contact or a line of sight (Tang et al., 2015; Zhang et al., 2008). RFID technology ranges over a broad frequency bandwidth, which results in different types of RFID operating modes, which are summarized in Table 2. The operating frequency band, the usual read and write range and data transfer rate, as well as typical applications or use cases, are described. The low frequency (LF), high frequency (HF), ultra-high frequency (UHF), and super-high frequency (SHF) bandwidths are examined.

Band (MHz)	Typical operating range	Typical industrial and commercial application	Data transfer rate
0.125 – 0.134 LF	Contact – 10cm	Pet tagging, Livestock identification, Access control, Car Key-Fob	Low read speed
13.56 HF	Near contact – 20cm	Smart cards, Mobile payments, Item or case level tagging	Medium read speed
860- 960 UHF	Near contact – 30m	Supply chain management, Race timing, Inventory tracking	High read speed
2,450 SHF	Near contact – 100m	Auto toll roads, Container rail car, Pallet level tracking	High read speed

Table 2. Different types of RFID technologies (AtlasRFIDstore, 2019a)

Due to the study's objective to develop a CPPS with a technologically advanced support system in a manufacturing environment, the technical specifications lead inevitably to UHF RFID technology as an appropriate choice. This type of RFID is thus explained in detail.

UHF RFID systems generally consist of three main components: RFID tag, RFID reader, and a host data processing system (Huang et al., 2011). Due to the variety and complexity of today's RFID antenna configurations, this study considers the antenna itself, which usually is an external component of the RFID reader, as an additional component. This results in four -instead of three- main components comprising an RFID system:

(1) UHF RFID tags

First, RFID tags of different types take on an essential role in an RFID system. There has been intensive development in the industry during recent years. The choice of an appropriate type of RFID tag for situational circumstances is a challenge for

system designers. In general, there are three main categories to be considered: Active tags, passive tags, and semi-passive tags (Choy et al., 2017). Tags are tiny electronic circuits which hold an electronic product code (EPC) as well as other information, that can be communicated between the reading device and the tag (Huang et al., 2011).

Figure 2. Omni-ID Power 400 Active RFID tag (Omni-ID, 2019)

Figure 2 displays an active RFID tag manufactured by Omni-ID. This type of tag holds an active power source such as a battery inside the rubber case. The battery supplies the microchip with external power and actively triggers communication between the tag and the reader. Thus, active tags can provide a higher range regarding communication with the reader than passive tags (Ni et al., 2003). In addition, this type of tag usually offers higher durability due to the isolation material, which protects the power supplying battery technology and transceiver around the circuit.

Figure 3. Passive RFID tag “ALN-9835 Express” (Alien Technology, 2019)

Figure 3 shows a typical design of a passive RFID tag manufactured by Alien Technology. This type of RFID tag does not have an on-tag power source or on-tag transmitter (Mehta, 2011). These tags reflect the signal received through the radio waves from the reader and add information by modulating the reflected signal (Ni et al., 2003). The RFID reader sends out radio frequency (RF) energy in attempt to read tags within the range of the RFID antenna.

The tag antenna is set to receive the energy transferred through radio waves. The so-called bridge rectifier charges a capacitor using the RF energy that the tag's antenna receives so that a voltage source is generated. As soon as enough energy is available to operate the internal circuitry of the chip, the tag starts to perform the demodulation and processes the commands received from the reader (Deavours, 2005).

Figure 4. Semi-passive RFID tag A927Z (CAEN RFID, 2019)

Semi-passive RFID tags can be classified as a hybrid solution between passive and active RFID tags. Both active and semi-passive RFID tags use internal batteries to supply power for their circuits. While an active tag also uses its battery to broadcast radio waves directly to the reader, a semi-passive tag relies on the reader to supply its

power for broadcasting. Figure 4 displays a semi-passive RFID tag manufactured by CAEN RFID.

The main difference between an active and semi-passive RFID tag is the signal transmitted by backscattering the carrier wave from the reader with a semi-passive tag (Mehta, 2011). An active tag -on the other hand- actively communicates with the reader and might also continuously broadcast a signal. That means the semi-passive tag remains in a dormant status until an RFID reader sends an energizing signal. The sensor, which is run by its own power supply, operates the circuitry and allows more RF energy from the reader antenna to be reflected back to the interrogator (Roberti, 2011).

(2) RFID reader

Second, a reading device which reads and/or writes data from and/or to RFID tags is required, which transfers data to a processing device discussed in (4). An RFID reader usually includes a module consisting of a transmitter and receiver, a control unit and a coupling element functioning as the RFID antenna which is further explained in (3) (Mehta, 2011). In an RFID system, the reader emits the signal through the antenna by a querying signal with enough power to activate a passive tag's application-specific integrated circuit (Chen et al., 2009). If the tag is located in the reading zone of the antenna, the tag is activated and interrogated for its content information by the reader. An example for an RFID reader device is the Invengo XC-RF861 RAIN RFID Reader which operates with the EPC global UHF Class 1Gen2 protocol and global frequency ranges from 840 to 960 MHz. Figure 5 displays the XC-RF861 RAIN Reader manufactured by Invengo.

Figure 5. Invengo XC-RF861 RAIN RFID Reader (Invengo, 2019a)

Especially the specification adhered to the RAIN standardization connotes a broad possible field of application. The norm is outlined in the next sub-section further below.

(3) RFID antenna

Unlike usual approaches in the literature, this study considers the RFID antenna as a component in addition to the RFID reader. Reader antennas in inductively coupled UHF RFID systems generate magnetic flux, which in the end powers the tag and enables the communication between the reader and the tag (Kim and Chong, 2008). Antennas can differ in their operating frequency, voltage standing wave ratio (VSWR), and gain value. Another main distinguishing feature is the polarization. The high-performance RFID antennas XC-AF12 manufactured by Invengo and ANT85C7070 built by Identix exemplify the various alternatives that are available in the global market. These two types of antennas are virtually predestined to further explain the differences between the global operating frequencies. Figure 6 displays both antennas.

Figure 6. High-performance RFID antennas (Invengo, 2019b; Identix, 2019)

Amongst other specifications, the Invengo XC-AF12 UHF RFID antenna is characterized by an adjustable operating frequency from 840 to 868 and 902 to 928 MHz and therefore covers all global frequency regulations (Invengo, 2019b). Thus, the antenna can be used all over the world without any restrictions.

The Identix-ANT85C7070 is a UHF RFID antenna of a similar type but only provides an operating frequency between the bandwidth of 900 – 928 MHz, which means it can only be employed in selected countries such as Argentina, Australia, Brazil, Canada, China, Indonesia, Israel, Japan, Russia, and the U.S. (Global Standards One, 2019). The global, neutral, non-profit standards organization Global Standards One (GS1) regularly publishes a complete list of the countries' regulatory status for using RFID in the EPC Gen2 band of the UHF spectrum.

Both RFID antennas are referred to as circular polarized far-field antennas. Their radiation pattern is described similarly by the manufacturers and can be modeled as shown in Figure 7. Figure 32 in Appendix A displays a comparison of the radiation patterns of linear polarized and circular polarized RFID antennas. The best choice in terms of the radiation pattern is dependent on the desired application of the system.

Figure 7. Radiation pattern of circular polarized far-field antennas (Identix, 2019)

A further detail that has to be taken into account when assessing a UHF RFID antenna is the gain value of the receiver which is measured in dBi (i.e., decibels relative to a dipole antenna). The key performance indicator generally describes how well the antenna converts input power into radio waves headed in a specified direction. Both the Invengo XC-AF12 (7.15 dBi) and the Identix ANT85C7070 are considered as high gain RFID antennas (8.5 dBi). The parameter VSWR is a measure that numerically describes how well the antenna is impedance matched to the radio or transmission line to which it is connected. In this case, the VSWR is the same for both antennas with a ratio of less than 1.4:1 across all frequency band.

(4) Host data processing system

A host system bundles the reader's output data and compares it with the information saved in the network. This backend IT-system transforms data and converts it into meaningful information which may be observed by workforce and therefore serves occasionally as a frontend system at the same time (Tang et al., 2015). The

majority of RFID readers come with their own software to visualize read data on a computer screen in real-time. In general, any computer can process the readers' output but must feature a suitable connector interface as well as the capability to run the readers' software application. The more data has to be processed, the better the computing performance should be in order to handle reliable data flow.

The information gained from the processing system is often further transferred to a business software application such as an enterprise resource planning (ERP) system to automatically benefit from the accurate information (Lu et al., 2006). Lee and Kim (2006) investigate parameters, design, implementation, and features of so-called RFID middleware, which is further defined as the product that processes RFID tag data to related technology.

EPCglobal is a GS1 initiative to innovate and develop industry-driven standards for the EPC to support the use of RFID and allow global visibility of items (Electronic Product Code Information Services; short: EPCIS) in today's fast-moving, information-rich, trading networks (Global Standards One, 2019).

The initiative, supported by industry leaders such as Walmart, Cisco, Procter & Gamble, and Hewlett-Packard (Baudin and Rao, 2005), accomplished a regulation that has been instituted in a norm by the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC). The ISO/IEC 15961:2019 and 15962:2019 standardizes the data protocol for the item management in RFID applications. More detailed information can be extracted from Table 3.

ISO/IEC 15961-1	defines the transfer of data to and from the application, supported by appropriate application commands and responses
ISO/IEC 15961-2	defines the registration procedure of RFID data constructs to ensure that the protocol supports new applications
ISO/IEC 15961-3	defines the data constructs and the rules that govern their use
ISO/IEC 15961-4	defines the transfer of data associated with sensors and batteries to and from the application, supported by appropriate application commands and responses
ISO/IEC 15962	specifies the overall process and the methodologies developed to format the application data into a structure to store on the RFID tag

Table 3. ISO/IEC standardization of the data protocol for RFID

A frequently used variable method is to transfer the reading data directly to the TCP/IP port of a computing device which enables other software or clients to access the data (Lee and Kim, 2006). The receiving module allows to listen to the read data stream from the middleware and can, therefore, capture real-time data.

The industry alliance RAIN RFID follows the mission to enable businesses and consumers to identify, authenticate, and engage items in their everyday world (Rainrfid.org, 2019). Today, around 160 manufacturers have become members of the alliance to promote the universal adoption of the GS1 UHF Class 1Gen2 protocol as a component of UHF RFID technology which is standardized in ISO/IEC 18000:63. The global alliance intends to function as a facilitator of standardization to overcome technical barriers which impede the establishment of RFID technology. The acronym RAIN, derived from Radio frequency IdentificationN, alludes to the link between UHF RFID and cloud solutions. Figure 8 briefly sketches the approach of RAIN-standardized RFID technology.

Figure 8. Functionality of RAIN UHF RFID technology (Rainrfid.org, 2019)

2.2.2 Advantages and disadvantages

RFID technology offers several contributions not only to supply chains but also to production lines in manufacturing environments. Brewer et al. (1999) discover major benefits of implementing such systems for industrial purposes at an early stage. It is possible to identify objects over a certain distance in a continuous or intermittent manner. The distance depends on the type of RFID technology used. Real-time control for monitoring or steering purposes is viable, which opens up new opportunities in terms of planning and scheduling of a system that implies a flow of objects (Lu et al., 2006). Furthermore, RFID tags, as well as the other components to some extent, can operate in rough and harsh environments and will not fade over time like visual symbologies such as barcodes. The advanced properties enable unique identification of objects, easiness

of communication and real-time generation and processing of data and information (Chen et al. 2013). The uniqueness of the EPC can ameliorate the traceability and visibility of objects in an entire supply chain, which leads to sped up operational processes, leading to advanced inventory flows and more transparent information.

Smith-Ditizio and Smith (2018) specify more advantages. The speed of the communication system is one. The reading time is indeed highly dependent on the RFID system used, however, it can be stated that readers can process each tag's individual response in rapid succession. Hence, thousands of reading operations can be performed within one second, which outrivals other technologies such as barcoding where one-by-one scanning applies.

Moreover, reading information over a certain distance without the requirement of being in the direct line of sight constitutes one of the main assets of an RFID system (Baudin and Rao, 2005; Huang et al., 2011; Seol et al., 2017; Tang et al., 2015). The nature of the tag's circuit and microchip enables reliable storing of accurate data which can be highly beneficial in the application of the RFID system (Chen et al., 2013).

RFID technology offers enormous potential advantages, but several drawbacks cannot be neglected. The systems often do not hold up to the standards which are communicated by the manufacturers; parameters deviate from promised performances. Uncontrollable interferences in the environment and unforeseen reflections negatively affect the system's reliability and overall performance (Lu et al., 2006). Kim et al. (2008) identify three different types of interference in RFID systems: tag interference, multiple reader-to-tag interference, and reader-to-reader interference.

Tag interference arises when multiple tags are simultaneously powered by the

reader's outgoing radio waves and reflect their respective signals to the reader. The mixture of scattered waves might result in an issue where the reader cannot differentiate individual EPCs. Anti-collision mechanisms are needed to solve this interference (Kim et al., 2008).

Multiple reader-to-tag interference occurs when a passive tag is located at an intersection of at least two reader interrogation areas. If communication signals are sent out from more than one reader, the receiving tag might behave in an undesirable manner.

Lastly, reader-to-reader interference happens when a signal from one reader reaches other readers. Signals transmitted from distant readers can be strong enough to impede accurate decoding of the signals back-scattered from the tags. Thus, reader-to-reader interference can cause severe problems in RFID system deployment (Kim et al., 2008).

Another issue is related to the standardization of parameters. A range of RFID application numbering systems exist, and it lacks globally agreed frequencies for RFID operations. Only Near Field Communication (NFC) is standardized to a worldwide operating frequency of 13.56 MHz. The frequencies for UHF RFID applications differ from 860 - 868 MHz in Europe, Africa, and large parts of Asia to 902 – 928 MHz in North America, China, Australia and large parts of South America (Smiley, 2014). These differences might limit the functionality of an internationally operating supply chain and must be considered in system development. (Lu et al., 2006).

2.3 The Kanban system

Lean thinking and practice can be seen as the most successful approach to business improvement of the last century, suggesting that it has excelled many other improvement approaches (Jones and Womack, 2017). The Kanban concept is part of the unique TPS and incorporates principles that aim at simplifying and enhancing production processes (Sugimori et al., 1977). To understand the value of the system, its roots give insight into the intentions of this concept.

The central aspect that corresponds to the principles of Kanban is the reduction of cost through elimination of waste. The major values and principles of the concept explain the capabilities of cutting cost through the removal of any type of waste. The goal of the TPS is to make products in the most efficient way to reach the ultimate goal of maximizing profit. Despite the strong relation of the production concept towards the automotive industry, the TPS philosophy has revolutionized the perspective of manufacturing on shop-floor bases for many industrial companies (Thun et al., 2010).

2.3.1 Definition and history of Kanban

The Kanban concept, developed by Taiichi Ohno in the 1950s and 1960s, is an information system that helps to control the production of the necessary products in the necessary quantities at the necessary time. This approach is known as JIT production (Powell, 2018) and the production concept of Kanban. A large number of reports in the literature describe the Kanban system as a means to accomplish lean production as part of the TPS (Ohno, 1988). According to Monden (2011), the concept of Kanban is regarded as a subsystem of the TPS enabling lean production. The traditional Kanban

system can be described as the production control information system that was developed to achieve JIT production. To avoid inventory unbalance and surplus equipment and workers, there is a necessity of adjustable schemes to conform to changes due to disruptions and demand fluctuations (Sugimori et al., 1977). The concept is characterized by the aspect of JIT production and therefore maintains only a small number of products or parts in line and in each buffer.

Today, Kanban is the manufacturing system of choice in many companies (Ruifeng and Subramaniam, 2012). System designers have developed individualized versions of the Kanban system to support their specific operations and management principles (Lage Junior and Filho, 2010; Kouri et al., 2008).

2.3.2 Functionality of Kanban

Graves et al. (1995) define Kanban as a material flow control mechanism which controls the proper quantity and proper time of the production of demanded products. In the traditional Kanban system, the type and amount of units needed are written or printed on a tag-like card referred to as Kanban, which is Japanese for “visual sign”. Figure 9 demonstrates a typical design of a Kanban card, which also includes barcodes as visual aids in this example.

Figure 9. Example of Kanban card (Kanbanize, 2019)

The Kanban cards are used on a pull principle. Workers of one process send cards to the workers of the preceding process indicating the demand for a particular material, product or process. This results in a connected network of operations throughout the whole production system, where processes are triggered by the use of visual signs (Monden, 2011). The concept enables better control of quantities needed for the products to be produced in the manufacturing system.

Figure 10. Framework of the main types of Kanban (Monden, 2011)

Figure 10 specifies the two main types of Kanban: a withdrawal Kanban and a production-ordering (or in-process) Kanban. The withdrawal Kanban holds information about the type and quantity of a product which the subsequent process should withdraw from the preceding process. The production-ordering Kanban determines the kind and quantity of the product which the preceding process is supposed to produce and provide (Monden, 2011). These two kinds of Kanban cards are directly attached to objects or

containers holding parts. When contents of a container begin to be used, withdrawal Kanban cards are removed from the container and the operator takes the cards to the stock point of the preceding process to pick up the parts. The withdrawal Kanban cards must be attached to the part or container holding the parts. Then the production-ordering Kanban card attached to the container is removed and becomes dispatching information for the process. Thus, the production activities of the final assembly line are interlinked between the preceding and subsequent processes (or even subcontractors) and materialize the JIT production (Sugimori et al., 1977).

There are six general principles of Kanban incorporated in subsystems of the concept (Kouri et al., 2008): Production smoothing, standardization of jobs, reduction of setup time, improvement activities, design of machine layout and automation. These principles constitute the backbone of developing a lean manufacturing environment.

As one of the most visible parts of a JIT production system, there are also six general practices which define essential activities for the executives managing the Kanban system (Anderson and Carmichael, 2016):

1. Visualize
2. Limit WIP
3. Manage flow
4. Make policies explicit
5. Implement feedback loops
6. Improve collaboratively, evolve experimentally.

2.3.3 Efficiencies and inefficiencies of Kanban systems

The overall asset obtained from applying the traditional Kanban system is the “reduction of cost through the elimination of waste” (Sugimori et al., 1977). Using the concepts of the TPS, including the Kanban system, companies can eliminate waste, produce efficiently, and gain a competitive advantage (Thun et al., 2010). The principles and practices outlined before help to accomplish those goals.

The pull production system controlled by Kanban cards has many advantages over push controlled systems (Kouri et al., 2008). The system is easy to use, highly visible, it links production operations tightly, eases quality management, and is cheap to adopt. Thun et al. (2010) ascertain that triggering production by Kanban cards automatically eliminates early or late production. In so doing, this simple steering mechanism does not need complex and costly computer support systems and automatically avoids the bureaucratic procedures related to a push production system (Sugimori et al., 1977; Thun et al., 2010).

Moreover, Kanban reduces costs by minimizing inventory levels, and it increases on-time performance by producing parts and components with short cycle times. Ohno (1988) states that with parts arriving any time before their precise time needed waste cannot be eliminated. By utilizing Kanban, however, waste of overproduction can be prevented entirely. Monden (2011) ultimately formulates the five most important advantages of a Kanban system:

- Elimination of unnecessary WIP inventory
- Grasping the overall capacity of production lines and disclosing the bottleneck process

- Shortening of the lead time
- Minimization of final product inventory
- Prompt adaptability to changes in demand

However, several drawbacks cannot be neglected when looking at the original system. Lage Junior and Filho (2010) note that the concept of Kanban has been developed under the premise of specific needs of a particular company (i.e., Toyota). Therefore, the system works effectively under specific production and market conditions, which are certainly not the same for all organizations applying the Kanban philosophy. Thus, several restrictions derive from that and are reported in the literature (Aggarwal, 1985).

The Kanban system is not adequate in situations with unstable demand. The pull principle with process customers triggering the request of a certain amount can surprise the preceding process. Unexpected jumps from large to small demands can negatively affect smooth production (Lage Junior and Filho, 2010).

In addition, unstable processing time at different work stations implies inflexibility and vulnerability in terms of machine idle time (Monden, 2011). Work steps might finish earlier, other tasks might take longer than expected which can lead to more WIP inventory or machine idle time when the subsequent process finishes earlier than the preceding process. If a subsequent process triggers the supply request late, there is a certain risk of running out of supplies.

The non-standardization of operations further amplifies this aspect. Different workers might have different skills and approaches towards a task which can affect not

only the processing time of tasks but also the correct flow of material, products and the associated Kanban cards.

2.3.4 Electronic Kanban applications

Although one of the major advantages of a Kanban system refers to the unnecessary of a backend computer system to maintain the simplicity of the concept, electronic Kanban systems (often e-Kanban systems) or closely related Kanban type systems have been developed during recent years (Kouri et al., 2008). Lage Junior and Filho (2010) examine different versions of the Kanban system and classify them in systems that do or do not follow the original Kanban logic. Most of these different systems imply desirable characteristics of the original concept but make use of adaptations in order to increase the adequacy to reality in manufacturing (Lage Junior and Filho, 2010). The traditional Kanban system which uses physical cards has some limitations primarily caused by the intentional or unintentional manipulation, loss or incorrect use of the cards (Drickhamer, 2005).

The major advantage of e-Kanban systems is the compatibility to connect the Kanban functions with the company's ERP system, which most likely improves the interactions and communication between themselves and their customers as well as suppliers (Mabert et al., 2001). This step enhances the overall responsiveness and quality of information by integrating data and information across the entire organization accelerating response time and decision-making processes (Graves et al., 1995).

Especially due to the increasing pace and production batch size in connection with manufacturing operations, the number of card transactions increases. This causes

immediate problems with JIT production (Kumar and Panneerselvam, 2007). With the replacement of traditional elements such as the physical cards with modern technology, including RFID, fewer errors occur, and decision-making is more transparent and flexible (Gupta et al., 1999). Graves et al. (1995) note that an e-Kanban system is generally more reliable.

2.4 Flow shop scheduling

2.4.1 Overview and notation

A flow shop is referred to as an ordered set of processors $P = (P_1, P_2, \dots, P_m)$ on such the first operation of each job is performed on processor P_1 , the second one on P_2 and so on, until the job completes execution on P_m . A classic example of a flow shop is an assembly line (Garey et al., 1976).

An assembly line can be described as a flow-oriented production system in which parts and components are brought together to merge into half-finished or final products (Alghazi and Kurz, 2018). A flow that can be normalized to a certain speed (i.e., paced assembly line) leads the manufactured products through serially aligned production units referred to as work stations. In many resources the term assembly line may imply one of the following two systems:

- (1) An assembly line consists of stations arranged along a conveyor belt or a similar mechanical material handling equipment. The parts are consecutively launched down the line and are moved from station to station (Becker and Scholl, 2006).
- (2) An assembly line comprises simple processing as well as assembly stations. At the latter, parts from two or more input stations have to be merged to form a new one for further processing. Between any two successive stations, there is a buffer with finite capacity (Manitz, 2008).

Both cases consider a particular type of station as a prime component which adds value to a product processed on a serial line. These stations are analog to the function

of the processors in the flow shop definition. The planning and scheduling of different operations on the different machines lies in the focus of flow shop scheduling.

To further describe scheduling problems in general, standardized parameter notations are helpful to explicitly specify the terms, conditions, constraints as well as objectives of different scheduling scenarios. Conway et al. (1976) have introduced a four-parameter notation to accurately describe scheduling problems. This notation shall be outlined briefly. This notation consists of four parameters divided by slashes from each other: $A / B / C / D$.

A describes the job-arrival process, which can be a probability distribution of the times between the arrivals for dynamic problems. For static problems, this parameter specifies the number of jobs considered in the scheduling problem. When n is given as the first parameter, it denotes an arbitrary, but finite, number of jobs.

B describes the number of machines in the shop. When m is given as the second parameter, it denotes an arbitrary, but finite, number of machines.

C determines the flow pattern in the shop. In this regard, the symbol F indicates the flow shop limiting case, R stands for the randomly routed job-shop limiting case, and G is the symbol for completely general or arbitrary flow pattern.

The fourth parameter D describes the criterion by which the scheduling problem is assessed. This parameter gives insight into the objective function of the scheduling problem.

An example for this notation is the general job shop problem where n jobs are scheduled in an arbitrary schedule in a shop of m machines so that the last job finishes as soon as possible: $n / m / G / F_{max}$.

Thereupon, Graham et al. (1979) and later contributions (e.g., Pinedo, 2012) developed a three-field classification $\alpha | \beta | \gamma$ where α specifies the machine environment (processors), β specifies the job characteristics (tasks), and γ denotes the optimality criterion (objective function). This notation is going to be used in the following to describe different scheduling problem variants. A detailed extract from the scheduling notation and the forms the different parameters can take is shown in Appendix B. This overview is based on the latest summary of Pinedo’s textbook “Scheduling” from 2012.

Three examples for this notation can be extracted from Table 4.

$1 prec L_{max}$	Minimize maximum lateness on a single machine subject to general precedence constraints. This problem can be solved in polynomial time.
$R pmtn \Sigma C_j$	Minimize total completion time on a variable number of unrelated parallel machines, allowing preemption.
$J3 p_{ij} = 1 C_{max}$	Minimize maximum completion time in a 3-machine job shop with unit processing times. This problem is NP-hard.

Table 4. Examples: Three-parameter-notation for scheduling problems

2.4.2 The flow shop scheduling problem

The FSSP is a widely discussed topic related to OR and has gained much attention in research over the last six to seven decades. Johnson’s (1954) remarkable article on FSSP drew great attention to this discipline and caused interest in further developing the research topic. The common manufacturing layout has a wide range of application in production systems (Benavides and Ritt, 2018). The general FSSP can be formulated as follows:

Each of n jobs is to be processed on machines $1, \dots, m$ in that order. Every job i ($i = 1, \dots, n$) is assigned with a processing time p_{ij} on machine j ($j = 1, \dots, m$). These processing times are deterministic and need to be given. At any time, each machine can only process at most one job, and simultaneously, each job can be processed on at most one machine (Osman and Potts, 1989). The schedule specifies the time at which each job is to begin processing and must ensure that (a) once a job begins execution it continues until it finishes and (b) job i must be completed by machine j before job $i+1$ can begin on machine $j+1$.

The result of a solved FSSP is an allocation of each job of one or more time intervals to one or more machines. These schedules can be denoted as π . A schedule in which the job sequence is identical for all machines can be referred to as permutation schedule i.e., it is not allowed to change the job sequence between different machines (Liao et al., 2006). The formulation above refers to a permutation FSSP since the jobs are processed on the machines $1, \dots, m$ **in that order**. In non-permutation FSSP scenarios, however, the sequence of jobs can be different on subsequent machines, inter-operational or intermediate buffers between two stages are necessary, and job passing is allowed (Ying, 2008; Rossi and Lanzetta, 2013). Looking back at the different existing forms of assembly line systems, these intermediate buffers refer to the finite- or infinite-capacitated buffers between two successive work stations.

Schedules may be represented by machine-oriented or job-oriented Gantt charts, as shown in Figure 11. The graphic shows two schedules (a) and (b). The first one is machine-oriented and does not follow the rules of a general FSSP since the jobs are not

processed on every machine. These schedules only serve as examples for Gantt charts, which are highly relevant in order to analyze schedules in general terms.

Figure 11. Machine-oriented and job-oriented Gantt charts (Brucker et al., 1999)

The second schedule (b) shows the inverted matrix of the same scenario. The four different jobs are assigned to the ordinate, and the machine utilization is laid on the horizontal axis.

An aspect that shall be explained in depth is the difference between permutation and non-permutation flow shop scheduling. Figure 12 displays the difference between the different scenarios on a physical flow shop level as well as in relation to the makespan optimization visualized by a Gantt chart. The makespan, defined as $\max(C_1, \dots, C_n)$, is equivalent to the completion time of the last job, which leaves the production system. Minimizing the makespan usually implicates a high machine utilization (Pinedo, 2012). The intermediate buffers and job passing can be seen in the non-

permutation flow shop schedule and Gantt chart. The FSSP is known to be an $\mathcal{NP}$ -complete combinatorial optimization problem in a strong sense when $m \geq 3$ are involved (Garey et al., 1976).

Figure 12. Permutation and non-permutation FSSP on a physical flow line and as Gantt chart (Rossi and Lanzetta, 2013)

Research primarily focuses on permutation schedules due to the relative simplicity of these schedules (Potts et al., 1991). In terms of practicability, this research focus is a rigid restriction for manufacturing, since a violation of the first come first served (FCFS) principle is usually allowed in most practical situations (Liao et al., 2006). Cui et al. (2016) note that non-permutation flow shops are very common in industrial practice but theory is still underdeveloped in literature. Figure

12 has shown that a non-permutation scheduling of the same machine and job input can result in a superior job/machine allocation in terms of makespan optimization.

The difference in the complexity of these problems can be easily shown in the number of possible sequences. The permutation of n jobs determined for permutation schedules results in only $n!$ possible sequences, whereas for non-permutation schedules, one needs to determine a sequence of n jobs for each of the m machines, which results in $(n!)^m$ possible sequences (Lin and Ying, 2008; Liao et al., 2006; Rossi and Lanzetta, 2013).

The FSSP consists in finding a schedule to optimize a particular objective function (Benavides and Ritt, 2018). The most frequently considered objective function is the minimization of makespan, but several other criteria exist which can be focused on optimizing other key performance indicators (Ruiz and Maroto, 2005). These criteria include, for example, the minimization of total weighted tardiness, total lateness, total weighted completion time, or unit penalty (Pinedo, 2012; Graham et al., 1979).

2.4.3 Deterministic vs. stochastic FSSP

A considerable amount of research has been focused on deterministic scheduling, and thus, the number and variety of developed models are astonishing (Pinedo, 2012). What has been introduced before is referred to as deterministic or off-line scheduling, which means that all problem input data is known at the outset (Uetz, 2001). The deterministic context implies that the behavior of a manufacturing system is known in advance (Gourgand, 2000). In terms of practical implications, deterministic models have been criticized as well as entirely questioned. Many practical situations,

especially in the industry, are characterized by a high degree of uncertainty as well as lack of information. This uncertainty might concern processing times of jobs, the availability of machines as well as the number and nature of jobs and operations, which are to be scheduled (Pinedo, 1982; Uetz, 2001). Industrial systems are subject to random disturbances such as machine failure, operator unavailability, out-of-stock condition, change in availability date and latest completion time (Gourgand, 2000)

Considering a system in a stochastic context appears to be more realistic (Pinedo, 2012; Uetz, 2001). Gourgand et al. (2003) propose a classification for two kinds of random events: machine breakdowns and random processing times. In the latter, it is assumed that the processing time p_{ij} of a job i on a machine j is subject to random fluctuations, and not known in advance. A machine breakdown implies total unavailability of the machine for a certain period of time, which is highly unpredictable and therefore complex (Gourgand et al., 2003).

To contrast the deterministic and stochastic FSSP, general characteristics and assumptions are summarized in the following: A deterministic flow shop system is composed of a set of n jobs and m machines. The n jobs are processed by the order of the machines and the job sequences, however, can vary or not (note the difference between permutation vs. non-permutation FSSP). Each job i takes a known and therefore deterministic processing time p_{ij} at each machine j . Assumptions for the deterministic FSSP can vary. Classic assumptions are the following:

- the release dates of the jobs are known in advance
- all machines are continuously available
- processing times p_{ij} are deterministic and independent from each other

- machine set-up, tooling and change-over times are either included in the processing times or negligible
- job splitting is prohibited (Non-preemption constraint: the scheduler is not allowed to interrupt the processing of a job)
- transportation times are neglected
- a machine can only process exactly one job at a time, and a job can only be processed on one machine at a time
- an intermediate buffer of limited or unlimited capacity may provide space for storing unfinished jobs between machines

The deterministic FSSP aims at finding a job schedule which minimizes a criterion. This criterion can be the makespan, the total flow time, the tardiness, etc. (Gourgand, 2003). In a stochastic scheduling environment, the first three and at the same time, most formative assumptions can be replaced by the following assumptions:

- the release dates of the jobs are *not* known in advance
- machines may break down at an unknown point in time
- processing times p_{ij} are stochastic and modeled by independent random variables

In comparison to the deterministic FSSP, the stochastic FSSP focuses on finding a job schedule that minimizes a criterion *in expectation*. It is assumed that the processing time p_{ij} is governed by a corresponding random variable denoted by $p_{ij} \in V$, which only becomes known on completion of the job (Uetz, 2001). The change from deterministic to stochastic processing times changes the complexity of the problem considerably. A stochastic FSSP can be no longer classified as a combinatorial optimization problem but must be viewed as a dynamic optimization. The solution of a stochastic FSSP is not a specific schedule but rather a scheduling policy (Radermacher, 1984).

CHAPTER 3 – METHODOLOGY

Chapter 3 develops the methodology applied in this research project. Considering the main objective of this study to develop an RFID-enabled serial production system, a frequently cited model framework is applied to guide through the process of developing a CPS.

The different levels of the model function as structural groundwork. The literature review in the previous section covers broadly three dimensions: (1) The technical perspective on UHF RFID technology, (2) the lean manufacturing approach realized through Kanban practices and principles, and (3) the scheduling problem related to a flow shop production environment. In the development of the CPPS, all three dimensions contribute in order to create an overall enhanced, technological enabled, and smart production system. Hence, the steps of the design framework, which is introduced in the following, is further enriched by these dimensions in the main part of this study.

3.1 5C architecture as a framework

In order to develop a CPPS, the 5C architecture by Lee et al. (2015) is adopted. Lee et al. (2015) propose a 5-level CPS structure referred to as 5C architecture, which describes a framework for developing and deploying a CPS for manufacturing application. Figure 13 shows the five levels in a step-by-step guideline of how to construct a CPS. In the following, the individual levels are briefly introduced. The development of the system is structured in its entirety within the generic architecture framework. Chapter 4 is completely based on the respective individual design steps.

Figure 13. 5C architecture framework (Lee et al. (2015))

The first step includes acquiring accurate and reliable data from the machinery and individual components. This data might be measured by sensors or obtained from microcontrollers or even directly from manufacturing support systems such as ERP systems or MES. In this phase, two major factors have to be considered. On the one hand, various types of data may be generated so that a seamless and coherent procedure is required to process and bundle the data. On the other hand, suitable sensors in terms of type and capabilities are the second consideration in the first phase of developing a CPS (Lee et al., 2015).

The second step consists of the conversion from data to meaningful information for which different tools exist. According to Lee et al. (2015), there has been an extensive focus on applying automated algorithms to process data in order to gain useful

information in the end. Hence, the second step of creating a CPS architecture involves bringing in a certain level of self-awareness to the technology.

The third step, which is referred to as cyber level, takes up a central role in constructing a CPS. This level functions as a central information hub and builds a network with the information gained from every machine connected. The cyber level can be seen as the backbone of a CPS as massive information is gathered from a holistic network of sensor-equipped technology. The information obtained from this level of a CPS enables the user to compare machine performances among the fleet of machines or over time, in comparison to previous assets which may help to predict the future behavior of a machine. With the aid of an efficient technique or methodology for managing and analyzing information at the cyber level, it is even possible to equip the machines with self-comparison abilities.

In step 4, the cognition level, knowledge is gained from the information obtained from the monitored system. This knowledge can be supportive in decision-making situations and is to be generated through the visualization of the information to experts. This visualization may be realized through interactive graphics, diagrams or automatically generated lists.

In the fifth and last step of creating a CPS, a feedback loop between the cyber level and the physical level or physical space of the system is created. The proceedings in this phase of a CPS architecture strongly resemble a feedback loop in control engineering. The loops take the system output into consideration, which enables the system to adjust its performance to meet the desired output response. The automation of this phase makes the system self-configurable and self-adaptive (Lee et al., 2015).

3.2 The scenario-based CPPS

3.2.1 Generic framework for an RFID-based manufacturing system

Based on the step-by-step guideline of how to create a CPS (see chapter 3.1), this research project develops an RFID-enabled CPPS. In order to utilize and improve the assets of the traditional Kanban system, its advantageous practices and principles are transferred to the new system to be designed. In so doing, the assets of the concept can not only be maintained but also enhanced by the deployment of RFID technology.

The inclusion of Kanban functionalities does not only imply the acquisition of all benefits but also brings along system requirements on which these features depend.

Figure 14. Framework for RFID-based manufacturing systems (Lu et al., 2006)

Figure 14 visualizes a framework of an RFID-enabled serial production system which has been introduced by Lu et al. (2006). This generic approach provides a strong foundation for the system design and development. The principles of the system will be applied to incorporate the Kanban functionality in an RFID-enabled serial flow shop

production system.

The system demonstrated in Figure 14 consists of several work stations which can perform different tasks. In this case, the manufacturing system is divided into general stages which express the progress of the production process (i.e., Machining, Assembly, and Packaging). The work stations, broadly categorized in these three sections, are equipped with RFID readers that must be placed in an optimized location in order to provide the best possible signal with the least possible interferences. In addition, readers are set in place to monitor all inventory facilities and its processes. Raw material, which can be stored in shelf systems, containers or similar storage objects, is tagged (e.g., passive or active RFID tags) and thus continuously readable for the RFID readers in place. The same applies to half-finished products or final products; the attached tags can enhance the transparency of the material flow. All these system elements are entirely connected to a holistic network which can be connected and therefore controlled and steered by an MES or ERP system. Based on the support system (e.g., MES or ERP system), the production plan delivers the information input for the actual production process.

3.2.2 Fictional scenario for system design

In order to transfer the main aspects of the generic framework to the design of the new system, a scenario must be outlined. The following fictional setup is considered: Similar to the generic framework, the production system is supposed to comprise four work stations which may operate distinctive jobs on, for example, four machines. These distinctive jobs realize a mixed model production environment which advances the

flexibility of a production line and simultaneously covers the customers' desire for individualized products. Different products are assembled through different operations on individual machines. This simultaneously leads to distinctive processing times on the different machines for different products. When product A needs a particular intense operation on the first machine, product B might not need the same amount of time on the first machine. Product B, however, might need a specific manufacturing step at another station which takes a larger amount of time compared to the other jobs.

The objects on the serial production line can be small-, medium-, or even large-sized and are moved along the stations manually. The scale of the production facility is highly dependent on the capabilities of the sensors. This issue is further described in the requirement section of this chapter.

The assembly line is not paced. The operators move the (half)-finished products manually from station to station. Every job entering the production line must go to all four stations in the exact order of the stations. The operations conducted at each station may vary from product to product as well as the time needed at each station. At this point, there are two further assumptions made. First, the transport from station to station is done in infinite speed so that a transportation factor is excluded. Second, intermediate storage buffers can hold half-finished products right after the individual stations and may let other jobs pass. The input of the system are orders received from process- or end customers, which vary in their operations to be conducted during the manufacturing.

3.3 System requirements

The system to be developed has several requirements which derive from the scenario in which it is supposed to be employed. The three aspects taken into account when analyzing the system's requirements correspond to the dimensions which have been introduced earlier. Namely, technological aspects of RFID technology, the lean factor related to the Kanban concept and the flow shop scheduling optimization approach entail requirements that must be fulfilled. Each of the three dimensions delivers value to the system design but implies necessary specifications. It can be noted that not only the three independent dimensions affect the design of the system but also interactional factors have to be considered.

3.3.1 Technological dimension

The original concept of the Kanban system is to be enriched by the electronic component of RFID technology. The advantages of the traditional system are supposed to be complemented by technology to enhance the overall capabilities. A smart e-Kanban production system, also referred to as IMS, is the result of technological enrichment.

As a production system in a specific setting, the conceptualization needs to consider technological properties. First of all, the technical devices used must match the generic framework, which has been proposed by Lu et al. (2006). This model represents an ideal for the new system which is aimed to be developed. Therefore, several technological components with specific capabilities are necessary in order to accomplish a functional concept.

Considering a flow shop environment, objects moving on a serial production system need to be equipped with appropriate RFID tag technology. The other three subsystems compiling an RFID system need to have the computing capability and range to read and process the data received from the tags on the line. The scale of the production environment must match the technical specifications of the RFID technology, especially in terms of the range.

Another issue is strongly related to the tag – reader interaction. It needs to be ensured that the readings of the tags can be achieved in a way that a distinction between the objects' current locations can be realized. To be specific, objects equipped with tags should only be read by the reading device of the station where the objects are currently processed. Duplicated readings are essentially to be avoided. This requirement derives from the thread of the multiple reader-to-tag interference, which must be prevented unconditionally. At the same time, the range of the RFID antenna needs to be sufficient in order to cover the work stations in the flow shop production environment. A reliable solution which balances out the range of the antenna, as well as the requirement of non-redundant reading capacities, is a major challenge.

Another considerable challenge is the host data processing system which must be capable of processing the amount of data that originates from the flow shop. But not only computing performance but also operability and ease of use need to be ensured since this system is to be operated by human workforce. At the same time, the host data processing system is the interface with the scheduling dimension. The backend and frontend software system which processes the data read by the reading device must be capable of providing the data in a way that a scheduling algorithm can grasp and further

work with. Especially with a large number of different jobs, the theoretically possible number of sequence solutions can exceed computer capacities such as the central processing unit (CPU) performance. This requirement is a bilateral factor affected by the technological and the scheduling dimension.

But not only the scheduling but also the lean dimension is interlinked with the technological element. When physical Kanban cards previously held information about the jobs and operations to be fulfilled at the exact locations, the tags need to store the same information. In fact, the tags must be capable of storing the desired information on the internal microchip.

A significant advantage of the Kanban philosophy is the visualization of information. The technology applied in this system design should be able to display information on a floor shop personnel but also management level. This realizes the desired availability of real-time information to the workers as well as production planners and managers.

3.3.2 Lean dimension

The lean dimension comprehends requirements which derive from the lean production philosophy and are related to the Kanban concept. It is not the objective to implement all traditional practices and principles related to the original Kanban system. In fact, some principles are taken into account; others are not included. According to Kouri et al. (2008), customized versions of the Kanban system which consider individual characteristics of the organizations are to be preferred. Simple employment without any adaptations can negatively affect the productivity of a manufacturing system.

A major advantage of the original Kanban system is the general practice of visualizing the flow of objects as well as the general progress of a scheduled sequence of operations. At this point, an integrated requirement occurs. The host data processing system must be able to visualize and conveniently summarize the WIP for a general gain in transparency throughout the system.

The second general practice of the Kanban philosophy is related to the limitation of WIP, which shall not be the objective of this system design. The minimization of WIP directly competes with the non-permutation flow shop scheduling approach, which instead aims to minimize the overall completion time. Hence, this requirement is excluded from this study. In fact, the minimization of the makespan is highly desirable since a high degree of machine utilization is consistent with the Kanban's philosophy of smoothing the overall production.

The objective of managing flow in a Kanban system is also to improve collaboratively and evolve experimentally. When it comes to the allocation of operations or jobs to the different work stations, a learning effect can be realized. The workers and production schedule managers should, therefore, implement general feedback loops in order to discover certain inconsistencies. The system should support this approach by being able to file elapsed jobs and schedules.

3.3.3 Scheduling dimension

The requirements regarding the scheduling dimension are simple. The design of the system is based on a fictional but preferably realistic scenario. This scenario has been chosen by the researcher at an earlier stage already. A fictional product in different

variations is produced on the serial flow line. The individualization along the lines of mass customization is realized through different work steps during the production process, which results in different processing times for different jobs.

In general, the scheduling problem derives from the fictional scenario and its assumptions. Hence, the characteristics of the scenario-based CPPS determine the kind of scheduling problem which has to be applied from the scheduling dimension's perspective. The non-permutation FSSP is imposed on this scenario. There are several assumptions to be made in order to fit the classic non-permutation FSSP on the new system. These assumptions are going to be clarified when the scheduling algorithm is introduced to the system.

Another requirement that is related to the scheduling dimension but also linked to the technological factor is the capability of the system to process real-time data. The feedback loop to be introduced in the final stage of the system must be capable of rescheduling a determined part of the initial schedule based on real-time updates gathered from the RFID tags on the line.

CHAPTER 4 – SYSTEM DEVELOPMENT AND OPTIMIZATION MODEL

This chapter aims to develop an RFID-enabled serial production system equipped with an automated scheduling algorithm which uses real-time information to improve the overall efficiency of the work station and task assignment. The main body of this study is based on the structure of the 5C architecture guideline, which has been proposed in the methodology section. The generic development framework of a CPS helps to compile the different components of the system stringently. General requirements, primarily deriving from the three dimensions which have been examined earlier, are taken into account.

4.1 Smart connection level

In the first phase of the development of a CPS, the primary focus is the equipment of the physical production system with the technological devices needed to set up the computing element. Hence, the technological dimension takes on an essential role during this stage. This section aims to integrate RFID technology in the production system to advance its capabilities and significantly modernize the concept of Kanban. Specific instruments of the previously examined design options related to RFID are chosen to equip the CPS with adequate technology.

4.1.1 Technical specifications of the RFID apparatus

The fictional production setting has been outlaid in the previous section. It can be noted that the technology to be chosen must match the layout and should be designed as realistic as possible. The work station arrangement is viewed as a general setting for small-, medium, or large-sized products to be processed. Due to the requirement of a

medium-sized, circular operation environment, the general operation with UHF RFID technology meets the demand best. The antennas' range has been specified to approximately 30m maximum so that almost all types of products can be covered by the technology.

There are several requirements which limit the choice of RFID technology to be used in the newly designed system. These requirements include primarily technical properties such as reader features, antenna range, and choice of tag type.

First, the fictionally created flow shop production line consists of four physical work stations, which require an RFID reader solution that is capable of processing data received from four physically separated locations. The Invengo XC-RF861 RAIN RFID Reader (short: Invengo reader) is considered to be an appropriate choice in terms of technical features. The UHF RFID reader supports the standardized EPC global UHF Class 1Gen2 protocol and can thus process all corresponding RFID tags using this communication protocol.

In terms of the operating frequency, the Invengo RFID reader supports all global UHF bandwidths from 840 to 960 MHz. Hence, a global operation can be ensured. The RF output power of 9 to 30 dBm, adjustable in 1dBm-steps, provides flexible control of the receiving range of the RFID system. An adjustment of the RF output power can significantly affect the range of the antenna in a controllable manner. The system makes use of this featuring property. Figure 15 shows the RFID antennas' RF output connectors in the top picture and power input, serial connector, ethernet adapter, and General-purpose Input/ Output (GPIO) connector in the picture below.

Figure 15. Input & output interfaces of the Invengo XC-RF861 RAIN RFID Reader

Thus, four UHF RFID antennas can be connected to the reader via the RF output connectors and the use of coaxial cables. A DC input 10 to 30V connector enables a power supply in connection with an AC/DC adapter. Via the ethernet connector and a standard ethernet cable, the output data gathered from potential RFID tags can be transferred to a host data processing device. The requirement of a simple connection between the reader and the host data processing device is therefore guaranteed.

Figure 16. Identix ANT85C7070 UHF RFID RAIN antenna

Second, the RFID antennas used in the designed system take on an important role. The Identix ANT85C7070 UHF RFID RAIN antennas (short: Identix antennas) are compatible with the Invengo reader and operate on the same standardized RAIN

norm. These circular-polarized antennas offer a range of up to 20m and are therefore an appropriate choice considering the production system scenario. To create as realistic of a setting as possible, where the antennas can cover a work station which handles small-, medium-, and/or large-sized products, this choice is considered to be best. A circular-polarized antenna pattern covers a 3-dimensional area directly in front of the antenna's forefront.

Moreover, the range of the electromagnetic field is easily adjustable by the flexible modulation of the output power so that lower ranges are easily accomplishable. Four coaxial LMR-240TNC cables with reverse polarity male and SMA male connectors incorporate the antennas into the system.

This study assesses active RFID tags as an appropriate choice for planning and control purposes. Due to the higher reliability in signal strength and their higher durability under harsh environmental conditions, the active RFID tags appear to be suitable in a flow shop production line. Although active tags are significantly more expensive than passive tags, the necessity for a constant flow of reliable data is the foundation for a functioning system. As soon as the connection between a tag and the reading device is lost, the systems' computation of a recommended sequence is biased and not adequate anymore. This has to be prevented.

However, it can be noted that any types of RFID tags introduced in this paper earlier can be used with the choice of the Invengo reader and the Identix antennas. Passive or semi-passive tags may be superior in other industrial applications. Especially concerning the significant difference in terms of procurement costs, alternatives to active RFID tags may be more suitable.

4.1.2 System layout

The system is modeled in a small-scale physical model in order to test the functionality in real-life conditions. Especially the behavior of the active RFID tags in a testing environment can uncover undesirable interferences.

Figure 17 outlines the generic design of the RFID system and displays the different technical devices used. It can be noted that essential design elements from the generic framework introduced by Lu et al. (2006) have been adopted. Their framework for developing an RFID-enabled manufacturing system can be seen as the foundation of this system. In addition, the four typical components of an RFID system, which have been explained in depth earlier, are applied. The specific components described in chapter 4.1.1 comprise the system.

Figure 17. System layout (own illustration)

To fulfill the requirement of a smooth operation in terms of reciprocal interferences, an RFID blocking fabric between the different work stations and their corresponding antennas is applied. Multiple reader-to-tag interference would diminish

the system's capability to collate one tag with one reader. In so doing, the requirement of singular RFID tag readings throughout the whole system can be guaranteed. Figure 18 shows the RFID blocking fabric, which is used in the system. The fabric consists of 23% copper, 27% nickel, and 50% polyester. It has a thickness of 0.08 to 0.09mm and promises a shielding efficiency of 99.99%, according to the manufacturer (Faraday Defense, 2019). Its attenuation capabilities range within an operating RF of 10 to 3,600 MHz and cover, therefore, all RFID types except for the LF band.

Figure 18. RFID blocking fabric

Since all decisions concerning the hardware have been made, an analysis of the

system's costs can give insight into the profitability for manufacturers. The Invengo reader can connect to up to four RFID readers and costs \$899. The four Identix Far Field RFID antennas add up to a total of \$172 with an individual price of \$43 per piece. To connect the antennas to the reader, coaxial cables are needed which are \$20 each, adding up to a total of \$80. The blocking fabric is available for around \$27 per 50" x 1' and comes in a roll. The amount of fabric needed is highly dependent on the size of the production system. For the small-scale model in this research project, only one roll is needed. Active RFID tags with the heavy duty rubber case cost around \$8 each. Passive tags which can also be used in this system design are approximately \$0.05. The costs for a host data processing system are neglected here. The costs for the system proposed consequently add up to a total of around \$1,200.

4.2 Data-to-information conversion level

The handling of inventory and production processes can be strategically aligned to lean management tools such as JIT delivery and production. The RFID-enabled Kanban system aids the transparency and flexibility of the system (Brintrup et al., 2010).

A high-performing host data processing device, however, is needed to execute the computations in an acceptable period of time. To make use of the data gained from the tagged objects in the flow shop production line, the reading device and the host data processing system must be equipped with a software which is capable of displaying and further processing the data.

4.2.1 Host data processing system and software application

The computer used for processing data and converting it into meaningful information has an Intel® Xeon® CPU E5-2670 v3 processor with 48 cores and an installed memory of 32 GB. The Windows Pro operating system runs on 64-bit and provides an interface for installing software applications. The computing performance is on a high level and therefore, an appropriate choice for the system design. The handling of incoming RFID tag data from the Invengo reader and especially the scheduling algorithm, which is introduced later, needs a sufficient amount of CPU cores in order to carry out the arithmetic computation successfully.

To display the data gained from the tags, the reader support software “Invengo ConneXion” connects the Invengo reader via ethernet connection to a computing device (i.e., host data processing device). Any details about the software application are extracted from the manual or the software itself; all screenshots originate from the

operation of the software on the host data processing system (Invengo ConneXion, 2019).

The application enables the visualization of the tags' properties on the host data processing system, which is fundamental for the further operation of the data. Once plugged in the computing device, the software can be started, and the Invengo reader is automatically recognized.

Figure 19. The user interface of Invengo “ConneXion” reader software application

Figure 19 displays the user interface of the software application that is used in the system design. The application is compatible with the chosen reading device. Invengo provides this open-source software with several functions that are useful for the data-to-information conversion. First, the application displays all currently read tags and more importantly, only shows each tag reading once although several antennas might communicate with one tag. Figure 20 demonstrates the user interface under

operation. The large numerical display visualizes the number of tags currently read in the whole system, which is 41 in this example. The column ribbons include a timestamp, the corresponding RFID antenna, the tag count, the EPC, and other tag-specific information.

The different rows display the currently read tags. Lighter shading indicates a smooth communication between the RFID tag and the reader, whereas a darker shading means that a connection is about to be lost. If the reading entry turns black, the connection is lost, and the entry is going to be automatically deleted from the list in the next second.

Figure 20. ConneXion user interface under operation

On the right-hand side of the software's interface, other information and settings are displayed. The reading device is further specified with additional information about the software status and other properties. Under the ribbon "General", the IP address is shown through which the connection to the host data processing system has been

established. Furthermore, the antenna settings can individually be adapted, which includes parameters such as the input power in dBi and the antennas' sensitivity, which adjusts the technical responsivity of the tag/reader communication.

4.2.2 Data processing operation

Without the processing of the obtained data, a benefit from the RFID tags cannot be accomplished. The simple visualization of RFID data on a processing device is not sufficient enough to gain valuable knowledge about the system or even enable steering mechanisms. By the use of a TCP/IP port, the Invengo ConneXion software application offers an exporting communication opportunity between the software itself and another downstream application. In so doing, the data can be provided as input data for other applications or software architectures for further utilization.

The screenshot displays the configuration interface for data transfer settings, organized into three main sections: Data, TCP / IP, and HTTP.

- Data Section:** Features a 'Device Name' text input field and a 'Date/Time' dropdown menu set to 'Universal'. Below these is a grid of 12 checkboxes, all of which are checked: UTC Timestamp, Device Id, Device Name, Antenna, Read Count, RSSI, EPC, Make, Model, Serial Number, TID, and User Memory.
- TCP / IP Section:** Includes an 'Enabled' checkbox that is checked. It also contains an 'Address' text input field with the value '192.168.0.100' and a 'Port' spinner control set to '9055'.
- HTTP Section:** Includes an 'Enabled' checkbox that is unchecked. It features a 'URL' text input field and an 'Update' spinner control set to '10' seconds.

Figure 21. TCP / IP data transfer setting

Figure 21 displays the software's setting panel, which includes the export of data through TCP/IP. In this example, the data extension is enabled and communicated through the IP address 192.168.0.100 towards port 9055. At this port, other applications such as Microsoft Excel or database applications can receive the data stream and utilize the incoming data in further use cases. This functionality allows live data streaming and is therefore highly beneficial in terms of real-time data transfer.

4.3 Cyber level

In general, the host data processing system, including RFID middleware, can be related to the third level of the 5C architecture of a CPS. The cyber level functions as a central information hub and builds a network with the information gained from every RFID reader. The host data processing system is supposed to consolidate the information gathered from the entire network of RFID devices. In this development stage of the CPS, the principles of the Kanban philosophy are incorporated.

4.3.1 Kanban practice implementation

The Kanban principles and practices help to create a more efficient, transparent, and simple-operating CPS. However, not all of the original practices related to the lean philosophy are beneficial to this project.

Physical Kanban cards are replaced in the system with active RFID tags. These tags are attached to WIP objects which pass through the work stations or machines. All jobs that need to be fulfilled on the production line are known in advance and can be seen as orders received from customers. At this point, the tags function just like production-ordering Kanban cards. The incoming order triggers the demand of a customer. This customer can either be the end-customer or a process customer who benefits from a preceding process. It must be noted that this procedure is not characterized by a pull principle which is fundamental to the Kanban concept. The approach in this system design rather resembles the method of a push-oriented technique. A certain demand for a product might be pulled by a customer, but in fact, the jobs represented in an order pool are pushed through the production line. The main

similarity towards Kanban still exists. The RFID tags hold relevant information about the order and specify the operations to be conducted at each station. In addition, the RFID tags are permanently attached to the WIP object. The transparency and ease of use facilitated by the physical Kanban cards in the original concept are further enhanced. Not only static information can be stored, but the reader software ConneXion enables a dynamic overwriting of the tags' properties. The tags functioning as physical cards are therefore superior to the traditional Kanban cards. The employment of RFID tags as production-ordering Kanban cards follows the practice of "Manage flow".

Another Kanban practice which is considered in the design of the system is the aspect of "Visualizing". While the traditional approach includes visible Kanban cards which hold valuable information, the RFID tags cannot provide that feature in the first place. Information cannot be visibly read by just looking at the tags with the human eye. The RFID technology, however, enables an even more desirable functionality. With the tags attached to WIP objects, real-time information can be obtained, and information about the progress of the product can be read as well as written. The host data processing device in the central system hub must provide the visualization of the tags' information. Another advantage beyond the visibility of information on physical Kanban cards emerges. In the central hub architecture, a clearly laid-out overview of all WIP objects can be realized. System managers have the opportunity to overview, manage, and steer the production system with this real-time information available.

The original Kanban concept follows the principle of limiting WIP. This system's objective, however, aims to minimize the makespan of a given set of jobs operated on a given set of machines. With enabling a non-permutation scheduling

approach, inter-operational buffers with an infinite capacity between the stations or machines are installed. Besides minimizing WIP inventory, minimizing the makespan can still be in accordance with the principles of Kanban. With efficiently optimizing of machine utilization, which is promoted by the minimization of the makespan, the waste of machine idle time and labor can be eliminated.

Figure 22. System layout with implemented RFID technology

The practice of implementing feedback loops is realized at different stages in this system. First, each RFID tag continuously interacts with the reader and therefore communicates and re-communicates its status permanently. Any progress such as proceeding from one station to another is realized by the Invengo reader and processed through the central hub. Another relevant feedback loop is implemented during the

configuration level of the CPPS design. It can be noted that an algorithmic feedback loop in combination with an MIP allows the real-time optimization of the flow shop. This loop is in accordance with Kanban practices but is not introduced before chapter 4.5

4.3.2 Kanban implications for system design

The tags can be easily attached to objects with removable adhesive. After finishing the product, the tag can be removed, and the product can either be delivered to the process or end customer. The active tags can be overwritten and are therefore reusable for new incoming orders. This supports the cost efficiency of the RFID-enabled serial production system. Another possible scenario is the storage of the finished item. In that case, the RFID tag can even stay attached and be used for inventory management purposes.

Figure 23 shows how the RFID tag adheres to a sample half-finished product on the production line. Information is not readable for the human eye in the first place, but the real-time processing through the RFID antenna, the Invengo reader and lastly the host data processing system enables a centralized visualization for system operators. Planned processing times, as well as actual times and the deviation between those values, can be displayed. Other information, such as the distinctive product features due to the mixed model characteristic can be visualized.

Figure 23. Active RFID tag attached to a half-finished product

The visibility of information for the system operators can be further enhanced through the application of, for example, re-writable e-ink displays. To realize information visibility along the lines of the Kanban philosophy, these displays can be attached by the work station. When linked to the central hub architecture, real-time information can be pulled up and displayed for the convenience of the station operator. Possible information to be displayed can be the operations which need to be conducted as well as processing times and next incoming objects.

By employing these displays, the visualization principle of the original Kanban concept is sufficiently satisfied. Figure 24 shows an example of a re-writable e-ink display which could be attached in close distance to the work stations. Relevant real-time information can be displayed through the connection to the host data processing system via an interface connector.

Figure 24. Example of re-writable e-ink display (Waveshare, 2019)

The system layout is modeled in a small-scale, as shown before in Figure 22. With an industrial application of the developed system, another important principle refers to the permanent improvement through collaboration and the evolvement through experiments. System operators are recommended to implement performance feedback loops in order to ensure smooth operation but also steadily improve the system's capabilities. The Kanban philosophy implies an iterative system quality check where workers and managers with different perspectives on the system share their experience and find potential improvement opportunities through experimental adjustments of technical settings.

4.4 Cognition level

4.4.1 Flow shop scheduling algorithm

The production scenario has been outlined before. Four work stations are separated from each other so that an explicit correlation between every tag and the current station can be realized. Based on the non-permutation FSSP problem discussed by Cui et al. (2016), the program can be formulated as follows:

Indices:	
i	= the index of jobs
j	= the index of machines
k, k'	= the index of the position in each machine

Sets:	
J	= the set of jobs; $J = \{J_1, J_2, \dots, J_n\}$
M	= the set of machines; $M = \{M_1, M_2, \dots, M_m\}$
O_i	= the set of operations of job J_i ; $O_i = \{O_{i1}, O_{i2}, \dots, O_{ij}, \dots, O_{im}\}$, O_{ij} is the operation of J_i in M_j

Parameters:	
n	= the number of jobs
m	= the number of machines
p_{ij}	= the processing time of O_{ij}
Z	= an infinite integer (Big number)

Symbols:	
J_{kj}	= the k th job in machine M_j
O_{kj}	= the operation of J_{kj}
C_{max}	= the finish time of the last operation of the last job

Decision variables:	
x_{ijk}	= the job sequence decision variable; if job J_i is in the k th position in machine M_j , $x_{ijk} = 1$, otherwise, $x_{ijk} = 0$. $1 \leq i \leq n, 1 \leq j \leq m, 1 \leq k \leq n$
pt_{kj}	= the processing time of O_{kj}
S_{kj}	= the start time of O_{kj}
C_{kj}	= the finish time of O_{kj}

Table 5. Indices, sets, parameters, symbols, and decision variables of FSSP

A set of jobs J are to be processed on a set of machines M . The objective function minimizes the makespan C_{max} . Every job J_i ($J_i \in J$) must be completed and therefore run through a sequence of m operations $\{O_{i1}, O_{i2}, \dots, O_{im}\}$. This FSSP is set to be deterministic. Thus, every operation O_i requires a processing time p_{ij} on machine M_j . All jobs can also be seen as orders in this case. A filled order book is another assumption that is made. All jobs or orders to be produced are known in advance and available at the beginning of the planning horizon.

As proposed in chapter 2.4, the sequence of jobs assigned to machines must not necessarily be identical. Hence, a non-permutation FSSP is considered in this study. In fact, job i must be processed in the sequence of the machines $M \{M_1, M_2, \dots, M_m\}$ in that order but machines M must not proceed jobs J in the identical sequence.

Figure 25. Gantt chart of non-permutation FSSP (Ying, 2008)

Figure 25 visualizes an example of a Gantt chart which considers a non-permutation approach to the FSSP. In this case, three jobs run through five machines. The sequences, which can be denoted as $\pi \{\pi_1, \pi_2, \dots, \pi_m\}$ of the jobs $J \{J_1, J_2, J_3\}$ on the different machines $M \{M_1, M_2, M_3, M_4, M_5\}$, are different:

$$\pi_1 = \{J_1, J_2, J_3\}$$

$$\pi_2 = \{J_1, J_2, J_3\}$$

$$\pi_3 = \{J_2, J_3, J_1\}$$

$$\pi_4 = \{J_2, J_3, J_1\}$$

$$\pi_5 = \{J_2, J_3, J_1\}$$

The sequences π in this example show that the sequence of jobs can differ although the operation of the jobs must follow the sequence of machine M_1 to M_5 . The objective in the cognition level of developing a CPPS is to solve the non-permutation FSSP with a mixed integer program (MIP) and enhance the makespan minimization as much as possible. The cognition level of creating a CPPS aims to generate knowledge as per the definition. The MIP is set up to maximize the gain of information and convert it into knowledge. The MIP model for the $Fm \parallel C_{max}$ non-permutation FSSP can be ultimately established as follows:

$\min C_{max} = C_{nm}$		<i>Objective function</i>	
s.t.	$\sum_{i=1}^n x_{ijk} = 1$	$\forall j, k$	(1)
	$\sum_{k=1}^n x_{ijk} = 1$	$\forall j, i$	(2)
	$pt_{kj} = \sum_{i=1}^n x_{ijk} p_{ij}$	$\forall j, k$	(3)
	$C_{kj} = S_{kj} + pt_{kj}$	$\forall j, k$	(4)
	$S_{11} = 0$		(5)
	$S_{kj} \geq C_{k-1,j}$	$\forall j, k \geq 2$	(6)
	$(2 - x_{ijk} - x_{i,j+1,k'}) Z \geq S_{kj} + p_{ij} - S_{k',j+1}$	$\forall j < m, i, k < k'$	(7)
	$x_{ijk} \in \{1, 0\}$		(8)
	$pt_{kj}, C_{kj}, S_{kj} \geq 0$		(9)

Table 6. MIP formulation for $Fm \parallel C_{max}$ non-permutation FSSP

The MIP for solving the $Fm // C_{max}$ non-permutation FSSP can be read as follows. The objective criterion of minimizing the makespan is expressed as C_{nm} . In a scenario of n jobs and m machines, this denotation refers to the finish time of the last job on the last machine. This variable is to be minimized ($\min C_{max}$).

This program is subject to several constraints. Constraint set (1) ensures that each job is placed at one position in the sequence of each machine, whereas constraint set (2) guarantees that explicitly one job is placed at each position in the production sequence. The sum of the product of x_{ijk} times p_{ij} specifies the processing time pt_{kj} of operation O_{kj} (constraint set (3)). The binary variable now enables the explicit relation between the deterministic processing times p_{ij} and the operations assigned to certain positions in the production sequence schedule.

Constraint set (4) establishes the relation between the start time, the processing time, and the finish time of operation O_{kj} . The determination of $S_{kj} = 0$ for k and $j = 1$ ensures the start of the first operation at a timestamp of 0 (constraint set (5)). Constraint set (6) ensures that the k th job cannot start before the immediate predecessor O_{k-1j} has finished and constraint set (7) guarantees that the start time of job i on M_{j+1} cannot be earlier than its finish time on M_j . Constraint sets (8) and (9) denote x_{ijk} as a binary variable and establish the non-negativity terms for the decision variables pt_{kj} , C_{kj} , and S_{kj} .

As outlined before, an n jobs and m machines scenario where $n = 5$ and $m = 4$ is considered in the first place. The deterministic parameters of this example are shown in Table 7.

		Machines M			
		M_1	M_2	M_3	M_4
Jobs J	J_1	1	7	1	7
	J_2	2	1	1	1
	J_3	5	1	1	1
	J_4	4	2	2	1
	J_5	1	2	3	4

Table 7. Processing times p_{ij} for jobs J_i on machines M_j

4.4.2 Simulation in GAMS

The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization. Since GAMS is tailored for complex, large-scale modeling applications as well as specifically designed for modeling linear, nonlinear and mixed integer optimization problems, this software is appropriate for solving the scheduling scenario (GAMS Development Corp., 2019).

To simplify matters, the programming language used in GAMS is not further specified. Instead, this chapter aims at stringently solving the scenarios' FSSP. However, Table 15 in Appendix C displays the exhaustive code and comments clarify the functionality of this GAMS program code.

It must be noted that GAMS operates on indices scales from 0 onwards. That is to say that J_1 as the first job i of n jobs in total is referred to as a value of $i = 0$. The set of jobs J_i , therefore, takes on the index numbers of $\{0,1,2,3,4\}$ whereas the same applies to the set of machines M_j . The machines are denoted in GAMS with index numbers of $\{0, 1, 2, 3\}$.

The input data derives from a Microsoft Excel spreadsheet which holds the number of jobs i and number of machines m as well as the corresponding planned

processing times p_{ij} in a customized table. In the GAMS program code, line 10 to 14 in Table 15 express the reference to the Excel input sheet named DATA1.xlsx. Figure 26 shows the design of the Excel input sheet: the values in column A refer to the number of jobs n , row 1 includes the number of machines m , and the values in the main body of the table, reference the processing times of job i on machine j (i.e., input variable p_{ij}). With this example, the differing denotation regarding the indices can be noted. GAMS also offers the opportunity to directly refer to the processing time values within the program code. Processing the data through an Excel spreadsheet, however, has the major advantage of real-time adaptability. The interface client, built for the communication between the Invengo ConneXion software through the TCP/IP port, is capable of pushing the real-time data into an Excel spreadsheet within small time intervals. Therefore a solution with an Excel spreadsheet as a dynamic input table is appropriate.

	A	B	C	D	E
1		0	1	2	3
2	0	1	7	1	7
3	1	2	1	1	1
4	2	5	1	1	1
5	3	4	2	2	1
6	4	1	2	3	4

Figure 26. Excel input sheet

After defining all indices, sets, parameters, symbols and decision variables consistent with Table 5 in lines 1 to 36 of the program code, the notation of the objective function as well as the different constraints are adopted in lines 38 to 47. This step is followed by the actual equations of the constraints analog to the formulation of the MIP

in Table 6 (lines 48 to 56). The program code lines 58 to 63 implicate option settings for solving the MIP such as type of solver (here CPLEX), solving time limit (here 400 seconds), and the optimal relative gap limit (here 0.1). Line 65 instructs the program to minimize C in accordance with the variable notation and the constraints listed. The display of the resulting decision variables is realized in line 67. This command visualizes the results of the MIP algorithm.

4.4.3 Simulation results

The relevant results of the solved MIP are displayed in the following tables. Table 8 shows the decision variable x_{ijk} , which essentially determines the flow shop schedule. All $x_{ijk} = 1$ are displayed. If the cell is empty, the binary variable equals 0. Line 3 serves as an example of how to read the results in Table 8: Job $i = 0$ on machine $j = 0$ is in the second position in the sequence ($k = 1$).

1.	k	0	1	2	3	4
2.	$i.j$					
3.	0.0		1.000			
4.	0.1		1.000			
5.	0.2		1.000			
6.	0.3		1.000			
7.	1.0			1.000		
8.	1.1				1.000	
9.	1.2			1.000		
10.	1.3					1.000
11.	2.0				1.000	
12.	2.1			1.000		
13.	2.2				1.000	
14.	2.3				1.000	
15.	3.0					1.000
16.	3.1					1.000
17.	3.2					1.000
18.	3.3			1.000		
19.	4.0	1.000				
20.	4.1	1.000				
21.	4.2	1.000				
22.	4.3	1.000				

Table 8. Results of decision variable x_{ijk}

All brought together, the decision variables $x_{ijk} = 1$ can be summarized in the sequential notation π_j :

$$\pi_1 = \{J_5, J_1, J_2, J_3, J_4\}$$

$$\pi_2 = \{J_5, J_1, J_3, J_2, J_4\}$$

$$\pi_3 = \{J_5, J_1, J_2, J_3, J_4\}$$

$$\pi_4 = \{J_5, J_1, J_4, J_3, J_2\}$$

The result shows the non-permutation flow shop sequence. The sequence of the jobs J_i on machine M_1 is J_5, J_1, J_2, J_3 , and then J_4 , whereas the sequence in the second machine M_2 changes to J_5, J_1, J_3, J_2 , and J_4 . The change of the sequence is possible. All required constraints are fulfilled. Despite the alternating sequences π_j on the machines M_j , the chronological completion of the different operations of each job from machine M_1 to machine M_4 is still satisfied.

1. j	0	1	2	3
2. k				
3. 0	0.000	1.000	3.000	7.000
4. 1	1.000	3.000	10.000	11.000
5. 2	2.000	10.000	12.000	18.000
6. 3	4.000	11.000	13.000	19.000
7. 4	9.000	13.000	16.000	20.000

Table 9. Start times of operations O_{kj}

Another decision variable that is important to determine the flow shop schedule holds the start times S_{kj} of the operations O_{kj} . Table 9 displays the start times of operations O_{kj} . The array of the decision variable x_{ijk} multiplied with the processing times p_{ij} for all j and k results in the processing times pt_{kj} , which are displayed in Table 10. The first operation on the first machine takes exactly one unit of time, whereas the first operation on the second machine requires two time units for completion.

1. j	0	1	2	3
2. k				
3. 0	1.000	2.000	3.000	4.000
4. 1	1.000	7.000	1.000	7.000
5. 2	2.000	1.000	1.000	1.000
6. 3	5.000	1.000	1.000	1.000
7. 4	4.000	2.000	2.000	1.000

Table 10. Processing times pt_{kj} of operations O_{kj}

The addition of Table 10 to Table 9 (i.e., addition of start times with processing times) results in the finish times of operations O_{kj} which are demonstrated in Table 11. The bottom right value represents the finish time of the last operation on the last machine, which is to be minimized in this MIP. In this example, the minimum makespan equals 21 time units.

1. j	0	1	2	3
2. k				
3. 0	1.000	3.000	6.000	11.000
4. 1	2.000	10.000	11.000	18.000
5. 2	4.000	11.000	13.000	19.000
6. 3	9.000	12.000	14.000	20.000
7. 4	13.000	15.000	18.000	21.000

Table 11. Finish times of operations O_{kj}

The results above can be visualized in a machine-oriented Gantt chart as proposed in chapter 2.4.2. For that, the start times S_{kj} of operations O_{kj} , as well as processing times pt_{kj} , are considered to set up a clearly arranged overview of the flow shop schedule. Figure 27 shows the machine-oriented Gantt chart of this first schedule calculated by the MIP with the aid of GAMS. The maximum makespan is marked on the timeline on the right-hand side with a value of 21 time units.

Figure 27. Machine-oriented Gantt chart

4.5 Configuration level

The focus of the configuration level within a CPPS is on a feedback loop which allows an adjustment in relation to changing factors within the system. This automation step adds self-configurability to the production system. At this point, the main advantage of the RFID system comes forward. All objects on the line are equipped with an active RFID tag so that processing times of the half-finished products can be live-tracked. Real-time control for monitoring or steering purposes opens up new opportunities in terms of scheduling the flow of objects (Lu et al., 2006).

Through the linkage of the tag reading time on a particular work station and the algorithm input variable of processing time p_{ij} , the system can be enhanced in terms of self-adapting capabilities. As soon as the processing times p_{ij} of those objects that have been at some of the work stations are available, deviations between the planned and the actual processing times can be considered for scheduling the jobs.

4.5.1 Rescheduling without a feedback loop

The schedule from the previous section is used as an initial sequence. When certain RFID tags attached to half-finished products are localized at one work station longer or shorter than initially planned, the theoretical optimal sequence might change. Under normal circumstances, the steering of the production flow would be highly complex and not flexible enough to fulfill the large requirements in terms of time sensitivity. Machines may be unavailable or delayed for different reasons in realistic scenarios, such as breakdowns or maintenance measures (Cui et al., 2016). A flexible steering mechanism is desired to exploit the potential of flow shop scheduling fully.

After the optimization of the sequence in the previous chapter, the same scenario is applied with a random involvement of machine delay and process acceleration. Compared to Table 7, the processing times p_{ij} for jobs J_i on machines M_j differ now in three specific job/machine combinations. Table 12 contains the processing times p_{ij} in a slightly adjusted form.

		Machines M			
		M_1	M_2	M_3	M_4
Jobs J	J_1	1	7	1	7
	J_2	2	6 (1)	1	1
	J_3	2 (5)	1	1	4 (1)
	J_4	4	2	2	1
	J_5	1	2	3	4

Table 12. Adjusted processing times p_{ij} for jobs J_i on machines M_j

Let these bold, red-marked processing times either derive from the RFID tags on the line or manually stated by the assembly line operator who discovers an inconsistency with a job/machine combination. In addition, preventive maintenance measures can be anticipated and considered in this scenario. The focus of interest is how the makespan criterion is affected by the delay of these jobs on the machines without re-scheduling the sequences in real-time. The Gantt chart from Figure 27 is used, and the three operations, which hold different processing times, are adjusted. The sequences π_1 to π_4 are not changed in this schedule. Let the progress of the processing of the jobs be at a timestamp of 4 time units. Due to the non-preemption constraint, the operations for individual jobs cannot be stopped but must be finished once started. Figure 28 displays the results.

Figure 28. Machine-oriented Gantt chart with adjusted processing times

Despite the decrease of processing time p_{31} , the increase of the processing times p_{22} and p_{34} significantly increases the makespan of the production schedule. The makespan of this schedule increases from an optimal of 21 time units to a value of 28 time units, which is an increase of 33.3%. When an assembly line faces unpredictable delays or time savings due to particular reasons, the flexible rescheduling of a flow shop environment with non-permutation character is a time-sensitive and challenging issue for manufacturers.

4.5.2 Rescheduling with a feedback loop

At this point, the advantage of real-time scheduling emerges. The line at a timestamp of 4 time units in Figure 28 and Figure 29 marks the live status of progress. The machines work on the corresponding operations which have been assigned to them in the initial schedule simulation.

In a real-time rescheduling, the changes displayed in Table 12, can be considered

although the operation of the assembly line is already running. Due to the non-preemption constraint, operations which have started at the corresponding point in time are also frozen. Operations cannot be stopped once they have started. To avoid the rescheduling of the entire job/machine allocation and sequence, the binary variables x_{ijk} for the operations, that have been finished or have already started at the time stamp of 4, are frozen to a value of 1. In so doing, the work finished in the past is not touched by the algorithm.

The rescheduling is simulated in GAMS with the adjusted input processing times and the frozen binary variables x_{ijk} . The results are not completely displayed in the main body of this study. Appendix D contains four tables (Table 16 through Table 19), which are analogous to Table 8 through Table 11. They display the decision variables for the corresponding schedule. These values can be transferred to a machine-oriented Gantt chart, which is visualized in Figure 29. A rescheduling of the operations under consideration of frozen operations, which have been finished or started, results in a real-time optimization of the operation schedule.

Figure 29. Machine-oriented Gantt chart with adjusted processing times after rescheduling

In comparison to the makespan of 28 time units after the revealing of random processing time changes, the real-time rescheduling of sequences under consideration of the changes enables a reduction of the makespan to a value of 24 time units. Concerning the initial schedule with a makespan of 21 time units, this optimization can reduce the effect of the machine delay. Hence, the overall makespan increases only about 14.3% instead of 33.3%.

The sequences π_j change after the rescheduling:

$$\pi_1 = \{J_5, J_1, J_2, J_3, J_4\}$$

$$\pi_2 = \{J_5, J_1, J_2, J_3, J_4\}$$

$$\pi_3 = \{J_5, J_1, J_2, J_3, J_4\}$$

$$\pi_4 = \{J_5, J_1, J_2, J_3, J_4\}$$

If the production system operator flexibly adapts this rescheduled sequence, a significant increase in the total makespan can be avoided. A situation-based

optimization is capable of limiting the potential time losses originating from unforeseeable delays.

Figure 30. Three schedules compared in a Gantt chart overview

Figure 30 joins all three Gantt chart from before in one graphic. It is shown that a rescheduling after the random change of three processing time variables significantly affects the initial schedule with a makespan of 21. The delay of machines leads to a makespan increase of 33.3% from 21 to 28 time units. With reference to the remarks in the section of the stochastic FSSP, machine breakdowns, delays or other disturbances are realistic in an industrial surrounding. A rescheduling of the remaining jobs and operations to be processed is beneficial. Table 13 summarizes the main results from this small-scaled simulation. The initial schedule, the reschedule without an optimizing feedback loop as well as the reschedule with the optimizing feedback loop are compared with each other. The sequences π_j for each schedule, the makespan in time units and the relative deficit between the reschedules and the initial schedules are displayed.

	Initial schedule	Reschedule <i>without</i> feedback loop	Reschedule <i>with</i> feedback loop
Sequence π_j	$\pi_1 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_2 = \{J_5, J_1, J_3, J_2, J_4\}$ $\pi_3 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_4 = \{J_5, J_1, J_4, J_3, J_2\}$	$\pi_1 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_2 = \{J_5, J_1, J_3, J_2, J_4\}$ $\pi_3 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_4 = \{J_5, J_1, J_4, J_3, J_2\}$	$\pi_1 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_2 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_3 = \{J_5, J_1, J_2, J_3, J_4\}$ $\pi_4 = \{J_5, J_1, J_2, J_3, J_4\}$
Makespan [time units]	21	28	24
Relative deficit to initial schedules' makespan		-33.3%	-14.3%

Table 13. Overview schedule simulations

Another relevant factor which has to be considered especially in a real-time situation is the computing time to solve the MIP. Since the number of possible sequences with $n \times m$ combinations results from $(n!)^m$, the computing performance might limit the flexibility of the rescheduling algorithm. The CPLEX solver needs around 0.17 seconds to solve the MIP from the example above with $n = 5$ and $m = 4$.

If the number of machines m increases, the computing time grows significantly. An $n = 5$ and $m = 5$ combination takes about 32.6 seconds to find the optimal solution with an acceptable relative gap (e.g., 0.1). As soon as the number of machines m exceeds a value of 6, the computing time surpasses the acceptable limit in a real-time environment. An $n = 5$ and $m = 7$ job/machine combination needs around 4 hours to find an optimal solution with a relative gap of 10%. This limitation is further considered in the concluding section in chapter 5.

CHAPTER 5 - CONCLUSION

5.1 Implications

This study takes an integrative approach and synergizes three entirely different dimensions which elicit individual and interactional benefits to the developed system. The ultimate goal of this research study to propose a CPPS that benefits from principles and practices of the Kanban philosophy, is enriched with technological resources as well as equipped with a real-time enabled optimization approach, has been a success. The 5C architecture framework has guided a path to develop an integrative CPPS under consideration of the three contributing dimensions.

After the technical assessment of the latest RFID technology, an appropriate choice has been made to enhance the production system with an advantageous technological improvement. The technology enriches a manually steered serial production line and offers great potential to enhance transparency and flexibility for planning, monitoring, and controlling purposes. Concerning the lean manufacturing aspect, major techniques of the Kanban philosophy as an enabler of JIT production have been adopted. However, not all original mechanisms find their way in the newly designed system.

To provide the CPPS with self-configurability and flexibility, an MIP is introduced in the cognition and configuration level of the system design. This algorithm has proved its capability not only to find an optimal sequence initially with the objective of minimizing the makespan but also to flexibly adjust a schedule in case of machine breakdowns or delays. The rescheduling with an integrated feedback loop shows that a flexible recalculation under consideration of several constraints can significantly

decrease the time loss caused by machine delays.

Figure 31. Business process model: Overall system functionality

Figure 31 summarizes the overall system functionality in a business process model with three different layers. This graphic shows the strong interrelation between different system components. The MIP is the backbone of the backend system and communicates with the production and management level. On both levels, the display of production-relevant information fulfills the Kanban philosophy's practice of visualization. The real-time feedback loop between the production and backend layer is realized through the RFID tags indicating any kind of machine delays. After recalculation by the MIP, the backend system sends the information to the production and management layer, where it is displayed. A manual input by the managers can prioritize orders; a manual input by production workers can indicate an unplanned or planned disruption of production. The MIP can flexibly be provided with data that improves the

accuracy of production planning, monitoring, and steering.

The developed system has several implications for practice and theory, which are outlined in this section. First of all, it is highly recommended for manufacturing organizations to apply innovative technology to their production lines since the progress in embedded system architectures has reached a point where practical advantages justify the financial expenses and effort. The quality, as well as availability of cost-efficient RFID technology that supports the operation, monitoring, controlling and steering of a production line, highly suggests an industrial utilization.

Secondly, the scheduling algorithm has shown that a rational calculation, as well as flexible re-calculation of situation-based optimal solutions, excels manual decision-making. With the implementation of smart scheduling systems, the distinction from competitors through a strong production logistics strategy mentioned in the introductory section of this study can be realized. The rise of Industry 4.0 implies technological progress but also offers a higher degree of freedom for manufacturers. An efficient steering mechanism that is capable of handling non-permutation scheduling excels over a rigid permutation schedule. Industry 4.0 enables more complex but also more efficient operation of production lines.

As a third dimension, the Kanban philosophy has shown that traditional principles and practices are not outdated but contribute to an economically powerful system. In practice, adaptations in comparison to the original concept are beneficial, and manufacturers are recommended to develop a customized version of technologically enhanced Kanban systems in order to accomplish a lean manufacturing environment.

5.2 Limitations

There are several limitations to this study which cannot be neglected. Some of these limitations may lead to further research questions which are outlined in the next section.

A major limitation must be drawn concerning the MIP used for the program simulation. The algorithm has proved that a combinatorial optimization approach can lead to fast and precise results, which can significantly reduce the time loss caused by machine delays. With large-scaled $n \times m$ combinations, however, the simulation of the MIP with the software GAMS absorbs a large period of time. This problem cannot entirely be resolved by the use of a high-performance computing device. Considering the objective of this study to reschedule job/machine allocations and sequences in a real-time manner, large computing times are unacceptable and diminish the main benefit of this project. The outlook section below provides possible solutions for this limitation.

The MIP is based on several assumptions that aim to simplify and generalize the dynamic production environment. An especially notable assumption is that machine set-up, tooling and change-over times are either included in the processing times or negligible. This assumption, however, distorts a realistic scenario. A significant challenge in mixed model production lines concerns the flexibility of work stations to fulfill several different operations. These operations often require specific set-up times for machines and tools. To include them in the processing times or even neglect them totally, does not reflect a realistic system representation.

Another inefficiency concerns the integrative system design. The greatest challenge in developing a CPPS may be the design of system interfaces. These interfaces

link different stages or dimensions with each other. Concerning the proposed system design, the interlink between the RFID application's output and the input of the simulation software is a complex issue which requires a customized software client solution. Especially the requirement of real-time functionality implies a considerable challenge. This study indicates a possible solution suggesting a data transfer through the TCP/IP port, but does not entirely develop a feasible solution.

The lean dimension in this study considers several principles and concrete practices of the Kanban philosophy as an enabler of a JIT production. During the development of a flexible production system, which is steered by an intelligent algorithm in order to optimize object flows, several relevant features of the traditional Kanban concept had to give way to essential elements of the technological and scheduling dimension. An example can be the intermediate buffers between the stations which enable the non-permutation scheduling characteristic but also strongly compete against the Kanban principle of minimizing WIP inventory. Literature has shown that customized versions of the Kanban concept add value to a production system on the lean dimension level. Therefore, this limitation has to be mentioned but is justified with regard to the overall system functionality.

5.3 Outlook

This research project shows potential development perspectives in several disciplines which can give guidance to research and practice to adjust their investigative efforts. From a technological point of view, RFID technology has emerged inexorably. The investment costs for implementing such technology in CPPS are still decreasing.

This provides an increasingly attractive opportunity for manufacturers to digitize their production. Regarding the development progress, the industrial utilization of CPSs still lacks assertion. Especially the standardization of system architectures is a challenge which should be taken on in order to provide integrative system designs. The system's internal interfaces are an especially notable challenge which should be examined in detail. Regarding RFID technology, in particular, a major exploratory focus should be on the control of interferences as well as standardization issues such as globalized frequency standards.

In the dimension of lean manufacturing, and especially the philosophy of Kanban as an enabler of JIT production, major uncertainty can be localized in integrated solutions with a digital element. Electronic Kanban systems offer great advantages, especially in simple production environments with mixed model operation. The ease of use and transparent availability of information at any time of the production process can be significantly leveraged by the implementation of technology. Further research could improve the functionality of electronic Kanban systems.

One of the greatest takeaways is the proof that RFID technology in connection with an intelligent algorithm is capable of flexibly steering a mixed model production system. The limitations concerning the MIP applied in this study have shown that a combinatorial optimization approach is limited by a time constraint. Despite the use of a high-performance computer, the computing time of larger $n \times m$ combinations have shown that an optimal solution can be found, but the calculation time exceeds acceptable time periods. At this point, it is highly recommendable to introduce a heuristic approach for solving the non-permutation FSSP. Research on techniques such as genetic

algorithms, simulated annealing, taboo search, or greedy algorithms can significantly decrease the computing time but accomplish comparable results with small relative gaps between an optimal and an approximated value. Hence, the introduction of an approximative algorithm taking a heuristic approach can increase the flexibility of the rescheduling. The MIP results in an optimal solution but might take up a significant amount of time, which can diminish the effect of a real-time rescheduling. The research focus on heuristic approaches for this particular system design offers an attractive opportunity to further enhance agility and configurability of the developed system.

APPENDICES

Appendix A

Figure 32. Linear and circular polarization patterns of RFID antennas (AtlasRFIDstore, 2019b)

Appendix B

α – Machine environment		
Single stage problems	I	single machine
	P	m parallel identical machines
	Q	m parallel machines with different given speeds, length of job j on machine i is the processing time p_j divided by speed s_i
	R	m parallel unrelated machines, there are given processing times p_{ij} for job j on machine i
Multi stage problems	O	open shop problem; every job j consists of m operations O_{ij} for $i = 1, \dots, m$. The operations can be scheduled in any order. Operation O_{ij} must be processed for p_{ij} units on machine i .
	F	flow shop problem; every job j consists of n_j operations O_{ij} for $k = 1, \dots, n_j$ to be scheduled in that order. Operation O_{ij} must be processed for p_{ij} units on machine i .
	J	job shop problem; every job j consists of n_j operations O_{kj} for $k = 1, \dots, n_j$ to be scheduled in that order. Operation O_{kj} must be processed for p_{kj} units on a dedicated machine μ_{kj} with $\mu_{kj} \neq \mu_{k'j}$ for $k \neq k'$
These letters can be followed by the number of machines m which indicates a fixed number of machines (e.g., $P2$ or $F4$).		
β – Job characteristics		
Release dates	r_j	job j cannot start its processing before its release date r_j . If r_j does not appear in the β field, the processing of job j may start at any time.
Preemptions	$prmp$	Preemptions imply that it is not necessary to keep a job on a machine, once started, until its completion. The scheduler is allowed to interrupt the processing of a job (preempt) at any point in time and put a different job on the machine instead. When preemptions are allowed $prmp$ is included in the β field; when $prmp$ is not included, preemptions are not allowed.
Precedence constraints	$prec$	Precedence constraints may appear in a single machine or in a parallel machine environment, requiring that one or more jobs may have to be completed before another job is allowed to start its processing. If no $prec$ appears in the β field, the jobs are not subject to precedence constraints.

<i>Sequence dependent setup times</i>	s_{jk}	The s_{jk} represents the sequence dependent setup time that is incurred between the processing of jobs j and k ; If no s_{jk} appears in the β field, all setup times are assumed to be 0 or sequence independent, in which case they are simply included in the processing times.
<i>Job families</i>	$fmls$	The n jobs belong in this case to F different job families. Jobs from the same family may have different processing times, but they can be processed on a machine one after another without requiring any setup in between. If this setup time depends only on the family about to start, i.e., family h , then it is denoted by s_h . If it does not depend on either family, it is denoted by s .
<i>Batch processing</i>	$batch(b)$	machines may be able to process a number of jobs, say b , simultaneously; that is, it can process a batch of up to b jobs at the same time. If $b = 1$, then the problem reduces to a conventional scheduling environment. Another special case that is of interest is $b = \infty$, i.e., there is no limit on the number of jobs the machine can handle at any time.
<i>Breakdowns</i>	$brkdwn$	Machine breakdowns imply that a machine may not be continuously available. Machine breakdowns are at times also referred to as machine availability constraints.
<i>Machine eligibility restrictions</i>	M_j	The M_j symbol may appear in the β field when the machine environment is m machines in parallel (Pm). When the M_j is present, not all m machines are capable of processing job j . Set M_j denotes the set of machines that can process job j . If the β field does not contain M_j , job j may be processed on any one of the m machines.
<i>Permutation</i>	$prmu$	A constraint that may appear in the flow shop environment is that the queues in front of each machine operate according to the <i>First In First Out (FIFO)</i> discipline. This implies that the order (or <i>permutation</i>) in which the jobs go through the first machine is maintained throughout the system.
γ – Objective function All the objective functions below are so-called <i>regular</i> performance measures. A regular performance measure is a function that is <i>non-decreasing</i> in $C_1, \dots, C_n$.		
<i>Makespan</i>	C_{max}	The makespan, defined as $\max(C_1, \dots, C_n)$, is equivalent to the completion time of the last job to leave the system. A minimum makespan usually implies a good utilization of

		the machine(s).
<i>Maximum Lateness</i>	$L_{\max}$	The maximum lateness, $L_{\max}$, is defined as $\max(L_1, \dots, L_n)$. It measures the worst violation of the due dates.
<i>Total weighted completion time</i>	$\sum w_j C_j$	The sum of the weighted completion times of the n jobs gives an indication of the total holding or inventory costs incurred by the schedule. The sum of the completion times is in the literature often referred to as the flow time. The total weighted completion time is then referred to as the weighted flow time.
<i>Total weighted tardiness</i>	$\sum w_j T_j$	This is also a more general cost function than the total weighted completion time.
<i>Weighted number of tardy jobs</i>	$\sum w_j U_j$	The weighted number of tardy jobs is not only a measure of academic interest, it is often an objective in practice as it is a measure that can be recorded very easily.

Table 14. Notation for theoretic scheduling problems (Pinedo, 2016)

Appendix C

```

1. SetS
2. i index for JOBS J1 .. Jn
3. j index for MACHINES M1 .. Mm ;
4.
5. Alias(i, k);
6. Alias(i, k1);
7.
8. Parameter pt(i,j);
9.
10. $onecho > DATA1.txt
11. dset=i   rng=DATA1!a1   rdim=1
12. dset=j   rng=DATA1!a1   cdim=1
13. par=pt   rng=DATA1!a1   rdim=1 cdim=1
14. $offecho
15.
16. $call GDXXRW DATA1.xlsx @DATA1.txt
17. $GDXIN DATA1.gdx
18. $load i
19. $load j
20. $load pt
21. $GDXIN
22.
23. Variables
24. Cmax                Objective
25.
26. POSITIVE Variables
27. C(k,j)              Finish time of O-kj
28. P(k,j)              Processing time of O-kj
29. S(k,j)              Start time of O-kj
30. ;
31.
32. Scalar MBIG /200/;
33.
34. Binary Variables
35. x(i,j,k)            'Job sequence decision variable'
36. ;
37.
38. EQUATIONS
39. ComplTime(k,j)        denotes the completion time of the last job
40. Con1(j,k)             ensures that all jobs are done
41. Con2(j,i)             ensures that every position k takes one job j
42. Con3(k,j)             specifies the processing time of operation O-kj
43. Con4(k,j)             link between the start and finish time of O-kj
44. Con5(k,j)             first job starts with a time stamp of 0
45. Con6(j,k)             kth job starts after finish time of its
immediate predecessor
46. Con7(i,j,k,k1)        ensures that the start time of job i in Mj+1 is
not earlier than its finish time in Mj
47. ;
48.
49. ComplTime (k,j)$ (ORD(k) eq card(k) and ORD(j) eq card(j)
.. Cmax =E= C(k,j) ;

```

```

50. Con1(j,k) .. SUM(i,X(i,j,k))=E=1;
51. Con2(j,i) .. SUM(k,X(i,j,k))=E=1;
52. Con3(k,j) .. P(k,j) =E= SUM(i,X(i,j,k)*pt(i,j));
53. Con4(k,j) .. C(k,j) =E= S(k,j)+P(k,j);
54. Con5(k,j)$ (ORD(k) eq 1 and ORD(j) eq 1 )
    .. S(k,j)=E=0 ;
55. Con6(j,k)$ (ORD(k) ne 1 ) .. S(k,j) =G= C(k-1,j);
56. Con7(i,j,k,k1)$ (ORD(j) ne card(j))
    .. 2*MBIG -X(i,j,k)*MBIG -X(i,j+1,k1)*MBIG =g= S(k,j)+pt(i,j)-
S(k1,j+1);
57.
58. MODEL FSSP /ALL/;
59. OPTION MIP=CPLEX;
60. OPTION RESLIM =400;
61. OPTION THREADS=48;
62. OPTION LIMCOL=20, LIMROW=20;
63. OPTION OPTCR=0.01;
64.
65. SOLVE FSSP USING MIP MINIMIZING Cmax;
66.
67. DISPLAY i,j, pt, X.l ,C.l, S.l, P.l, Cmax.l ;

```

Table 15. GAMS formulation code for $Fm // Cmax$ non-permutation FSSP

Appendix D

1.	k	0	1	2	3	4
2.	i.j					
3.	0.0		1.000			
4.	0.1		1.000			
5.	0.2		1.000			
6.	0.3		1.000			
7.	1.0			1.000		
8.	1.1			1.000		
9.	1.2			1.000		
10.	1.3				1.000	
11.	2.0				1.000	
12.	2.1				1.000	
13.	2.2				1.000	
14.	2.3			1.000		
15.	3.0					1.000
16.	3.1					1.000
17.	3.2					1.000
18.	3.3					1.000
19.	4.0	1.000				
20.	4.1	1.000				
21.	4.2	1.000				
22.	4.3	1.000				

Table 16. Results of decision variable x_{ijk} with adjusted processing times

1.		0	1	2	3
2.					
3.	0		1.000	3.000	7.000
4.	1	1.000	3.000	10.000	11.000
5.	2	2.000	10.000	16.000	18.000
6.	3	4.000	16.000	17.000	22.000
7.	4	6.000	17.000	19.000	23.000

Table 17. Start times of operations O_{kj} with adjusted processing times

1.		0	1	2	3
2.					
3.	0	1.000	2.000	3.000	4.000
4.	1	1.000	7.000	1.000	7.000
5.	2	2.000	6.000	1.000	4.000
6.	3	2.000	1.000	1.000	1.000
7.	4	4.000	2.000	2.000	1.000

Table 18. Adjusted processing times p_{ij} for jobs J_i on machines M_j

1.		0	1	2	3
2.					
3.	0	1.000	3.000	6.000	11.000
4.	1	2.000	10.000	11.000	18.000
5.	2	4.000	16.000	17.000	22.000
6.	3	6.000	17.000	18.000	23.000
7.	4	10.000	19.000	21.000	24.000

Table 19. Finish times of operations O_{kj} with adjusted processing times

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