CHALMERS
UNIVERSITY OF TECHNOLOGY

Smart Manufacturing systems – a Testbed for decision support tool requirements

Master' Thesis in Production Engineering

Christian Eliasson Lilja

Master's Thesis in Production Engineering – 2018

Smart Manufacturing systems – a Testbed for decision support tool requirements

Christian Eliasson Lilja

Department of Industrial and Material Science
Division of Production Systems
Chalmers University of Technology
Gothenburg, Sweden 2018

Smart Manufacturing systems – a Test bed for decision support tool requirements.
Christian Eliasson Lilja

Company Supervisor: Johan Andersson, Axxos
Supervisor: Mukund Subramaniyan, Ph.D., Department of Industrial and Material Science
Examiner: Anders Skoogh, Director, Department of Industrial and Material Science

Master's Thesis 2018
Department of Industrial and Material Science
Chalmers University of Technology
SE-412 96, Gothenburg.
Sweden
Telephone +46 (0)31-772 1000

Cover: Smart Manufacturing systems – a Testbed for decision support tool requirements.

Printed by Reproservice, Chalmers
Gothenburg, Sweden 2018

Abstract

Staying competitive in today's global pushes companies to continuously work on improving operations to increase productivity while decreasing downtime. By focusing maintenance activities and production improvement work on bottleneck machines, system-wide productivity increases. But implementing new methods into existing production environments brings with it challenges, knowing these challenges is critical to minimize disruption during installation. The purpose and aim of this thesis are to demonstrate analysis algorithms utilizing a test bed to help facilitate knowledge exchange between industry and academia while examining the specifications put on a production system by a data-driven shifting bottleneck (SBN) method. A literature study regarding testbed architectures and data collection was conducted to gain knowledge regarding the current challenges and solutions in the research field. Critical aspects were identified during a stakeholder analysis and testbed system was then designed and built. The result was a testbed system consisting of four workstations each with an accompanied PLC box. Using OPC UA communication to connect the testbed with a data collection system provided by Axxos that was installed on a virtual server. Finally, a computerized maintenance management system (CMMS) software provided by IFS was installed. A shifting bottleneck algorithm using the data obtained from the testbed was also implemented. Three main requirements for the testbed was found that focuses on data collection, storage, and formatting. Existing research on shifting bottleneck is limited to simulation and imported production MES data scenarios. Expanding the field into testbed systems benefits academia by offering new avenues of cooperation with various partners while facilitating to solve potential challenges for the industry.

Keywords:
Maintenance, data-driven, smart manufacturing, test-bed, data analysis, shifting bottleneck, requirements

Acknowledgments

A master thesis is always a testing ordeal and thus I would like to give my thanks to all the people that have been involved to make this possible. First and foremost, I would like that thank Anders Skoogh for making it possible for me to work on this thesis. I would also like to give my greatest of thanks to my supervisor Mukund Subramaniyan for the constant support and patience during this project.

I would like to thank Sven Ekered and Åsa Fasth Berglund for the work and expertise provided during the work with designing and installing the demonstrator in the Chalmers Smart Industry Lab.

I would like to thank Johan Andersson at Axxos for helping me throughout the project with the data collection and letting me come and visit their company in Jönköping.

I'm also extending thanks to my colleagues Patricia Quijada Fumero and Omkar Salunkhe for the challenging work and support while working at the CSI lab, thank you for making this a wonderful experience!

Last but in no way the least I would like to thank friends and family that have helped and made my time at Chalmers a very enjoyable.

Christian Eliasson Lilja, Gothenburg, 2018

TABLE OF FIGURES

Table of Contents

1. Introduction

1.1 Background

The digital transformation of manufacturing industry has recently started but already reached an impressive pace in companies around the globe. Initiatives like Industry 4.0 have gained substantial attention to create smart factories with high productivity, flexibility, robustness, and sustainability. However, when discussing the topic, the focus is mainly from a business perspective where one look at it from an elevated level. This leads to an information gap where the technical complexity that is the foundation on which Industry 4.0 and Industry Internet of Things a built on takes a back-seat role (Gilchrist, 2016). Acquiring knowledge about the technical aspects then becomes the key to both understanding how it all works but also what benefits go with them. The concept of the Industrial Internet is to gain better insight and visibility of the company's operations by integrating software, cloud computing, storage systems and machine sensors. The drive to change the traditional manufacturing facilities into highly flexible and optimized smart factories stems from the data-driven revolution gaining traction (O'Donovan *et al.*, 2015). These initiatives combined with the ever-evolving digital world brings with it an immense increase in data production. Three main characteristics of big data were identified in (Gantz and Reinsel, 2012), the produced data itself, data analytics, and data visualization. In the end, big data should be approached with a holistic view to manage, analyze and process the various aspects of the big data. The ability of companies to embrace this revolution in big data to gain decisive competitive advantages will play a significant role in the rapidly changing market (Fosso Wamba *et al.*, 2015).

Manufacturing execution systems are on the powerful tools companies can use for production management support. They act as the backbone for data acquisition and communication from the sensors and information on the machine level all the way to the system level. The data gathered in the production environment is the basis on which the production system plans and executes its operations and it is thus imperative that the data is accurate to a high degree (Lee, Nam, and Lee, 2012). Findings in (Zelbst *et al*. 2011) indicates that the adoption of Radio-frequency identification (RFID) technology into the production system and the data being collected from it affects the ability in which the organization can move, leading to a positive impact on logistic and operational performance. This is but one example of the impact of the big data revolution, it is spread throughout every aspect of the company. With the advent of smart factories, all departments and their role will be affected, maintenance is one of them. With the increase of big data analytics, methods are being developed in a wide variety of areas to take advantage of the vast amount of production data to increase productivity. Ylipää *et al.* (2016) show that the average OEE in the manufacturing sector is 51.5%, the utilization of finite production resources paints a picture of vast possibilities for improvements. In the maintenance sector the usage of decisions support systems (DSS), such as computerized maintenance management system (CMMS) will only become more prevalent. Utilizing methods for bottleneck detection using real-time data-driven information in the DSS, one takes advantage of the production data flowing from the system and using it for big data analytics. Studies done by (Li and Ni, 2009; Li, Ambani and Ni, 2009) has shown potential productivity increase by focusing maintenance work on the throughput critical machines.

1.2 Purpose and aim

The purpose of the thesis is to demonstrate analysis algorithms using a test-bed to exchange knowledge between academia and industry. The aim of this thesis is to examine the specifications required for a production or test-bed system for implementation of a data-driven bottleneck detection method. By gaining knowledge of current test-bed research one can see what type of components are needed when building a demonstrator so that all areas of interest are included. Observing how current manufacturing executions systems handle data collection, communication and storage are necessary for the feasibility of any implementation of the data-driven bottleneck method.

The thesis is a part of a larger project called Data Analytics in Maintenance Planning (DAIMP) that aims to address the problem with insufficient availability and robustness in Swedish production systems. Within this overarching idea lies various challenges such as the ability to implement digital production, capabilities of introducing new products and limited productivity. By utilizing and improving maintenance planning based on big data analytics there are great possibilities to increase the competitiveness of the Swedish automotive industry.

The thesis takes place at Chalmers Smart Industry Lab (CSI) that acts as both a laboratory and demonstration facility for next-generation productions systems. Offering technological solutions within the areas of fast communications systems, augmented reality assembly and open robotics environment. The CSI lab works with training future engineers while also providing the opportunity for the industry to test innovative technologies in practical test beds.

1.3 Research questions

- Research Question 1: What type of architectures are available when constructing a demonstrator test-bed system?

By understanding the different foundations, a test-bed system is built upon, one can more readily gain knowledge about the challenges faced when implementing analysis methods or algorithms.

- Research Question 2: What are the requirements for shifting bottleneck method implementation in a test-bed or production environment?

Introducing new methods of detecting the productions system bottleneck is a necessity to be able to improve productivity. By understanding the requirements put on a production and manufacturing execution system it simplifies the installation into the existing environment.

1.4 Delimitations

Delimitations have been made for the timeframe of the project but also for the availability of materials and equipment in Chalmers Smart Industry Lab

- No real-time continuous shifting bottleneck calculations were done, instead, it was run whenever the database was imported into the algorithm.
- The production systems have a low level of automation and all assembly work is being done manually by operators.
- Only one product variant was assembled in the demonstrator system

2. Methodology

2.1 Research methodology

Methodology is, in the essence, the way researchers conducts their research. Procedures fitting the project at hand are followed to achieve a desired result (Jonker and Pennink, 2009). Depending on the premises of the project different approaches can be utilised. The purpose of the thesis is to demonstrate analysis algorithms using a test-bed to exchange knowledge between academia and industry while the aim of this thesis is to examine the specifications required for a production or test-bed system for implementation of a data-driven bottleneck detection method. To be able to gather the necessary information to answer the research question mixed methods (Denscombe, 2014) will be utilized. Quantitative and qualitative data will be gathered and analysed and worked into an adapted version of the Cross-industry standard process for data mining (CRISP-DM) model that is used for this project. The basic premises of the CRISP-DM is shown in figure 1 and a short explanation for each step is done based on (Chapman *et al.*, 2000).

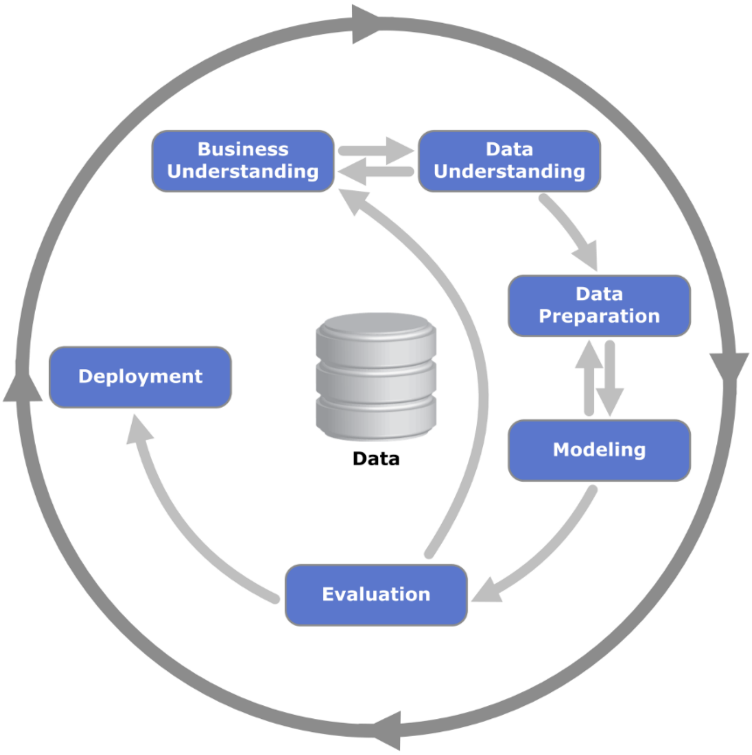


Figure 1: CRISP-DM reference model (Chapman et al. 2000)

Business understanding:

The focus on the initial step is to both gain an understanding of the projects objectives and requirements based on a business perspective and later converting said information into a usable problem definition for data mining.

Data understanding:

This phase consists of the initial data collection tasks. Activities to familiarize with the data, data quality identification, insight discovery regarding the data and conducted.

Data preparation:

Any activity that are needed to construct the final dataset and covered in this phase. Repetition of these tasks are likely needed to finalize the phase.

Modeling:

During this phase the various modeling techniques are selected and applied. Several techniques can be used for the same data mining problem with each having their own set of specific parameters. Due to this there is a necessity to move between this and the previous phase.

Evaluation:

When reaching this stage of the project and working model is likely built. It is crucial to both evaluate the model and the steps taken to reach this stage so that all the business objectives from previous phases are met.

Deployment:

After having evaluated and tested the models one reaches the deployment stage. This stage can either be completed by the researcher or the costumer, the final deployment can take various forms depending on the desired outcome. What is important to not that reaching the final stage is generally not the end of the project due to the iterative nature of the methodology.

2.2 Work Flow

CRISP-DM is a very adaptable methodology and can be used to fit different projects. For this thesis the crisp-dm model has been adapted into the project work flow shown below in figure 2.

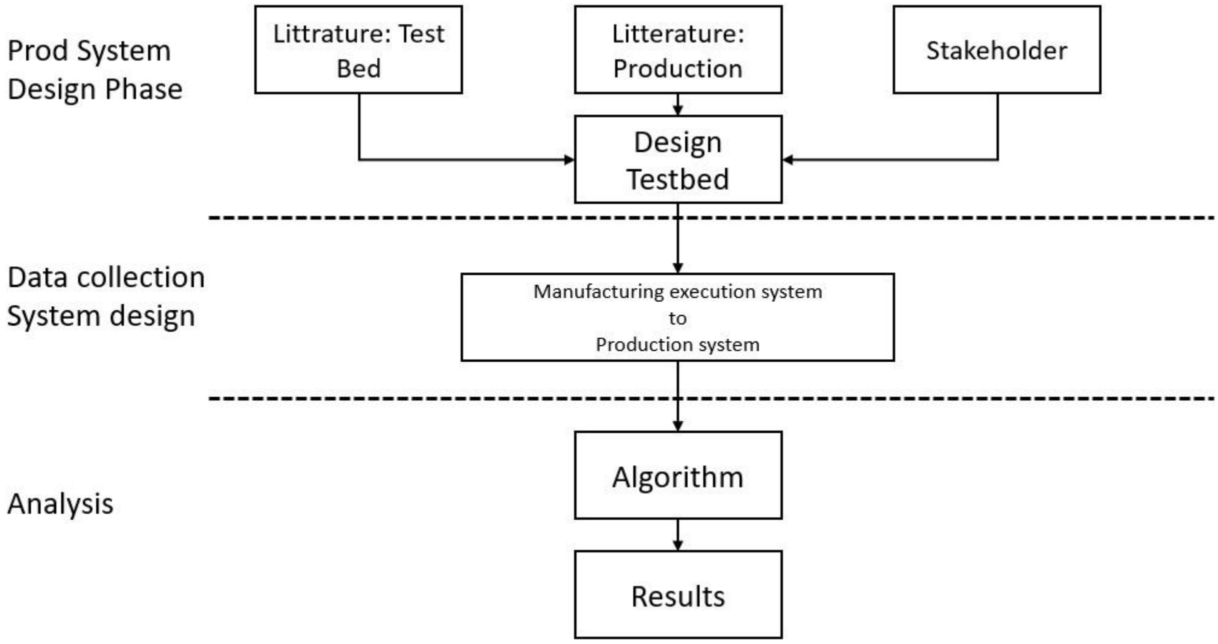


Figure 2: Methodology structure

2.3 Literature review

As part of the methodological framework of the thesis, a literature review was conducted to gather quantitative data. Two distinctive paths were identified and literature regarding both are analyzed first and then later combined to produce the basis for the design of the test-bed.

Scientific databases such as Scopus, Google Scholar and Summon, the Chalmers University Library database, were used to find suitable knowledge.

The first path investigated were literature pertaining to test-bed systems and their design. Main search strings such as; test-bed; demonstrator; cyber-physical systems; smart manufacturing; Manufacturing execution systems; CMMS; Learning Factories were used to filter our article from the databases.

The second path investigated was based on the first research question where information about the bottleneck method and decision support was the main focus. Keywords used were shifting bottleneck; decision support; data-driven; real-time; bottlenecks.

2.4 Stakeholder analysis

With the thesis being a part of the large project DAIMP a stakeholder analysis is conducted to identify the different requirements of the system. The methodology behind the stakeholder analysis in this report is based on the framework put forth in Reed *et al.* (2009). Semi-structured interviews were completed with each of the identified stakeholders to collect the needed data. The analysis was later done on the collected data to classify the relationship between the stakeholders and consider future actions that could be taken after the completion of the thesis.

The identified stakeholders within the scope of this thesis were; the examiner and supervisor for the thesis, both researchers in DAIMP project; one employee at the company providing the data collection system and two employees at the company providing the CMMS for the system.

2.5 Data collection and system design

By combining the literature review and stakeholder analysis a clearer picture regarding the requirement and design of a test-bed system will be available. A small demonstrator system will be built in the CSI lab using the principles gathered together with already existing available resources. Beyond that, the software from the companies participating in the DAIMP project will be installed in the proposed system. Any requirements regarding this implementation such as server installation or other infrastructure will be undertaken by the authors and employees at the CSI lab.

2.6 Analysis tools

After the demonstrator has been installed in the lab to the specifications of a possible test-bed system, combined with the requirements put on the system by the bottleneck method the implementation of a shifting bottleneck analysis tool will be done.

3. Theory

The purpose of this thesis was to examine the specifications requirement on a demonstrator system for the shifting bottleneck method. This was done by building a demonstrator at the Chalmers Smart Industry lab as part of the Data Analysis in Maintenance planning (DAIMP) project. Knowledge regarding test-bed and demonstrator systems, manufacturing execution systems, data collection, and communication, and bottleneck detection will be presented and becomes the basis for the construction and development of the CSI lab system.

3.1 Test-bed and Learning Factories

With the advent of the data-driven revolution spurred on by concepts such as Industry 4.0 and IIoT, it is of utmost importance for both companies and researchers to develop innovative ideas to facilitate the new era. New advanced manufacturing capabilities and complex digital technologies lead us into smart manufacturing. This area is needed to satisfy the increased demand for improvements to manufacturing systems agility, productivity, and its sustainability. The concept of the cyber-physical system is built upon the collaboration between the digital world and the physical instances in the manufacturing environment (Liu & Zhang, 2016). To enable companies and academia to evaluate new analytical methods, software, middleware, and hardware a new platform design will need to be envisioned. A problem that often occurs is that access to the information required for this endeavor is hampered by both intellectual property and security risks. Meaning that is it hard to fully understand the necessary means of how to collect, analyze, transmit or act on data and information that is present throughout the whole enterprise. Instead one must rely on other methods such as simulations and test-beds that emulate manufacturing systems (Helu and Hedberg, 2015; Lee *et al.*, 2015). In the end, it is vital that both industry and researchers have access to a trusted system in which they can evaluate methods, data, and tools (Lee *et al.*, 2015; Schuh *et al.*, 2015)

Learning factories are a type of expanded test-bed environment that tries to provide a reality-conform production environment as a learning environment where only minor abstractions are possible (Abele *et al.*, 2015). Key features of learning factories are explained, and a distinction is made between such facilities in a narrow and broader sense in the article. Figure 3 details the different variants of facilities that can be used to test out innovative technologies and methods while also being utilized for learning. Selecting to use any specific test-bed solution suited to the needs of the experiment brings with it challenges that will have to be overcome. Tisch and Metternich (2017) highlight some limitations with physical test environments such as limited resources restraining the ability to expand the facility where single leaning factories need to emphasize specific topics (Abele *et al.*, 2015), mobility, scalability and limited mapping capability. Shariatzadeh (2014) investigates and develops a virtual concept of learning factories while discussing the difference between virtual and physical systems.

Each solution has their advantages and disadvantages that will play a part in the decision for which solution should be used. An overview of these is shown in table 1.

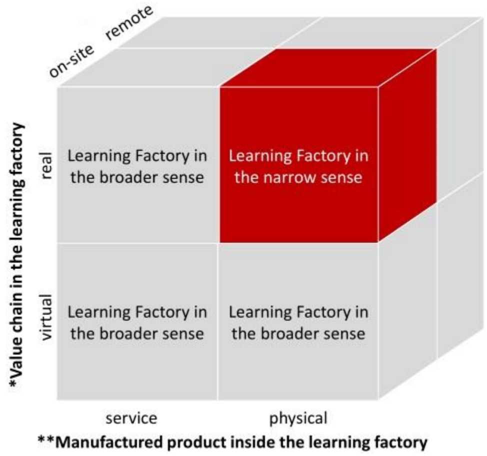


Figure 3: Distinction between narrow and broader sense in learning factories (Abele et al. 2015)

Helu and Hedberg (2015) and Lee *et al.* (2015) proposes two different test-bed concepts that try to extend the already existing system to incorporate cyber-physical infrastructure and product lifecycle, thus helping to enable research and development for smart manufacturing. The designs should highlight any of challenges such as cyber-security (Helu and Hedberg, 2015), privacy, data analytics, visualization (Liu & Zhang, 2016), scalability issues and time constraints (Galán *et al.*, 2008). Gaining an understanding of how such a test-bed system would look is a vital part of design a demonstrator system. An in-depth explanation of the proposed system in (Helu and Hedberg, 2015) will be necessary.

Table 1: Advantages and Disadvantages of test bed structures

Test Bed Architectures			
	Industrial environment	**Laboratory Facility**	**Virtual environment**
+	Real world production system Reliability and Validity of collected data	Flexibility in the scope of production Hands-on experience	Ease of making changes to the production system Holistic analysis possibilities Decreased budget and space limitations
-	Costly and time-consuming implementation Scope limited to current production	Problem with scalability Resources intense Mobility issues Mapping abilities	Requires reliable model data No hands-on experience to facilitate learning

3.1.1 Design structure of test-beds

From the literature about learning factories and test-bed systems, one can see that there is a multitude of different options varying from the industrial production system to laboratory facilities and virtual models. Two different architectures will be looked at in further detail.

3.1.1.1 Industrial – Laboratory Design

Smart manufacturing is the combination of digital and the physical, due to this the test-bed will need two separate components to provide the necessary coverage. The Manufacturing Lab (ML) and the Computer-Aided Technologies Lab (CATL) are those two parts. An overview of the main test-bed structure is shown in figure 4.

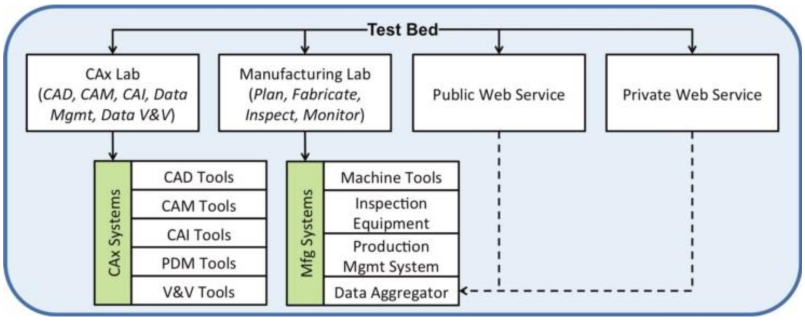


Figure 4: Proposed Testbed structure in Helu & Hedberg (2015)

Manufacturing Lab

The Manufacturing Lab main purpose is to facilitate the development of technologies and standards relating to the collection, analysis, and transmission of information that happened during production or inspection so that decisions can be based on said data. A deeper understanding of the design will enable successful and safe deployment into existing manufacturing environment. One important aspect of the ML is the concern about the validity of the data being collected, by building the lab inside an already existing facility this can be ensured. Filtering the real manufacturing data of any sensitive information means it can be used for research purposes without placing the company is a bad spot. Being a new design platform means that while you're able to collect data across the whole facility's levels, both machine and shop-floor with the current equipment. The need for extra external sensors would be necessary to complement normal data to gain a complete understanding of the system. The underlying structure of the manufacturing lab includes three components that are networked within the facility are the following.

Production Management Systems: This is the component that provides data and information of a facility-level, production schedules and times.

Machine Tools & Inspection Equipment: Any sensors that are needed for monitoring equipment and its processes fall into this component. Data analytics tools supporting both simple and more complex tasks is also included in the component. Machine tools & Inspection acts as the provider of the infrastructure and data that is used for validation of the technologies applied in the test-bed for quality assurance, performance, maintenance and any other shop-floor level task.

Data Aggregator: Interconnectivity is a vital part of the manufacturing lab and the data aggregator acts as the hub for data collection from all sources. Here the data is processed and given a timestamp so that information from the equipment relates to its relevant sensor output. By utilizing the Aggregator this way enables the creation of robust databases for the facilitation of the various types of analytics.

Computer-Aided Technologies Lab

The link between the physical and virtual world is an important part of smart manufacturing. In the test-bed system, the CATL provides the platform for the design and planning of experiments for the Manufacturing lab. CATL is used for developing, testing and maturing systems integration technologies that handle the information flow throughout a product's lifecycle. Requirements will be set to be able to handle all different areas of interest. Here open-source is included together with the top and middle-tier software in a way that aligns with the concepts of smart manufacturing. While also supporting research studies into interoperability of application in manufacturing environments. The following components make up the CATL.

Computer-Aided Design: A component used for testing both the capabilities of any CAD system while also examining the effect of the produced downstream data. It is an integral part of the development and validation phases of test cases applied in the manufacturing lab.

Computer-Aided Manufacture & Inspection: A component for the testing and developing of CAM and CAI tools that can be used for experimentation of either CAD models or Manufacturing lab test cases.

Product Data Management: Responsible for the organization of data and test cases implemented in the test-bed system. By applying numerous PDM system one can test the data exchange capabilities between systems.

3.1.1.2 Other test-bed systems

Virtual Model

The proposed testbed system shown in the previous section by (Helu and Hedberg, 2015) utilizes already existing production systems as the basis for data collection and further analysis. This might not always be possible and thus other options need to be investigated. In (Lee *et al.*, 2015) the physical production system seen in (Helu and Hedberg, 2015) is replaced with a model manager where the system one wants to perform the experiment on is built in a virtual model. The complete architecture of the virtual test-bed system is shown in figure 5.

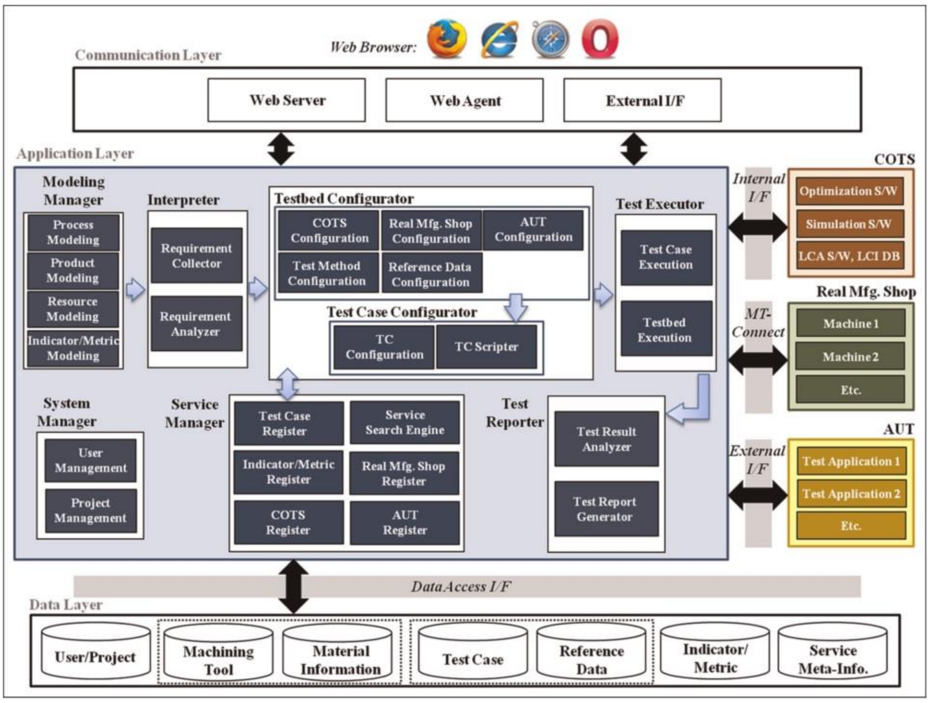


Figure 5: Testbed system architecture from Lee et al. (2015)

3.2 Manufacturing execution systems and data collection

In today's fast-paced industry, the need for new systems that handle production planning, control and performance analysis grows. A Manufacturing execution system (MES) is an integral part of almost every production system. It's a powerful production management tool that supports production optimization throughout the whole production chain, from the initiating processes until final shipment (Lee, Nam, and Lee, 2012). It handles production execution activities such as work orders, quality management, scheduling and work performance. The MES acts as the central hub for information flowing to and from the production into other systems such as Enterprise resource planning, supply chain management or customer relationship management. While being a crucial part of a production system that brings with it plenty of benefits by making it easier to handle, track and later execute business decisions based on said information. It is extremely crucial that inside the MES there is an integrated and developed data acquisition system able to gather accurate production data in real-time.

An MES is made up out of numerous different components handling different areas of the production system. Various MES implementation standards have been developed by several institutions, one of these is MESA (Manufacturing Execution Solutions Association). They describe the function structure of the MESA as shown in figure 6. Any reasonable number of combinations of these components make up an MES. For a project in this thesis, the focus is put on components dealing with the collection of production information such as data collection acquisition, performance analysis, controls, PLC, DCS.

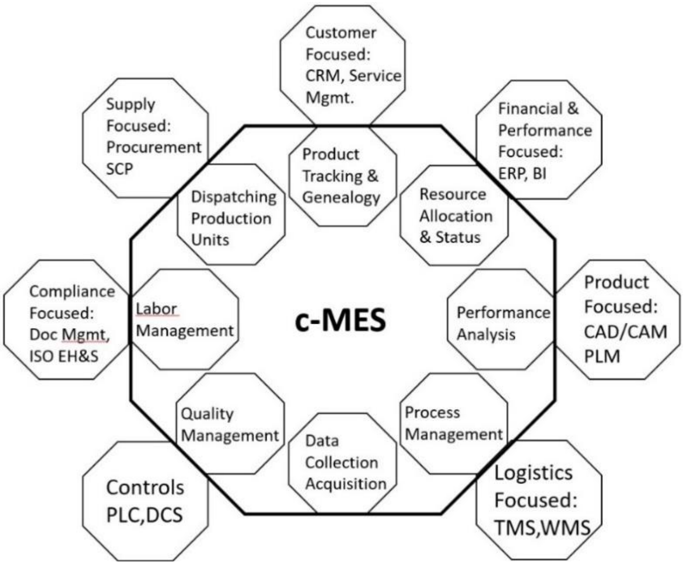


Figure 6: MES Function Structure

To facilitate the gathering of information down at the shop floor requires that a structure for data collection and communication is implemented. The ISA organization have developed the ISA-95 standard, within this standard, there are different operational levels. Based on this definition Lee et al (2012) developed and proposed a data acquisition systems architecture. Figure 7 shows the overall view of the framework with its levels. The entirety of the MES constitutes level 3 to level 0 whereas level 0 to level 2 is the equipment interface. The level at which the data is being collected depends on what type it is and where it is

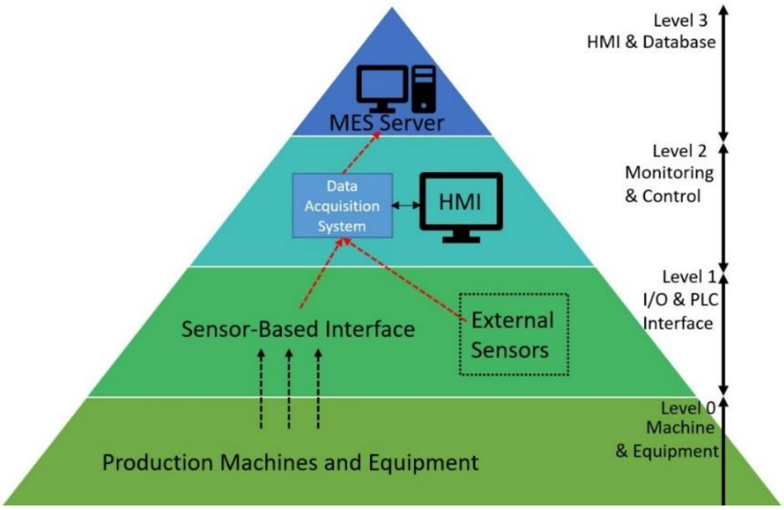


Figure 7: Proposed data acquisition architecture based on ISA-95

coming from. Data gathered either directly from sensors built into the equipment itself, technology solutions such as RFID or through the sensors-based interface connected to the HMI will flow up the levels until it is stored in the MES servers. This stored data can be utilized by other applications either for business- or performance analysis.

After shop floor data have been collected by the sensor-based interface it will be processed by any type of data parser implemented in the system. Here primary data from the machines such as on/off, RPM, voltage, temperature etc. were used to calculate secondary data. Operating-, idle-, breakdown-times, quality metrics for example defects and good products, setup times are some of the possible secondary data that can be calculated. From here the secondary data can be mapped with the help of system reference data into distinct categories containing the product, equipment, worker, process data. By combining the secondary and the mapped system's data the tertiary shop floor data is generated. Some examples could be total daily production, average production time by equipment, start and stop times for work.

Real-time data acquisition is the end goal of the MES system, to realize this it is essential to gather the data mention above. Communication between the sensors, equipment and the MES database will need to work seamlessly. Some type of communication standard will need to be implemented. PLC can handle a large array of different sensors it is not a universal solution, for a lot of situation adopting OPC-UA technology will help collect data to the upper systems (Jeon *et al.*, 2017)

3.3 Bottleneck and Decision Support

With the increasing demand from a customer for products focusing on their special customization, the pressure is put on manufacturing enterprises to reduce costs, increase quality, improved flexibility to remain competitive (Bastos and Lopes, 2009). Developing and implementing new strategies or methods into the production is necessary, Lean Manufacturing, agile manufacturing, Mass customization or similar paradigms are being used. The growing complexity of the production system is adding pressure on the maintenance departments. But maintenance is often seen as a financial cost to the enterprise (Narayan, 1998) which can be supported by the fact that the maintenance costs are growing and can be as much as 15-70% of the total production costs (Bevilacqua and Braglia, 2000). With the maintenance costs being high and the average OEE throughout the industry being low (Ylipää *et al.*, 2016) the room for improvements through different maintenance approaches are huge.

To support the increasing complexity of maintenance planning a support system is needed to aid in the task of allocating the finite resources available and prioritize the system critical machines. Plenty of research has been conducted in this area start all the way from the 1960s (Kletti, 2012). To comprehend what a decision support system (DSS) should do one must understand what it means. From Carnero (2005) a DSS for maintenance can be defined as the systemic way of selecting a set of diagnostic and/or prognostic tools to monitor the condition of a single component or machine. Lee *et al.* (2006) introduce a DSS that can transform the traditional “Fail and Fix” maintenance practices to a “Predict and prevent” methodology. This is done by implementing tools for performance assessment and prediction to allow allocation predictive maintenance tasks to hinder machine breakdowns. But by focusing too much on the machines themselves one might miss the bigger picture. The decision making from a plant and system level is necessary because machines never work in isolation. Li, Ambani, and Ni (2009) propose a plant-level maintenance decision support system (PMDSS) that combines the short-term and long-term effects seen in figure 8. For the different time frames different methods and tool for analysis are used, that in the end decided what actions will be taken.

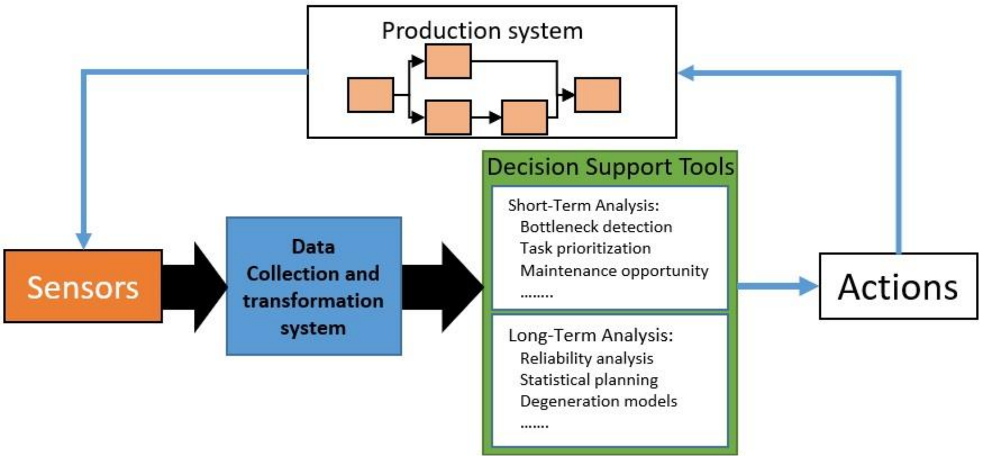


Figure 8: PMDSS Framework from Li et al. (2009)

One major indicator of a production systems performance is the production rate or throughput. Bottlenecks are the single or multiple machines in the system that constrains the throughput in the system (Goldratt and Cox, 2004). Due to limited resources in the production system such as maintenance operators, machines, robots etc. improvements need to be prioritized to critical machines for effective utilization (Li, Ambani and Ni, 2009).

Bottleneck detection methods used as support tools can be categorized into three different sections, analytical, simulation-based or data-driven. Table 2 Summarizes available bottleneck methods and sorts them into each category.

Category	**Method**	**Reference**
Data-driven	Turning Point	(Li, Chang and Ni, 2009)
Simulation-based	Average Active Period	(C. Roser, Nakano, and Tanaka, 2002)
	Active Period percentage (Utilisation)	(Roser, Nakano and Tanaka, 2001)
	Shifting bottleneck	(C. Roser, Nakano, and Tanaka, 2002)
	Queue time	(Faget, Eriksson and Herrmann, 2005)
	Inactive Period	(Sengupta, Das and VanTil, 2008)
	Inter-departure time variance	(Betterton and Silver, 2012)
Analytical	Queue length	(Lawrence and Buss, 1994)
	Utilisation	(Hopp and Spearman, 2001)

Table 2: Bottleneck methods (Subramaniyan *et al.*, 2016)

Currently, simulation-based methods are the most used, this approach needs a validated and up to date model to work which is a time-consuming task (Skoogh, 2011). Historical input data is needed for these production system models to work, gathering this data takes time on top of the already time-consuming model construction. Fowler and Rose (2004) discuss the challenges involved in building a simulation model that accurately represent a real production system without introducing too many errors due to computational abstraction. Development of computer technology and an increasing amount of data being collected by MES presents a new way for the detection of bottlenecks through data-driven algorithms. The choice of bottleneck method fell on the Shifting method due to its ability to provide more information regarding the bottleneck than the other methods. It is able to detect the current bottleneck at any given time, provide the average bottleneck, distinguish between primary and secondary bottleneck machine, information about the where and when of bottlenecks shifting between machines (Subramaniyan *et al.*, 2016).

3.3.1 Shifting Bottleneck

In this project, the shifting bottleneck method will be the focus and an explanation of the method will be given. The method was first developed by (Roser, Nakano, and Tanaka, 2002a) and was later tested and validated in a simulation environment (C. Roser, Nakano, and Tanaka, 2002a, 2003a, 2002b, 2003b). The shifting Bottleneck is based on the active periods of the machines. Essentially the method divides the active periods into either active or inactive status. Active period is any state of the machine when some sort of action is being performed such as setup, maintenance repair work during breakdowns, tool changes etc. or producing. Inactive states are when the machine can perform work order but can't either due to being blocked or starved by connecting machines (C. Roser, Nakano, and Tanaka, 2002a). Figure 9 shows an example of the different states of a machine during production.

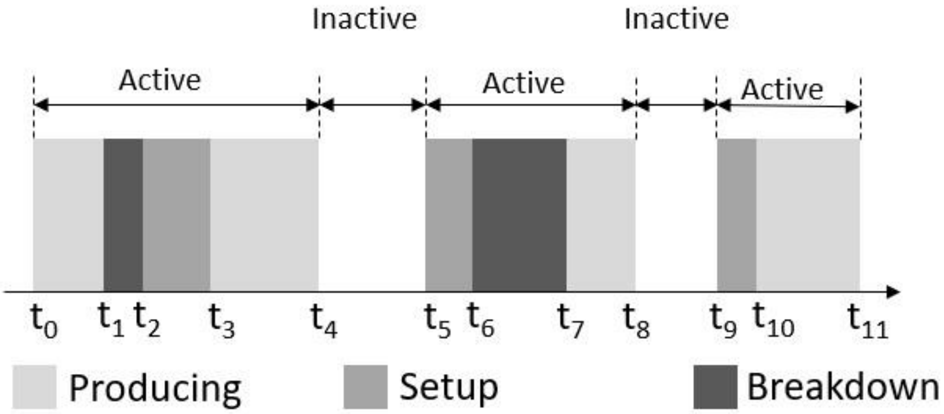


Figure 9: Active and inactive machine states

The methods main idea is that, given any time instant t_i, the machine with the longest uninterrupted active period among all the machine in the production line is called the momentary or current bottleneck at the time instant t_i. Machines can either be the sole bottleneck at any time or in a shifting state. Being a shifting bottleneck means that the active period of the current bottleneck machine overlaps with the previous or subsequent bottlenecks. If there is no shifting occurring then the current machine is the sole bottleneck, an illustration of this concept is shown in figure 10 using three machines (M1, M2, and M3). By calculating the amount of time each machine has been either the sole or shifting bottleneck during any given time period (Minutes, hours, shifts, days) the machine with the highest impact in limiting the throughput can be seen.

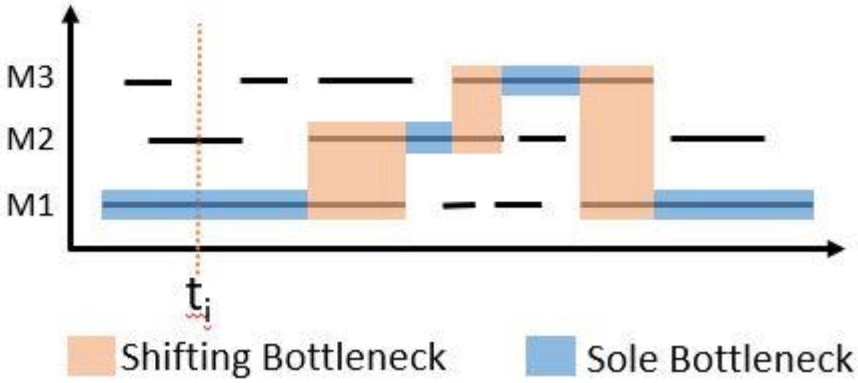


Figure 10: Illustration of sole and shifting bottlenecks

Subramaniyan (2016) developed a shifting bottleneck data-driven algorithm and tested it using two MES dataset from production lines. The full algorithm on the shifting bottleneck method is showing appendix C. To understand the requirements put on an MES data collection and storage system a short rundown of the major parts of the algorithm will be conducted.

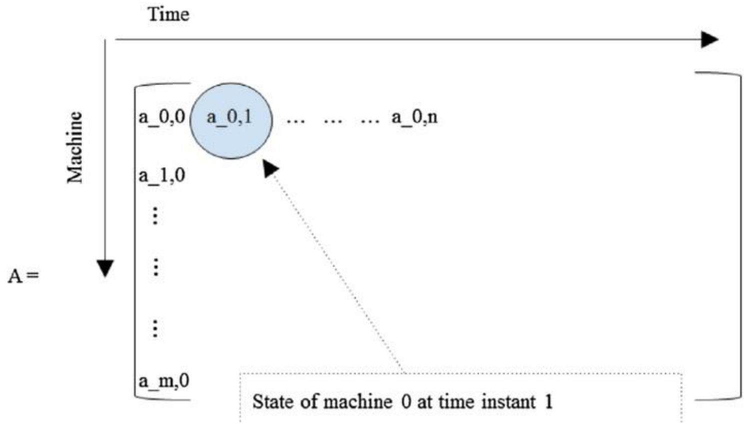


Figure 11: Source input Matrix A (Subramaniyan, 2016)

The algorithm starts by collecting the machines states at any given time instant, figure 11 showing the source matrix A that is the start of the algorithm. Here we can see that the number of rows in the matrix is the number of the machine in the production line, while the column corresponds to the machines state at any given sample time. Each element in the matrix takes either the value 1 if the machine is active or 0 if the machine is inactive.

Since the data being used for the algorithm is imported from the MES server's database some filtering or cleaning might be required before it can be used in the algorithm. Since the machines can only have one value for any given time instant there can be no overlapping information regarding the state of the machine in the MES data. If the data collected has information that the machine is both producing and suffering a breakdown at the same time it cannot be used. Another requirement, while not breaking the algorithm itself, is that the frequency of the sample times for the states occurs close enough together. If the time between sampling the states is too long, it can bring into question the validity of the produced results. Because if the gaps are too long the machine could change between active and inactive states without that information being visible to the algorithm.

4. Results

4.1 Stakeholder Analysis

A stakeholder analysis was conducted with parties working within the DAIMP project, both industry representatives and university researchers while also considering the views of the author. Unstructured interviews were conducted to obtain an understanding of what each party wanted out of the project.

Two companies were involved in the construction of a test bed system dealing with data collection and analysis for bottleneck detection and criticality assessment. This thesis deals with the bottleneck analysis while Salunkhe and Fumero (2017) present the results of the stakeholder analysis from the criticality assessment angle.

During the interview with the company employee involved with data collection, some specific topics were discussed regarding desired results coming out of the project. The testbed itself has an intrinsic value by allowing for a more detailed view when working with analysis methods. The Bottleneck methods itself being developed and implemented in the system was a major topic. Being able to use the data collected by the MES in the test bed system for analysis while also making it possible to feed this data for use in other systems, such as a CMMS.

With maintenance being the focus of the DAIMP project the researchers expressed a desire to be able to use the methods being tested to push research forward regarding maintenance and decision support. By looking into the requirements of a test bed system one can get a more detailed view of what needs to be achieved in this area to push maintenance concepts from the current paradigm into more complex areas such as predictive and prescriptive maintenance. There was also a desire to not only use the test bed system for method analysis but as a demonstrator for industry and educational purposes as well.

From the author's point of view, there is a desire to conduct research about topics that could have a meaningful impact both in academia but also for the industry. Highlighting difficulties with the implementation of methods into existing production systems is a driving factor.

Table 3: Stakeholder Interests

DAIMP Stakeholder interests		
Industry	**Academic**	**Author**
Testbed – intrinsic value	Demonstrator	Impact of thesis
Usage of data	Driving research	Good report
Bottleneck calculation method	Facilitating Industry – Academia connection	

4.2 Realisation of the demonstrator

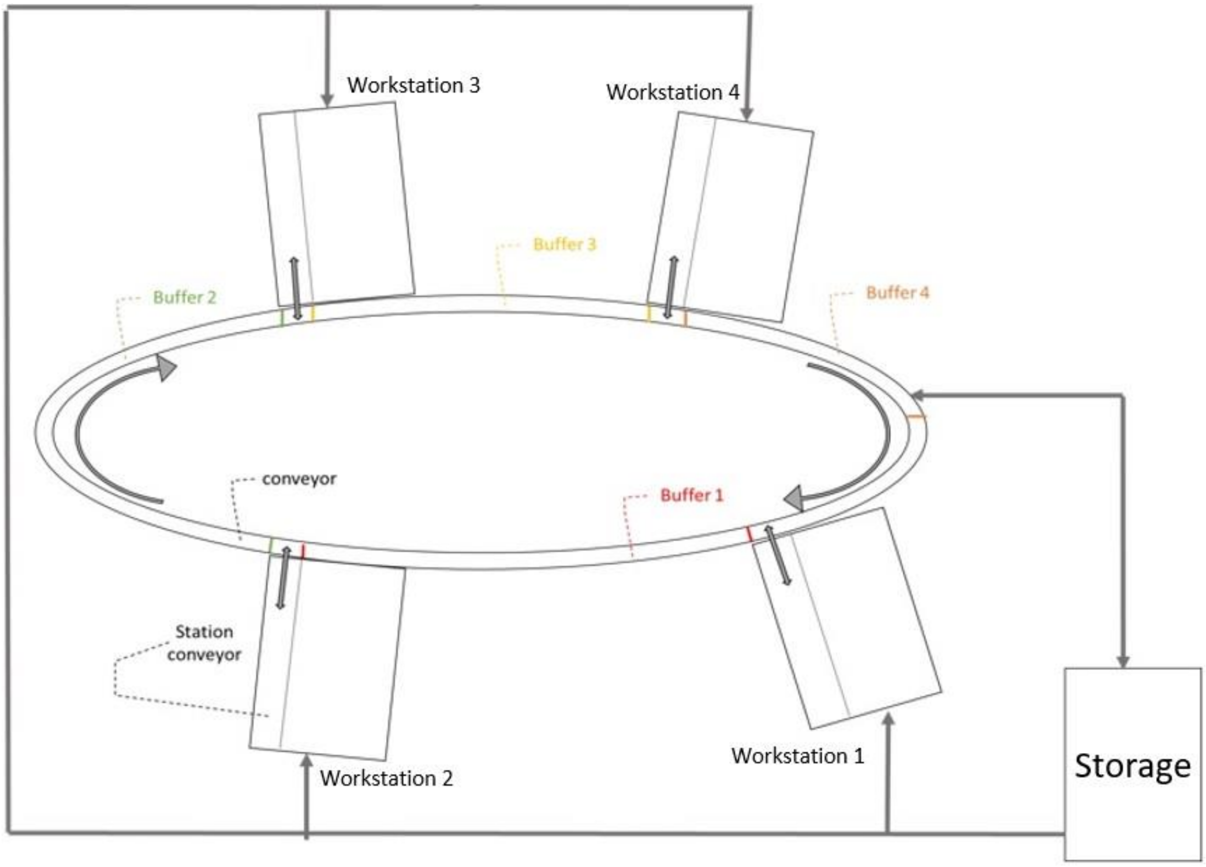


Figure 12: Layout of the test-bed system

4.2.1 Description of the demonstrator.

The demonstrator is going to have four workstations. Also, a storage managed by a material handler. The current VSM is as follows, we would like to have around 1.5 min cycle time per station:

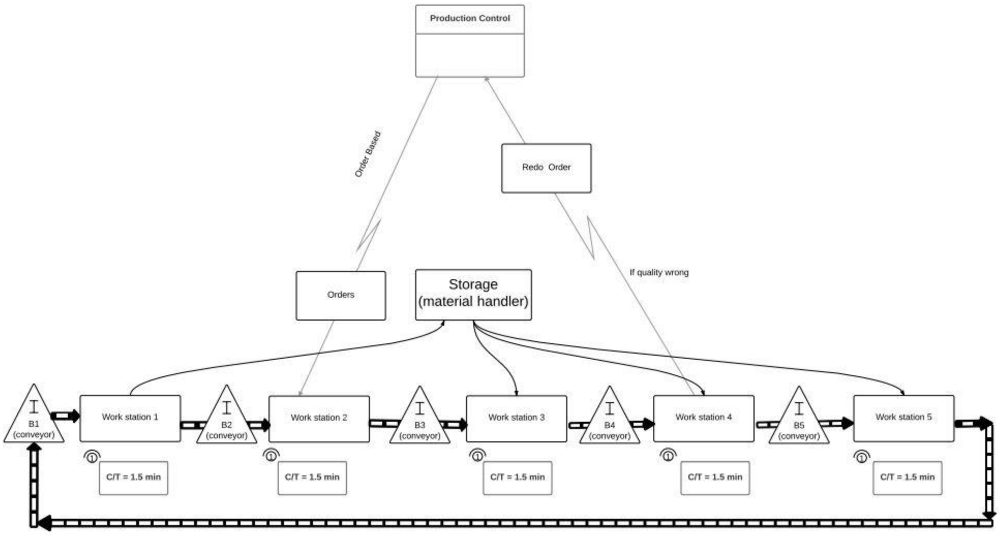


Figure 13: Value stream map over the test-bed system

The idea is that the system is going to be ordered based so, the orders are going to be electronically transferred to workstation 2. In Storage, a worker is going to prepare and handle the parts needed for all workstations by using Kanban system described later. Workstation 2 uses a kit provided by workstation 1, which is the one for kitting and, for disassembling the product. The parts of the disassembled product are going to be placed in boxes that the material handler is going to take to classify and prepare the material needed for each station, the operator will retain the parts needed for kitting. As it can be seen in the VSM, it is a push system that has buffers between stations, these buffers are going to be placed on the conveyor by using a queue system.

The functioning in each station is the same in terms of how the product enters to be built (see the flow in pictures below) but station activities are different. All workstations are manually managed by one operator each. Also, all stations have a small conveyor (where the work is developed) and the system goes on a big conveyor that acts like buffers by establishing queues before and after each station. The flow situations are:

1. Situation 1: the product enters the station. From “buffer i” in big conveyor, the product enters in “station i” by using the station conveyor when “situation 2” has happened:

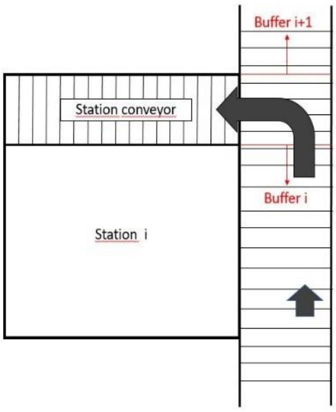


Figure 14: Product entering workstation

2. Situation 2: product goes out of the station. Once the work is done, the product goes out to the “station i” using the station conveyor to be incorporated into the “buffer i+1”. Now, “situation 1” can start:

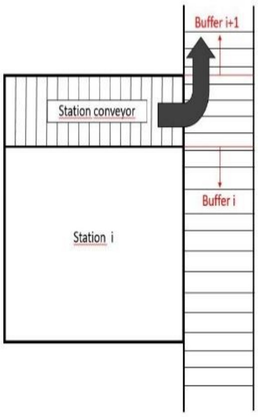


Figure 15: Product leaving the workstation

In workstation 3, there are going to be two types of buffers, one for product A and a second for product B. So, the operator takes pieces depending on the product he/she needs to produce according to orders, instructions are going to be shown in a screen.

There is a quality check that is going to be done after workstation 4. If the product is wrong, it would continue to Buffer 4 to be disassembled but the cause of failure should be detected by the operator. This order would be unsatisfied and needs to be reprocessed so, it is electronically communicated to production planning and a new order will be communicated to Storage.

Each station will have 1 operator and the storage will be managed by one too. The start and end of the flow is the Storage as the pieces are going to be reused.

According to the roles, apart from the operators mentioned, a back-office responsible and maintenance technician is needed to meet the research purposes.

Material Handling:
All workstations need to have a parts-inventory on the workstation to fulfill its tasks. The plan is to have the material handler make a round every three-four minutes to restock (pick up empty boxes) at the stations that need parts. So, every station that needs parts will have a set of boxes (3x5, 2x7, etc), the number of boxes will be dependent on the customer demand.

Workstation 3 will have 2x7 boxes for a product with gear shaft A (Product A). The operator picks parts from the first set of boxes and when the parts run out, the empty boxes are then the signal to the "Kanban" system that they need to be picked up and refilled at the storage station by the material handler.

Workstation 4 is a manual assembly and 2x3 boxes for Product A. The same "Kanban" signaling system is used on this station. The boxes will be restocked by the material handler like station 2.

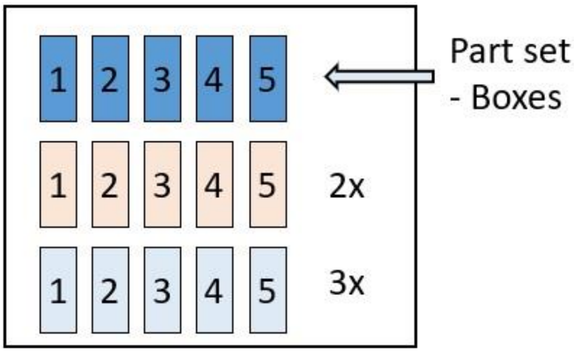


Figure 16: Material handling station

Example workstation with 3x set of 5 boxes with needed parts. After a pre-determined number of products produced, the boxes will be empty. Represented in the picture as blue boxes. This is then the signal for the material handler when he's making his round to pick them up and move them to the storage for restocking. During the next round (or the round after that) he will come back to the station with full boxes and put them in the empty places at the workstation.

4.3 Manufacturing execution system to production system

Inside the test-bed system, one of the most vital parts is the data collection system. The data being generated from the demonstrator can be used for different applications. This report focuses on the data needed for the shifting bottleneck method while also creating the information needed to do criticality assessment, though the report does not go into detail about the CMMS feature and the future use of this data. This part is shown in Salunkhe & Fumero (2017).

This Thesis is a small part of a larger project called DAIMP, working on this project is the company Axxos. The Axxos OEE application is the heart of the data collection system set up in this thesis. It acts as the central hub for all the data collected from the workstations, the collected data can then be used to monitor the day to day production, collected information about up/downtime for stations, a way to monitor breakdown causes, how many products are being produced. The application is only used for the SBN calculations and criticality assessment now but there is a multitude of possibilities to expand on in future applications of the test system.

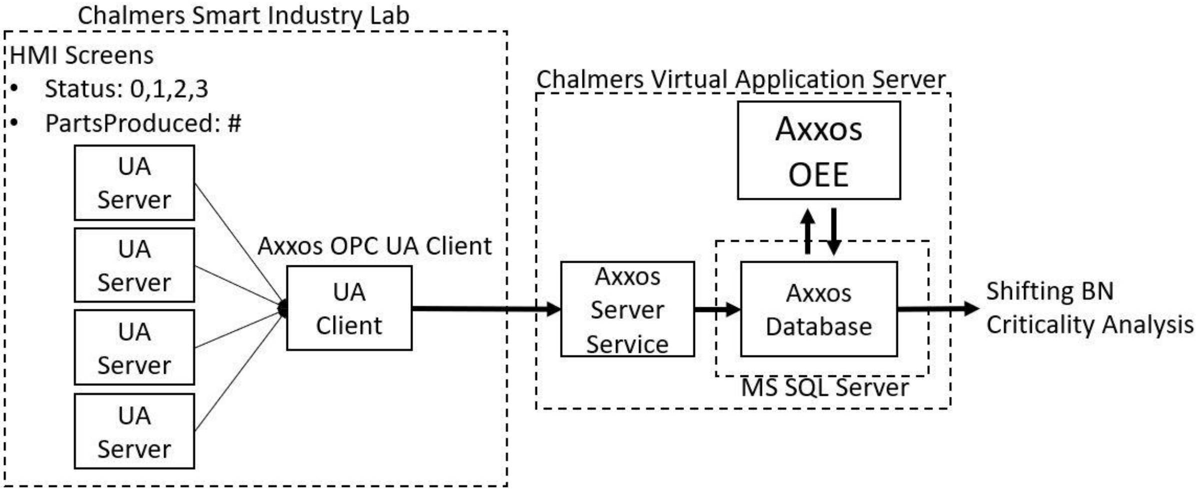


Figure 17: Structure of the data collection system

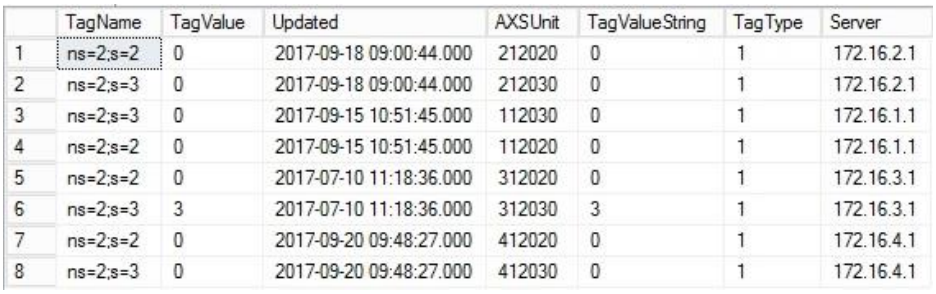
An overall view of the system is displayed in figure 17 above, each part of the system will be explained in detail below. The data collection system starts with each of the four workstations in the test-bed system. Each individual station has an identical data collection setup comprised of one Beijer Electronics HMI screen; PLC box, see Appendix A for a clear picture and one wireless Zyxel Router.

Data is collected either from the HMI screen by manual inputs of the operator or the Digital input/output board feeding information to the PLC from different sensors. In the current configuration of the test-bed system, no real sensors are being utilized and all communication originates from the HMI system. OPC UA Servers were set up to operate in each HMI screen and act as the main communications hub for each workstation. Each of the HMI screens is connected to the Zyxel router to enable communication over the local WLAN available in the CSI Lab. By using a wireless router for each station, you enable communication not only with the Axxos OEE application but also with the different OPC UA Servers themselves.

The Axxos OEE application is installed on a virtual server located in one of Chalmers IT server halls. A virtual server was used because it makes for easy setup and adds no components in the lab; no need to be physically present in the lab if you need to install of gain access to the server.

A UA client application from Axxos is installed on a laptop located in the CSI lab and works as the bridge for the information flow between the virtual server that holds the application and the demonstrator in the CSI lab. The UA client is configured to monitor the individual IP-addresses given to the HMI screens and then send all that information to the application on the virtual server. Appendix C displays the inner mechanisms of the Axxos OEE system when the information from the OPC UA client is received it passes through the Axxos Server Service before it gets stored in the MS SQL Database for further use. All the data being collected in the database can then be utilized by the OEE system, saved and exported for information display to the operators.

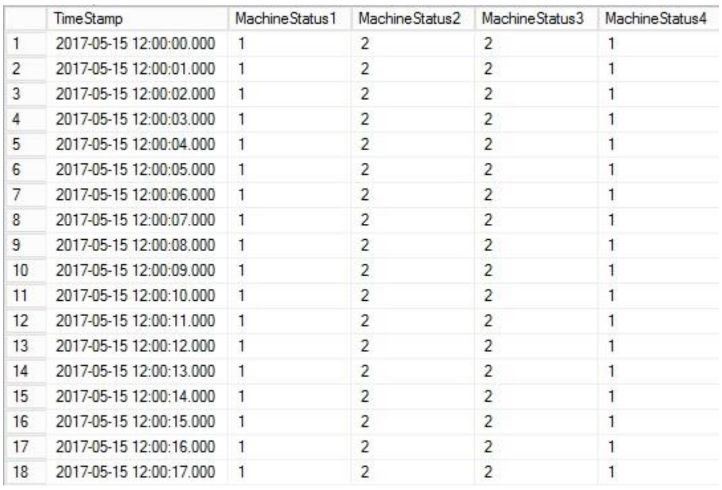
For both the SBN/Criticality methods the data coming from the system is saved only as their current value in the SQL database in the table “OPCValues”, shown in figure 18.



	TagName	TagValue	Updated	AXSUnit	TagValueString	TagType	Server
1	ns=2;s=2	0	2017-09-18 09:00:44.000	212020	0	1	172.16.2.1
2	ns=2;s=3	0	2017-09-18 09:00:44.000	212030	0	1	172.16.2.1
3	ns=2;s=3	0	2017-09-15 10:51:45.000	112030	0	1	172.16.1.1
4	ns=2;s=2	0	2017-09-15 10:51:45.000	112020	0	1	172.16.1.1
5	ns=2;s=2	0	2017-07-10 11:18:36.000	312020	0	1	172.16.3.1
6	ns=2;s=3	3	2017-07-10 11:18:36.000	312030	3	1	172.16.3.1
7	ns=2;s=2	0	2017-09-20 09:48:27.000	412020	0	1	172.16.4.1
8	ns=2;s=3	0	2017-09-20 09:48:27.000	412030	0	1	172.16.4.1

Figure 18: OPCValues table in Axxos Database

The OPCVaules table is then sampled every second and this information is saved in the “StatusMatrix” table in the database, figure 19. Each sample point now holds the information of the status of each workstation for that specific timestamp. The data is now structured correctly for use in the SBN algorithm.



	TimeStamp	MachineStatus1	MachineStatus2	MachineStatus3	MachineStatus4
1	2017-05-15 12:00:00.000	1	2	2	1
2	2017-05-15 12:00:01.000	1	2	2	1
3	2017-05-15 12:00:02.000	1	2	2	1
4	2017-05-15 12:00:03.000	1	2	2	1
5	2017-05-15 12:00:04.000	1	2	2	1
6	2017-05-15 12:00:05.000	1	2	2	1
7	2017-05-15 12:00:06.000	1	2	2	1
8	2017-05-15 12:00:07.000	1	2	2	1
9	2017-05-15 12:00:08.000	1	2	2	1
10	2017-05-15 12:00:09.000	1	2	2	1
11	2017-05-15 12:00:10.000	1	2	2	1
12	2017-05-15 12:00:11.000	1	2	2	1
13	2017-05-15 12:00:12.000	1	2	2	1
14	2017-05-15 12:00:13.000	1	2	2	1
15	2017-05-15 12:00:14.000	1	2	2	1
16	2017-05-15 12:00:15.000	1	2	2	1
17	2017-05-15 12:00:16.000	1	2	2	1
18	2017-05-15 12:00:17.000	1	2	2	1

Figure 19: StatusMatrix Example in database

4.4 Shifting Bottleneck

With the completion of the production system and its data collection process, the shifting bottleneck algorithm was implemented in the MATLAB environment. Figure 20 displays the information path from the test-bed into the data collection framework. From the software, the data needed for the shifting bottleneck algorithm was extracted and imported to MATLAB. The result from the operation was then displayed on a screen in the Backoffice to the operators.

The implemented algorithm for the shifting bottleneck method followed the process laid out in Subramaniyan (2016). The full algorithm with step by step instructions can be seen in Appendix C. The practical process in the test-bed environment was as followed. The StatusMatrix SQL table shown in the previous data collection section was exported to an Excel sheet. The built-in import function "xlsread" in MATLAB was utilized to create the source matrix from the excel sheet that the SBN algorithm uses for further operations. Results from the algorithm are the percentage of time each machine acted as a shifting or sole bottleneck within the test-bed system during the available production timeframe.

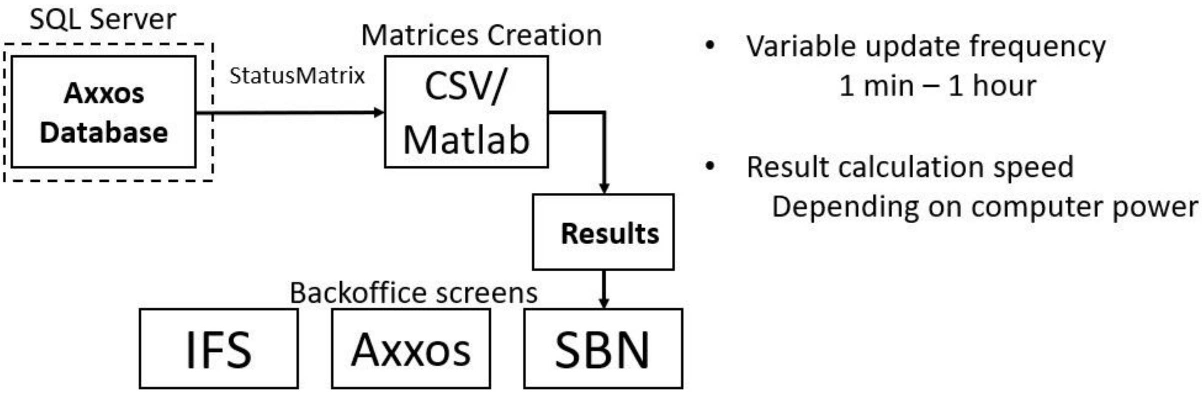
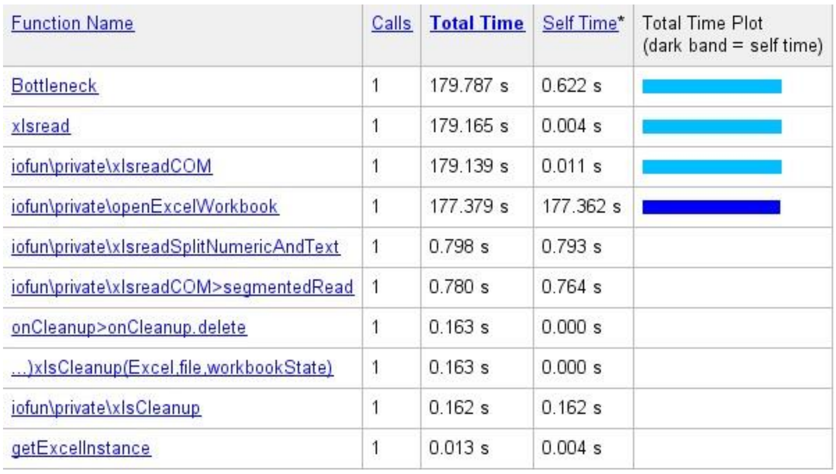


Figure 20: Shifting bottleneck flow at CSI lab

One of the goals of the shifting bottleneck method is to head towards an implementation that can be updated in real-time. To understand the challenges, one faces the current algorithm and the import methods were timed. This got an overview of what steps in the process was taking the longest amount of time. MATLABs built-in "time and run" function was utilized and the results from this are shown in figure 21. The Bottleneck function is the current implementation of the shifting algorithm when looking at the demonstrator system with five machines. The demonstration of the runtime for the algorithm used around twenty-nine thousand lines, meaning roughly 8 hours of sampling data once per second. The function openExcelWorkbook is the import time of the data from excel to MATLAB.



Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
Bottleneck	1	179.787 s	0.622 s	
xlsread	1	179.165 s	0.004 s	
iofun\private\xlsreadCOM	1	179.139 s	0.011 s	
iofun\private\openExcelWorkbook	1	177.379 s	177.362 s	
iofun\private\xlsreadSplitNumericAndText	1	0.798 s	0.793 s	
iofun\private\xlsreadCOM>segmentedRead	1	0.780 s	0.764 s	
onCleanup>onCleanup.delete	1	0.163 s	0.000 s	
...)xlsCleanup(Excel,file,workbookState)	1	0.163 s	0.000 s	
iofun\private\xlsCleanup	1	0.162 s	0.162 s	
getExcelInstance	1	0.013 s	0.004 s	

Figure 21: Calculation time for shifting bottleneck in MATLAB

5. Discussion

The objective of the thesis was to build a demonstrator system at the CSI lab together with the implementation of existing data collection and CMMS software for the companies involved for the use in analysis methods regarding bottleneck detection and criticality analysis. A shifting bottleneck algorithm was created in a MATLAB environment where it can utilize the production data collected from the system. Problems related to the design of the built demonstrator, data collection and implementation of the algorithm will be discussed to help highlight any challenges that need to be overcome.

5.1.1 Methodology

The methodology used for the thesis is based on CRISP-DM, in the end, it is a cyclical process where after the model has been implemented and tested one can go back and repeat the same process again. A stakeholder analysis was completed to gain a basic understanding of where the project could lead to, information was gathered from both industry and academia thus covering all important angles. For the literature review, there was some initial trouble finding enough detailed articles about building a testbed, this was later sorted but during that time the project had moved forward regarding the design and what resources that were available. In the end, only one pass in the process was completed and there was no feedback of the results reached with the parties involved. This was due to the time constraint on the project.

5.1.2 Shifting Bottleneck Implementation

When working on the creation and implementation of the shifting bottleneck algorithm the problems and challenges faced can be separated into two categories. Integration into the demonstrator system and algorithm creation.

Researching the requirements set on the test-bed, data collection software and SBN algorithm to be able to move towards real-time data-driven analysis is the focus of the thesis. The requirements specified specifically by the shifting bottleneck method on the data collection system (Christoph Roser, Nakano and Tanaka, 2003; Subramaniyan *et al.*, 2016) bring with it some challenges that had to be tackled. One of these was the requirement that the system would be able to accurately capture production data from the workstations every second. By utilizing the OPC UA standard as a means of communications between workstations and MES made the transfer of data very smooth. While the capability of the demonstrator system is limited only to capturing data from virtual signals created at the HMI screens the PLC box that was built and placed on each workstation makes it possible to easily add external sensors that can send collected data to the MES to enhance any analysis tools being tested.

In the current state, the algorithm is limited to a 4 machines system but has no time limitation, an example of this can be seen in figure 19 in the section above. Most of the issues faced during the creation of the algorithm and the import of data collected lies with lacking experience from the authors part regarding coding. The ability to test the algorithm in different scenarios with active and inactive machines took precedence over a fully optimized code. Though it is important to note that no deviations from the algorithm, that can be seen in Appendix C, was done. Looking at the results shown in figure 21 when running a test scenario from a days' worth of collected data it is visible that the algorithm itself does not require a substantial amount of time to calculate the results. The major hurdle to overcome as seen is the time in which it takes to import the data into the MATLAB environment as shown in figure 22. Due to a lack of previous research exploring the laboratory approach, it is hard to compare the results from this thesis to other SBN research. The articles tackling the SBN method has either been virtual simulations (C. Roser, Nakano, and Tanaka, 2002), where it is not possible to directly compare the calculations times or the semi-industrial approach with MES data where the calculation times were not published (Subramaniyan *et al.*, 2016).

Importing of collected data became a two-part sequence where the information is first exported into Excel and later imported to MATLAB where the algorithm calculates the result. By cutting down on the current complexity of the data transfer from two steps is a major step towards the ability for real-time calculations. The challenge about minimizing time will always be present in these scenarios as long as the data is stored and exported from a server, in our case Microsoft SQL. While not implemented in the current setup a viable way to minimize import time is to move away from the bulk export of data from the server. Meaning that instead of importing the full StatusMatrix table every time the algorithm is calculated like it currently does it only imports the data from the last time it was run and add those to the source matrix. While the real-time calculation is the end goal there is always a discussion about whether or not this is the best way from a maintenance and work order priority view. Gopalakrishnan, Skoogh, and Laroque (2015) discuss if a real-time shifting of bottlenecks for maintenance might be the best option. If that is the case, then even with a slow import and export time it will not particularly hinder the calculation and updating of bottlenecks on hourly or shift basis and still gain the benefit that it entails.

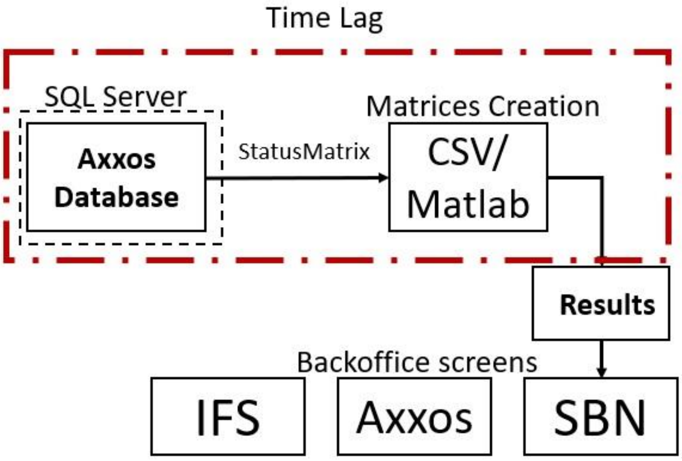


Figure 22: Visualization of challenge area for shifting bottleneck calculation.

5.1.3 Impact on Industry

Bringing research forward while working together with the industry are both major focuses when doing research. Studying the current knowledge regarding data-driven analysis tools and more specifically bottleneck detection one can see that testing of these methods has been done from the virtual perspective and on a limited scope for industry application (Roser, Nakano and Tanaka, 2001; C. Roser, Nakano and Tanaka, 2002, 2003; Christoph Roser, Nakano and Tanaka, 2002). Meaning that real production data from the MES has been conducted and sent to the researcher for analysis but no physical implementation connecting the MES system and the algorithm has been done (Subramaniyan *et al.*, 2016). By producing this report there is hope that it will help facilitate the ease of implementation into existing production system for companies seeking new methods of decision support, highlighting challenges that were faced combining shifting bottleneck and a laboratory setup. Since making changes to current production systems might lead to impairment in the running production.

5.1.4 Impact on the research field

At the same time, the impact on academia is two-fold, on one hand, you have the attraction of companies looking at testing new technologies the research brings for the universities. While all research does not have the same pull the ability to investigate new ways that could lead to an increase in productivity and reduce cost always seems attractive. On the other hand, you have the impact on the scientific community at large by taking the first steps into something that hasn’t been studying before. This can lead to other researchers creating studies of their own that might help the industry. Becoming a cycle of knowledge transfer that both industry and academia can gain from.

Figure 23 and Table 4 was constructed to explain and highlight how knowledge regarding the shifting bottleneck detection is transferred between three areas of the research field. It is also a way to demonstrate the uniqueness of this thesis since at this point in time, it is the first lab-implementation of the data-driven shifting bottleneck detection method.

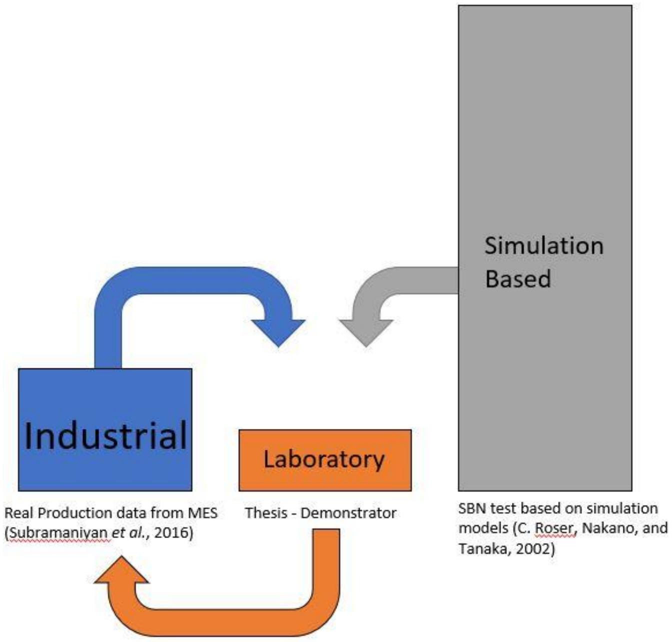


Figure 23: Information flow inside the shifting bottleneck research field.

Table 4: Shifting bottleneck research in different testbed scenarios

Test Bed Architectures – Current Research field			
	Industrial environment	**Laboratory Facility**	**Virtual environment**
+	Real world production system Reliability and Validity of collected data	Flexibility in the scope of production Hands-on experience	Ease of making changes to the production system Holistic analysis possibilities Decreased budget and space limitations
-	Costly and time-consuming implementation Scope limited to current production	Problem with scalability Resources intense Mobility issues Mapping abilities	Requires reliable model data No hands-on experience to facilitate learning
Shifting Bottleneck Research	Real Production data from MES (Subramaniyan *et al.*, 2016)	Project Thesis – SBN Demonstrator system	SBN test based on simulation models (C. Roser, Nakano, and Tanaka, 2002)

5.1.5 Demonstrator and design challenges.

There are plenty of challenges to overcome when choosing a design for a test-bed system. When looking at the current research being done on smart manufacturing test-beds and learning factories the design options are plentiful. As shown in Abele et al. (2015) and later Tisch and Metternich (2017) the aim is to come as close to a reality-conform production environment that fits the needs for what is trying to be achieved with the testbed. New manufacturing practices bring with it challenges, testing them out in running production is costly and disrupt your ongoing work. Because of this, the testbeds play a vital role in being the testing grounds that make implementation easier. While it is tempting to try and fit everything into the testbed limitations to what can be done is always present. As have been shown by (Galán *et al.*, 2008; Abele *et al.*, 2015; Schuh *et al.*, 2015; Tisch and Metternich, 2017) the scale of the system is highly dependent on both time, cost and already available resources. The idea of the demonstrator was to be able to showcase implementation of different analysis methods that utilizes real-time captured data from the demonstrator for both companies interested in expanding and improving their operation or for educational purposes both a university level and all the way down to primary education. The aim of this thesis is to examine the specifications required for a production or test-bed system for implementation of a data-driven bottleneck detection method. Virtual and semi-industrial testing of the shifting bottleneck detection method has been done before (C. Roser, Nakano, and Tanaka, 2002; Subramaniyan *et al.*, 2016). Due to this a laboratory design was chosen over virtual or industry models. By utilizing a physical location you can acquire valuable learning experiences that are not present when implementing a digital testbed, this is highlighted in (Abele *et al.*, 2017).

The challenges one might face when building a demonstrator was not fully understood when going into the project and thus the final design did not have as much detail as was first planned. The final design is a very generalized system where the “machines” on each workstation is simulated by manually pressing a button on the HMI screen. While this does not hinder the implementation of the data collection system and how the SBN was developed and deployed. Doing it this way the accuracy and likeness to a real production system might be degraded since it is all based on assumptions made by the authors who built the system.

As discussed in the previous section regarding the impact this thesis might have in academia and industry. The goal is to transfer the combined knowledge from virtual and semi-industry setting into a laboratory environment so that this new knowledge can be fead back into a real industry setting. The requirements for an implementation of SBN found in this thesis highlights where the focus should be when moving into real production, Schuh *et al*. (2015) discusses these problems. Looking at the requirements one can see that the one mostly affecting the active production environment is the data collection. Depending on the production system in use the effect of implementing a data collection system varies, with more advanced machines capturing data is an easier task due built-in data collection than if a more manual system is used. It is of vital importance to examine all the possible ways to collect active and inactive data from machines to make implementation faster and less costly.

6. Conclusion

During the work of this thesis, a laboratory-based testbed was constructed in the CSI lab facility, it tries to mimic a real production environment at a generalized level using four manual workstations. With the construction of the testbed, a production monitoring and data collection system from Axxos was installed together with a CMMS supplied by IFS. Utilizing the testbed together with the data collection a shifting bottleneck algorithm was constructed based on the work done by (Subramaniyan *et al.*, 2016).

Research Question 1: What type of architectures are available when constructing a demonstrator test-bed system?

From the literature study done in this thesis, one can see three distinct layouts being used as the basis for test-bed systems.

- The industrial testbed collects data from a real production environment. Getting reliable and validated data is great when trying out different analysis methods, the drawback is that it's very costly to implement anything new into the production and you are limited to the current scope.
- Laboratory facilities add flexibility that isn't available to industrial testbeds while keeping the physical aspect of real production. Drawbacks being added time and cost investment when scaling up the system.
- Virtual testbeds where the production environment is made up of simulations models. This adds even more flexibility to making changes to match the needs of the research, decreasing time, cost and space investment. Reliability of the model is critical for validation of the system.

The choice of layout for the test-bed depends on the type of research being conducted. The lab facility layout in this work was chosen as a mean to facilitate the implementation of the shifting bottleneck algorithm into real production environments. Being able to gain hands-on experience in installing data collection systems and connecting them to the SBN algorithm is essential for effective implementation.

Research Question 2: What are the requirements for shifting bottleneck method implementation in a test-bed or production environment?

The shifting bottleneck method is based on active and inactive times for machines, automated guided vehicles or manual tasks in the production environment. The illustration in figure 8 shows the basic concept being dividing up active and inactive tasks. For the SBN method to work data must be collected and stored in a specific way to be viable.

- The first requirement is that the necessary equipment to measure active and inactive time in a variety of different application needs to be present. In the thesis, this was done by using the PLC Box and OPC UA server installed in the HMI system available in the lab and then sending this information to the Axxos system.
- The second requirement is the ability to store this data in some capacity, the current solution is the Microsoft SQL database in the Axxos system.

- The third requirement is that the collected data from the production environment must be formatted in the correct way in the database. There can be no overlap of information at each sample point. Either the machine is active or inactive if the data wasn’t collected correctly and have contradictory information assumptions must be made to complete the calculation and thus hurting the validity of the results.

7. Future Recommendations

Current demonstrator and algorithm implementation suffer from certain limitations that need to be fixed to bridge the gap for real-time analysis. Recommendations from the author will be put forth below.

Collecting data with the HMI and transfer it through the OPC UA servers shows great promise and was relatively easy to set up. Adding external sensors that connect through the available PLC box will be an important next step, not all machines in an active production environment have built-in sensors capacity. Complementing the manual workstations with robots or other machines moves us closer to a real system and will highlight any potential problems with inactive and active measurements.

The algorithm in its current state lacks the needed scalability for an increasing number of machines and will have to be adjusted accordingly. Solving the time lag issue discussed in a previous section is the major next step towards the algorithms capacity for real-time calculations. Moving the coding from the MATLAB environment to a more suitable coding language is also recommended, thus making it easier to connect directly to the MSQL database and moving away from a two-step process.

References

Abele, E. *et al.* (2015) ‘Learning factories for research, education, and training’, *Procedia CIRP*. Elsevier B.V., 32(Clf), pp. 1–6.

Abele, E. *et al.* (2017) ‘Learning factories for future oriented research and education in manufacturing’, *CIRP Annals - Manufacturing Technology*. CIRP, 66(2), pp. 803–826.

Bastos, P. and Lopes, R. (2009) ‘Maintenance behaviour-based prediction system using data mining’, *… , 2009. Ieem 2009. Ieee …*, pp. 2487–2491.

Betterton, C. E. and Silver, S. J. (2012) ‘Detecting bottlenecks in serial production lines - A focus on interdeparture time variance’, *International Journal of Production Research*, 50(15), pp. 4158–4174.

Bevilacqua, M. and Braglia, M. (2000) ‘The analytic hierarchy process applied to maintenance strategy selection’, *Reliability Engineering & System Safety*, 70(1), pp. 71–83.

Carnero, M. C. (2005) ‘Selection of diagnostic techniques and instrumentation in a predictive maintenance program. A case study’, *Decision Support Systems*, 38(4), pp. 539–555.

Chapman, P. *et al.* (2000) ‘Crisp-Dm 1.0’, *CRISP-DM Consortium*, p. 76.

Denscombe, M 2014, *The Good Research Guide. [Electronic Resource] : For Small Scale Research Projects*, n.p.: Maidenhead : Open University Press, 2014., Chalmers Library Catalogue, EBSCO*host*, viewed 23 August 2018.

Faget, P., Eriksson, U. and Herrmann, F. (2005) ‘Applying discrete event simulation and an automated bottleneck analysis as an aid to detect running production constraints’, *Proceedings - Winter Simulation Conference*, 2005(2001), pp. 1401–1407.

Fosso Wamba, S. *et al.* (2015) ‘How “big data” can make big impact: Findings from a systematic review and a longitudinal case study’, *International Journal of Production Economics*. Elsevier, 165, pp. 234–246.

Fowler, J. W. and Rose, O. (2004) ‘Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems’, *Simulation*, 80(9), pp. 469–476.

Galán, F. *et al.* (2008) ‘A Model-driven Configuration Management Methodology for Testbed Infrastructures’, *Transformation*, pp. 747–750.

Gantz, J. and Reinsel, D. (2012) ‘THE DIGITAL UNIVERSE IN 2020: Big Data, Bigger Digi tal Shadows, and Biggest Growth in the Far East’, *Idc*, 2007(December 2012), pp. 1–16.

Gilchrist, A. (2016) *Industry 4.0: The Industrial Internet of Things*, *Library of Congress Control Number*.

Goldratt, E. M. and Cox, J. (2004) *The Goal: A Process of Ongoing Improvement*, *Book*.

Gopalakrishnan, M., Skoogh, A. and Laroque, C. (2015) 'Simulation-based planning of maintenance activities by a shifting priority method', *Proceedings - Winter Simulation Conference*, 2015–Janua, pp. 2168–2179.
Helu, M. and Hedberg, T. (2015) 'Enabling Smart Manufacturing Research and Development using a Product Lifecycle Test Bed', *Procedia Manufacturing*. Elsevier B.V., 1(June), pp. 86–97.

Hopp, W. J. and Spearman, M. L. (2001) *Factory physics: foundations of manufacturing management*. 2nd edn. New York: Irwin/McGraw-Hill.

Jeon, B. W. *et al.* (2017) 'An architecture design for smart manufacturing execution system', *Computer-Aided Design and Applications*, 14(4), pp. 472–485.

Jonker, J. and Pennink, B. W. (2009) *The essence of research methodology: A concise guide for master and PhD students in management science*, *The Essence of Research Methodology: A Concise Guide for Master and PhD Students in Management Science*.

Kletti, J. (2012) *Manufacturing Execution System - MES*, *Uma ética para quantos?*
Lee, J. *et al.* (2006) 'Intelligent prognostics tools and e-maintenance', *Computers in Industry*, 57(6), pp. 476–489.

Lee, J. Y. *et al.* (2015) 'Toward development of a testbed for sustainable manufacturing', *Concurrent Engineering Research and Applications*, 23(1), pp. 64–73.

Lee, S. W., Nam, S. J. and Lee, J. K. (2012) 'Real-time data acquisition system and HMI for MES', *Journal of Mechanical Science and Technology*, 26(8), pp. 2381–2388.

Li, L., Ambani, S. and Ni, J. (2009) 'Plant-level maintenance decision support system for throughput improvement', *International Journal of Production Research*, 47(24), pp. 7047–7061.

Li, L., Chang, Q. and Ni, J. (2009) 'Data driven bottleneck detection of manufacturing systems', *International Journal of Production Research*, 47(18), pp. 5019–5036.

Li, L. and Ni, J. (2009) 'Short-term decision support system for maintenance task prioritization', *International Journal of Production Economics*. Elsevier, 121(1), pp. 195–202.

Narayan, V. (1998) 'The raison d'être of maintenance', *Journal of Quality in Maintenance Engineering*, 4(1), pp. 38–50.

O'Donovan, P. *et al.* (2015) 'Big data in manufacturing: a systematic mapping study', *Journal of Big Data*. Journal of Big Data, 2(1), p. 20.

Reed, M. S. *et al.* (2009) 'Who's in and why? A typology of stakeholder analysis methods for natural resource management', *Journal of Environmental Management*. Elsevier Ltd, 90(5), pp. 1933–1949.

Roser, C., Nakano, M. and Tanaka, M. (2001) ‘A practical bottlenec detection method’, in *Proceedings of the 2001 Winter Simulation Conference*, pp. 949–953.

Roser, C., Nakano, M. and Tanaka, M. (2002) ‘Shifting bottleneck detection’, *Proceedings of the Winter Simulation Conference*, 2, pp. 1079–1086.

Roser, C., Nakano, M. and Tanaka, M. (2002) ‘Tracking shifting bottlenecks’, in *In Japan-USA Symposium on Flexible Automation*, pp. 745–750.

Roser, C., Nakano, M. and Tanaka, M. (2003) ‘Comparison of bottleneck detection methods for AGV systems’, *Proceedings of the 2003 Winter Simulation Conference, 2003.*, 2, pp. 1192–1198.

Roser, C., Nakano, M. and Tanaka, M. (2003) ‘Constraint Management in Manufacturing Systems’, *JSME International Journal*. JSME International Journal, 46(1), pp. 73–80.

Salunkhe, O. and Fumero, P. Q. (2017) ‘Demonstration of real-time criticality assessment using a test-bed’, *Chalmers Master thesis*.

Schuh, G. *et al.* (2015) ‘Promoting work-based learning through industry 4.0’, *Procedia CIRP*, 32(Clf), pp. 82–87.

Sengupta, S., Das, K. and VanTil, R. P. (2008) ‘A new method for bottleneck detection’, in *Proceedings of the 2008 Winter Simulation Conference*, pp. 1741–1745.

Shariatzadeh, N. (2014) ‘Digital Learning factories: conceptulization, review and discussion’.
Subramaniyan, M. *et al.* (2016) ‘An algorithm for data-driven shifting bottleneck detection’, *Cogent Engineering*, 3(1), pp. 1–19.

Tisch, M. and Metternich, J. (2017) ‘Potentials and Limits of Learning Factories in Research, Innovation Transfer, Education, and Training’, *Procedia Manufacturing*. The Author(s), 9, pp. 89–96.

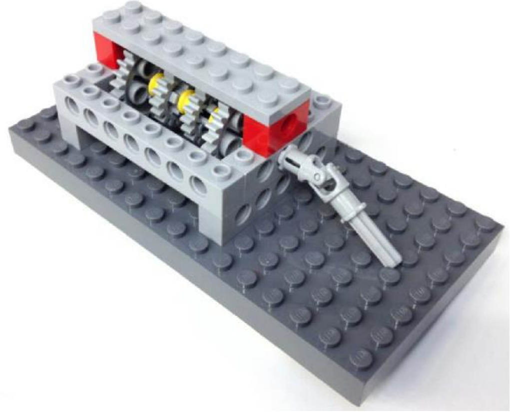
Ylipää, T. *et al.* (2016) ‘Identification of maintenance improvement potential using OEE assessment’, *International Journal of Productivity and Performance Management*, 66(1), pp. 126–143.

Appendices

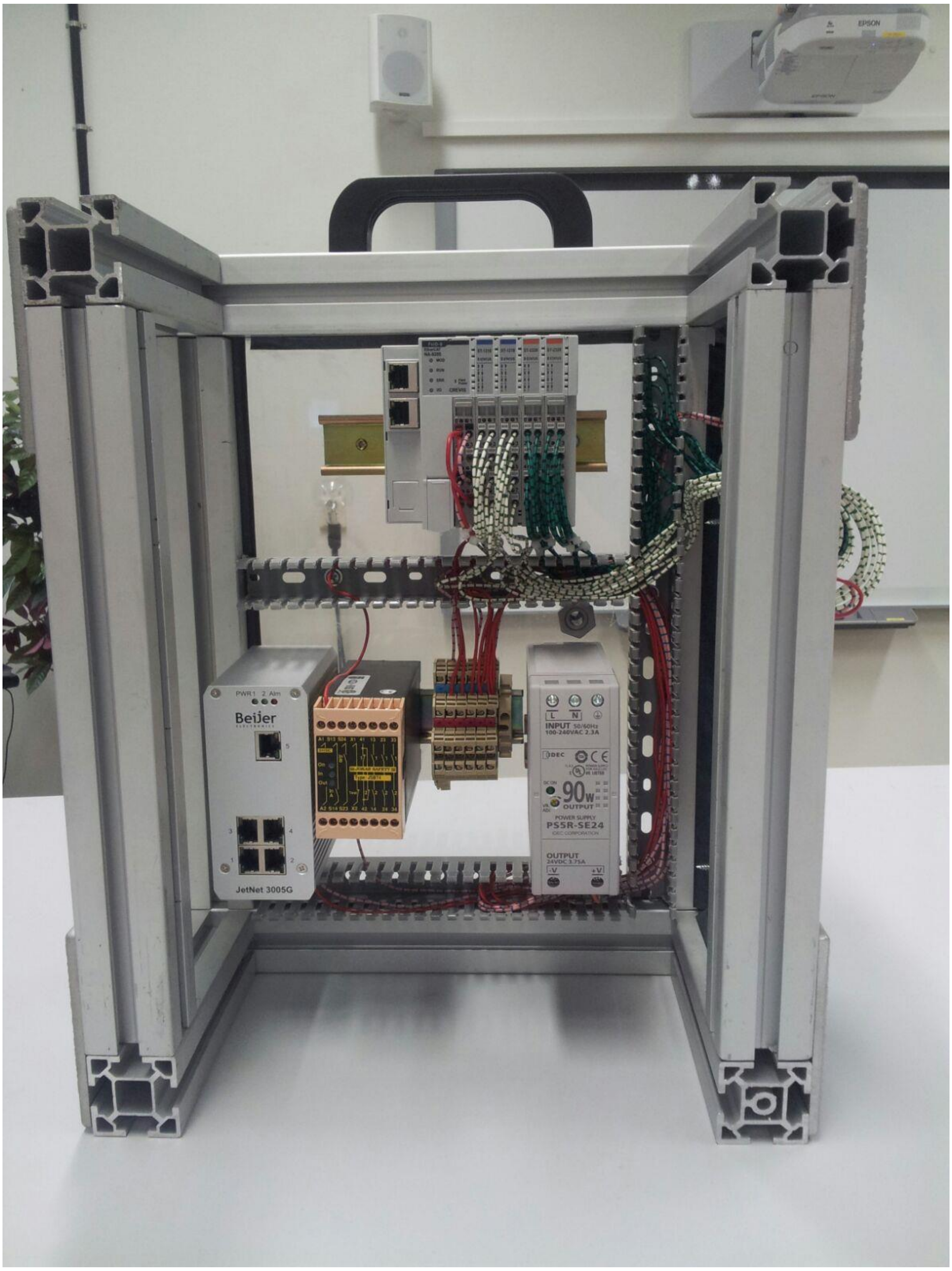
Appendix A: pictures

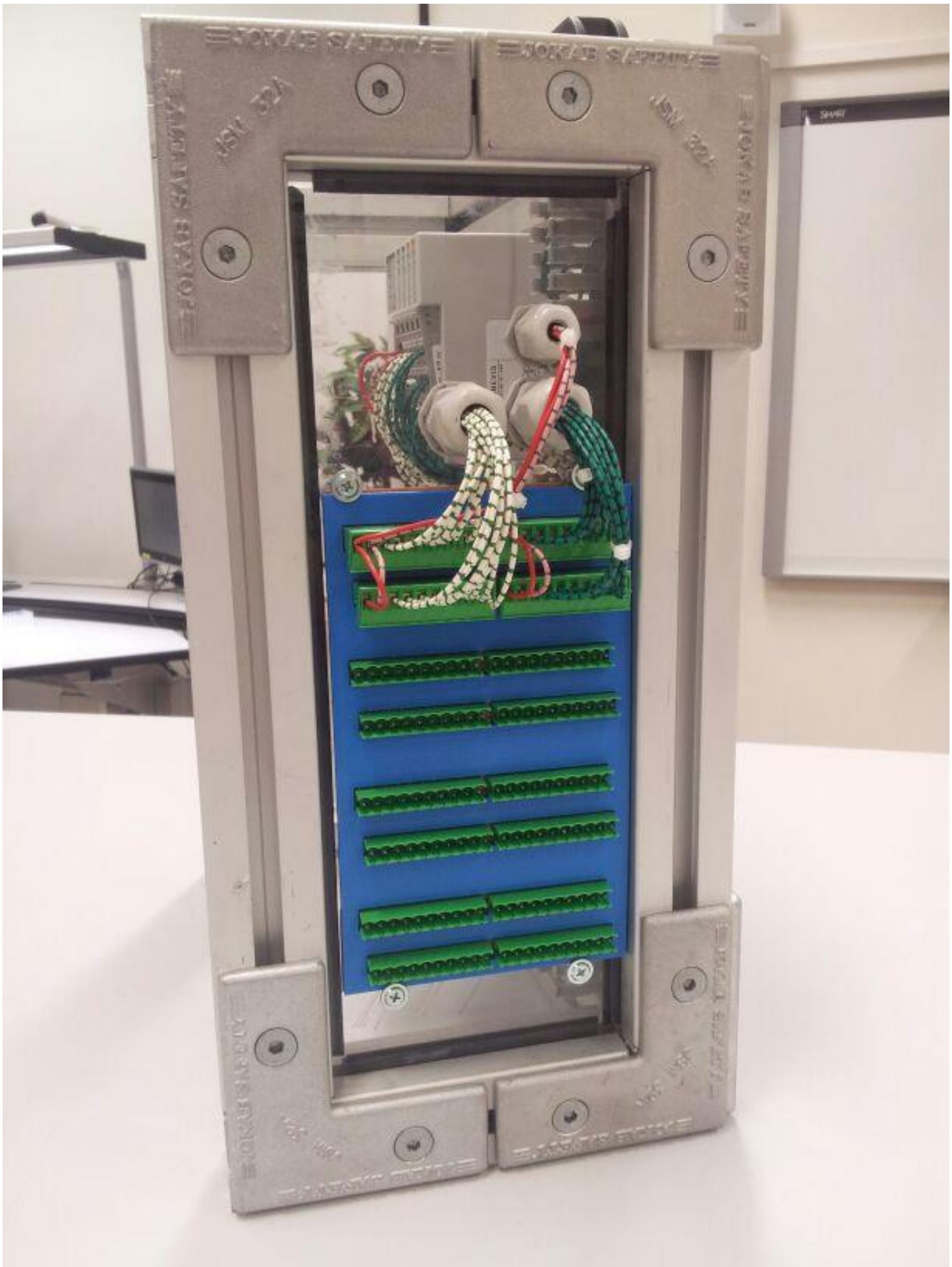
Product A and B will only vary according to what is done in the manual station (workstation 2) so, what makes one product different is the part it has:

Product A manual assembly:



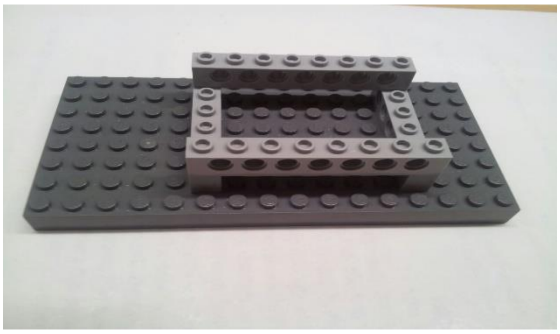
PLC box:


Beijer
JetNet 3005G
INPUT 50/60Hz 100-240VAC 2.3A
90W OUTPUT
POWER SUPPLY PS5R-SE24
OUTPUT 24VDC 3.75A

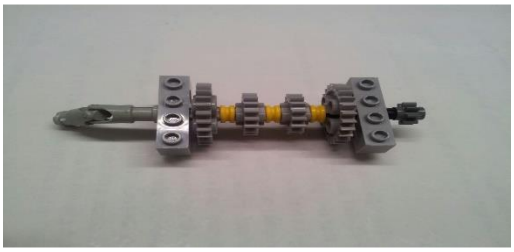

JOKAB SAFETY
JSM 32A

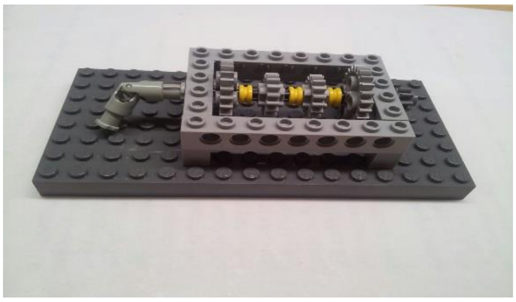
PRODUCT: gear box

Station 1 (22 seconds):



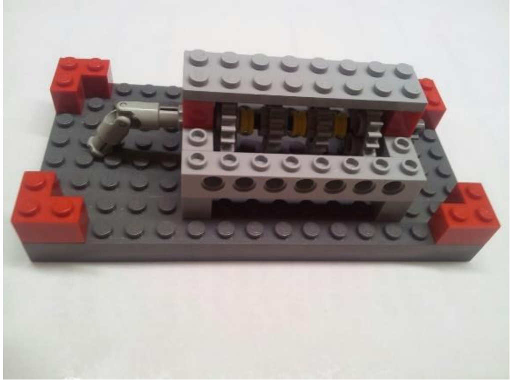
Station 2 (1 minute):





Station 3 (11 seconds):

Station 4 (13 seconds):



Appendix B: Workstation description and States

Station - Task Descriptions

Workstation 1: *First stage assembly*

1. Product arrives from the conveyor
2. Built product using workstation buffer and instructions.
3. Move Product From workstation to the conveyor
4. Produce Product to refill workstation supermarket buffer
5. Repeat when next product arrives from the conveyor

Workstation 2: Base Assembly

1. Product arrives from the conveyor
2. Built product using workstation buffer and instructions.
3. Move Product From workstation to the conveyor
4. Produce Product to refill workstation supermarket buffer
5. Repeat when next product arrives from the conveyor

Workstation 3: Gear Box/Engine Assembly - Manual

1. Product arrives from the conveyor
2. Built product using workstation buffer and instructions.
3. Move Product From workstation to the conveyor
4. Produce Product to refill workstation supermarket buffer
5. Repeat when next product arrives from the conveyor

Workstation 4: Assembly

1. Product arrives from the conveyor
2. Built product using workstation buffer and instructions.
3. Move Product From workstation to the conveyor
4. Produce Product to refill workstation supermarket buffer
5. Repeat when next product arrives from the conveyor

Below is a rundown of the different states the machine can be in and its corresponding status.

Workstation 1: Kitting for Assembly / Disassembly

Active: Repairing, Blocked, Producing, Breakdown

Inactive: Waiting, Non-active, Starved, Blocked

Workstation 2: Base Assembly - Manual

Active: Starved, Blocked, Producing, Breakdown

Inactive: Waiting, Non-active, Starved, Blocked

Workstation 3: Assembly - Manual

Active: Starved, Blocked, Producing, Breakdown

Inactive: Waiting, Non-active, Starved, Blocked

Workstation 4: Assembly - Manual

Active: Starved, Blocked, Producing, Breakdown

Inactive: Waiting, Non-active, Starved, Blocked

Storage / Material Handling:

Part amounts,

Criticality assessment data

On top of the data collected for the shifting bottleneck, some data is also being collected for the criticality assessment analysis being done by another thesis group working with the test-bed system. The following information is in some way tracked and collected through the collection system and outside input. Number of incidents (health, safety, environment), MTTR, cause of failure, spare parts needed for cause of failure, cost of spare parts, cost of man/h, cost of new equipment, MTBF, availability, failures per period, utilization factor, age, quality impact factor, redundancy, number of unplanned maintenance interventions.

Appendix C: Shifting Bottleneck Algorithm and AXXOS OEE System

Input: Matrix *A*

Output: Current bottleneck, average bottlenecks and non-bottlenecks

```
    States Accumulation transformation

1   Set $i = 0$ and $j = 0$
2   If $i < m$ go to Step 3. Otherwise go to Step 7
3   If $j < n$ go to Step 4. Otherwise set $j = 0$ and go to Step 6
4   If $j$ is 0 set $b_{i,j} = a_{i,j}$. Otherwise set $b_{i,j} = a_{i,j} * (b_{i,j-1} + 1)$
5   Set $j = j + 1$ and go to Step 3
6   Set $i = i + 1$ and go to Step 4
    Potential Bottlenecks detection transformation
7   Set $j = n-1$ (last time instant)
8   Find machine $i^*$ with the highest accumulated state, $b_{i,j}$, at time instant $j$ and set $c_{i^*,j} = 1$. If all
    elements are zero set $j = j-1$ and go to Step 11. Otherwise go to Step 9
9   Set every element $c_{i^*,j^*} = 1$ for $k < j^* < l$, where $k$ is the last time instant machine $i^*$ was inactive
    before $j$ and l the first inactive state after $j$
10  Set $j = k$
11  If $j < 0$ go to Step 13. Otherwise go to Step 8
12  Machine $i^*$ is the current bottleneck

    Shifting bottlenecks

13  Set $j = 0$
14  Calculate $s_j = \sum_{i=0}^{m-1} c_{i,j}$ If $s_j > 1$ set $d_{i,j} = c_{i,j}$ for all $i$
15  Set $j = j + 1$
16  If $j < n$ go to Step 14. Otherwise go to Step 18
17  Calculate the shifting bottleneck percentage of machine $i$ according to equation below,
```

$$r_i^{(shifting)} = \frac{1}{n} \sum_{j=0}^{n-1} d_{i,j} \tag{1}$$

```
    Sole Bottlenecks

18  Set $e_{i,j} = c_{i,j} - d_{i,j}$
19  Calculate the sole bottleneck percentage of machine i according to equation below,
```

$$r_i^{(sole)} = \frac{1}{n} \sum_{j=0}^{n-1} e_{i,j} \tag{2}$$

- *Normally IIS parts are installed on AXXOS Server*
- *SQL Server could be installed on AXXOS Server*

** Optional*

AXXOS OEE 4.3 - Site