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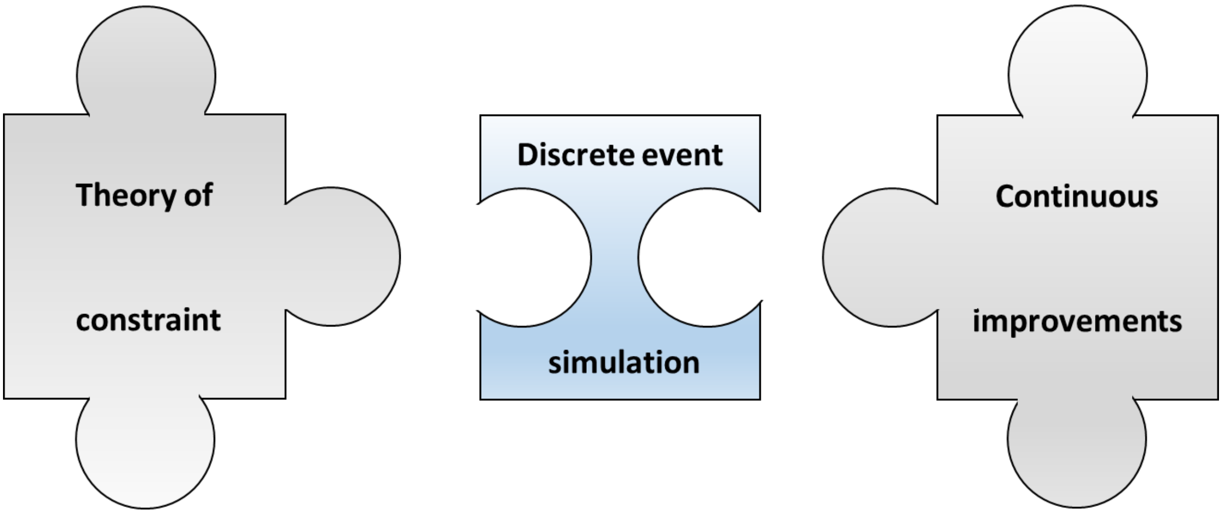

Simulation of integrated theory of constraint and continuous improvement

Master's thesis in Production Engineering

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Simulation of integrated theory of constraint and continuous improvement
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Abstract

There is no such thing as the perfect production system. Improvements can be made in all manufacturing plants, even the world leading ones. Companies have therefore turned their attention to adopting philosophies that focus on improvement work. One of these philosophies is the Lean philosophy; it has a focus on continuous improvements.

Continuous improvements are done wherever improvements can be made, without regard to the overall system performance. Improvements are not harmful, but carrying out improvements wherever they may be applied occupies resources that can be used for more effective improvements. This project aims to find areas of improvement that the whole system can benefit from. This approach can then be referred to as a focused improvement, instead of a continuous one.

A more accurate approach for focused improvement is the Theory of constraints (TOC). TOC aims to find where the system is constrained. All efforts should then be placed on improving this constraint so that the overall system performance is improved. In order to find a strong approach to focus the system improvements, both continuous improvements and TOC was studied. The best of these two theories are then put together, integrated to a method called Focused system improvements (FSI).

FSI is a decision-making method that bases its decisions on experiments and observations of the production system. In order to carry out experiments and observe the production system, discrete event simulation (DES) was used. This tool simulates the system graphically and produces data that a user can then study how changes impact the system, without disturbing the real system.

FSI, with the support of DES, was used in an industry based case study. The results indicate that DES has attributes that greatly benefit improvement work by indicating where improvements should be focused. FSI is proven to be a strong decision-making method when used together with DES.

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Table of abbreviations

DES	Discrete event simulation
FSI	Focused system improvement
KPI	Key performance indicator
MTTF	Mean time to failure
MTTR	Mean time to repair
TOC	Theory of constraint
TPS	Toyota production system
UI	User interface
VSM	Value stream mapping

1. Introduction

This chapter includes a brief background and the reasons behind this master thesis project. Purpose is derived from identified problems in the field. Goals are formulated in a manner to serve project's purpose.

1.1. Background

In order to find improvement potential in production systems with Lean methodology, value stream mapping (VSM) is used. VSM is a deterministic method that produces the same output with unaltered input (Marvel & Standridge, 2006). However, many important characteristics of manufacturing systems are random variables and time dependencies, such as customer demand and machine breakdowns. Therefore the validity of this method for complex production systems is questionable.

Continuous improvements are beneficial for the organisation. But they might not be the most effective way of improving overall performance. Continuous improvements are focusing on improved efficiency but neglect the effectiveness of changes (Cox & Schleier, 2010).

Marvel and Standridge claim that simulation is needed for industrial applications where the continuous improvement fails to make a trade-off on which improvement to focus on to get the highest return (Marvel & Standridge, 2006). Theory of constraint (TOC) is a method that with discrete event simulation (DES) can focus on solving the operational issues in industrial applications that is influenced by random variables.

1.2. Problem formulation

Theory of constraint and Lean are two production management paradigms, but they are based on fundamentally different assumptions. The aim of TOC is to find and eliminate a constraint in an unbalanced production system where Lean philosophy perceives any unbalance as waste. This leads to following problem:

Is it possible to integrate these paradigms to get the best from both worlds?

Furthermore, both paradigms were formulated before an era of simulation possibilities. Therefore they were developed with deficiencies. Modern computerized tools have come far since the introduction of these paradigms, which leads to the following question:

Can discrete event simulations' attributes account for the deficiencies in those paradigms?

1.3. Purpose

The purpose of this project is to show how productivity of a production system can be increased by using DES to support an integration of TOC and Continuous improvements.

1.4. Goals

In order to fulfil the purpose of this master thesis, the following goals are set. The objective of both goals is to increase the productivity of production system.

1. Present specific DES attributes that can be used to overcome current deficiencies of Theory of constraint and Continuous improvement.

2. Demonstrate possibility of integration between Theory of constraint and Continuous improvement by using DES technology.

1.5. Delimitations

Delimitations were set at the initial phase of the master thesis. The main criterion to determine delimitations was the trade-off between value to the project compared to saved time that the delimitation carries.
They were determined with mutual agreement with project stakeholders. Delimitations used in the project were:

- No modelling of operators
- No modelling of internal logistics
- Raw material is unlimited
- Finished goods stock is of unlimited capacity
- Not available, but collectable data is composed from an existing similar production plant
- Historical data is limited to 12 months
- Normal distribution is assumed where data distribution cannot be calculated
- Economical aspects are not considered to any large extent, low cost changes might still be favoured.

Because of confidentiality, the demand used in experiments presented in chapter 5, Results, is non-realistic. However, the result section aims to highlight the utility and advantages of DES supported integration of TOC and Continuous improvement.

1.6. Case description

The case study is performed at a company that will not be named in the report because of confidentiality, and will therefore be referred to as The Company throughout the report. The case study is performed at one of The Company's factories, named Factory A in the report. The company is currently engaged in the continuous improvements as a part of their lean strategy.

1.6.1. Product description

Factory A is producing products from particleboards. A supplier is providing Factory A with raw material in the form of panels in different dimensions and colours. The raw panels will be machined into more than 500 different parts that will be packed together. When the parts are packed together they form more than 200 different articles that are then sold to the customers.

1.6.2. Production process description

The first process in the production will take the raw panels and produce smaller parts that are then placed on so called baseboards. Baseboards are utilized for internal logistics. All parts on one baseboard are of the same type and will therefore travel the same route through the Factory to be machined in the relevant processes. After parts from baseboards are packed into articles, the baseboards are reused for new parts. There are both manual and automatic machines in the Factory, presented below:

- *Panel sizing*
    - The input to the machine is raw panels which are cut into smaller parts and then placed on baseboards. The baseboards are sent to either safety buffer or strip line machine.
- *Safety buffer*
    - A buffer with capacity of X baseboards.
- *Strip line*
    - This machine takes baseboards from the previous machines and unloads the parts for machining. The parts are then placed on baseboards and sent to the next buffer, racking.
- *Racking*
    - A buffer with capacity of X+72 baseboards. Baseboards wait here until the connecting machines have free capacity.
- *Cross edge band*
    - This machine takes baseboards from the previous machines and unloads the parts for machining. The parts are then placed on baseboards and sent to the next buffer, transit.
- *Drill 1*
    - This machine is utilized if parts are not going through cross edge band. Baseboards of parts are unloaded then fed in, machined, and then placed on baseboards after the machining.
- *Narrow part machine*

    - This machine is parallel to drill 1 an cross edge band. Parts arrive here on baseboards from racking buffer and are put onto baseboards after machining and then sent to transit buffer.
- *Transit*
    - A buffer with capacity of X+15 baseboards.
- *Drill 2 & 3*
    - Two parallel machines that are identical to drill 1. After machining, baseboards with parts are sent to storage.
- *Manual machines*
    - These machines are placed parallel to drill 2 and 3. Baseboards with parts arrive here from transit and are either sent from one manual machine to another or to the next buffer, storage.
- *Storage*
    - The capacity of this buffer is X+669 baseboards. Baseboards carrying parts are sorted so that they are placed next to other baseboards with the same kind of part. If baseboards are not fully consumed of the parts they are carrying in the next process, they are sent back to this buffer.
- *Packaging 1 & 2*
    - These machines are parallel and identical, they will pack parts into articles and send baseboards back to the previous buffer if they are not fully consumed.
- *Shrink foil*
    - This machine pack parts into articles. It operates differently than packaging 1 & 2, but will also send parts back to the previous buffer if they are not fully consumed.
- *Packed*
    - The final storage for the packed articles.

2. Theoretical framework

Theories used to meet the master thesis´ purpose are presented in the following section. The theory behind TOC and continuous improvement are offered in detail. They are the components of the theory of focused system improvements (FSI) that follows. Thereafter, the theory of DES is presented. Finally, theoretical background about how DES can support FSI is examined.

2.1. Theory of constraint

“Can we condense all of TOC into one sentence? I think that it is possible to condense it to a single word—focus” (Eliyahu M. Goldratt).

Not all possible improvements can be done instantly because of limited resources needed to perform change. The Pareto principle has proved that small amounts of elements contribute to a big impact. Therefore, a focus on the right elements is of outmost importance. Pareto’s 80-20 rule in which he proved that 20 per cent of element contribute to 80 per cent of the impact is valid only when there are no interdependencies and variability between those elements. In a production system with many interdependencies and variability, the 80-20 situation becomes even more extreme. Fewer elements contribute to an even bigger impact. Those few elements are identified as constraints and should be in focus (Cox et al., 2010).

The basic idea of TOC can be explained through a chain analogy. A chain is only as strong as its weakest link. Weakest link is therefore a constraint of the entire chain. TOC promotes system thinking in which improvement that does not increase performance of the weakest link or the constraint, does not improve strength of the chain or the performance of the system.
TOC emphasizes on the need to improve and manage how the system constraint performs in context of the dynamic of the total system. This system dynamic includes interdependencies and variability. By focusing on sensitive and relevant points in the system and then analysing how different factors impact them a total system improvement can be achieved (Cox et al., 2010).
The five steps of working with TOC in a structured way are:

1. Identify the constraint.
2. Decide how to exploit the constraint.
3. Subordinate everything else to the constraint.
4. If needed, elevate the system’s constraint.
5. If the constraint has been broken, go back to Step one.

These steps are further explained in chapter 4, Work description.

2.2. Continuous improvement, pillar of Lean philosophy

Toyota production system (TPS) has changed production management by introducing an improvement method that uses small incremental continuous improvements. Liker (2004) is describing TPS with four categories (Figure 1). This 4P model is showing the importance of continuous improvement work for waste elimination. In Toyota´s internal handbook, “Toyota way”, they point out the importance of continuous improvement work as a basis for further development (Liker, 2004). The final goal of TPS is not continuous improvement but to meet business objectives, such as profits, market share and customer loyalty (Alukal, 2007: 70).

Waste is characterized by any activity that does not add value to the customer. Waste is categorized in to eight groups. These groups suggests that waste are defects, overproduction, waiting, non-used creativity of workers, transportation, inventory, movements and extra processing. Elimination of waste with continuous improvements approach has quantitative and qualitative benefits.

Quantitative benefits can be measured in terms of monetary benefits. Benefits include saved time and fewer people required, reduced lead-time, fewer process steps, improved first pass yield, and reduced inventory.

Qualitative are intangible benefits that are harder to measure. They excel cultural change and commitment among employees. They contribute to change in a way of thinking and not only to change in a process (Manos, 2007: 47).

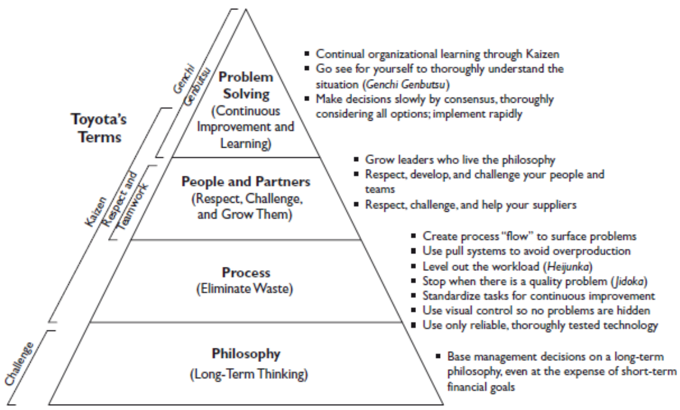

Figure 1: The principles of Lean (Liker, 2004)

Tools often used for continuous improvements include 5S system, standardized work, rapid setup reduction, elimination of non-value added waste, total productive maintenance, andon, mistake proofing, visual tactics, control charts, capability studies (Cox et al., 2010).
Standardized work is seen as a fundament for enabling continuous improvement rather than its limit (Liker, 2004).

A continuously changing production environment requires an organized use of incremental and breakthrough improvements (Alukal, pg.70, 2007). The following section discuss how these requirements can be met with integration of Continuous improvements and TOC.

2.3. Integration of Theory of constraint and Continuous improvements

This section explains how integrated Theory of constrains and Continuous improvement result in Focused system improvement (FSI).

In TPS the production system is designed according to the calculated takt time, based on customer demand. Then resources and equipment capacity are aligned to that takt. Any capacity exceeding that rate is overproduction and therefore considered as waste. Continuous improvements are focusing to eliminate that waste in order to balance the system to the takt time. Some waste in terms of excess capacity is accepted because of expected variations. As continuous improvements are aiming to reduce variations the related excess capacity is also expected to be reduced.

Therefore in TPS every operation could become the system's constraint if there is any variation in demand, product, or process. TOC is suggesting different approach, since according to Deming (1943) there will always be a variation. The balanced line approach is more applicable in cases with little or no variation in the demand, product mix or process times (Cox et al., 2010).

In contrary to TPS, the TOC method is based on the premise that every system has a constraint that limits the output. An hour lost on the constraint is an hour lost for entire system. Therefore the TOC design would promote excess capacity on a non-constraint to ensure that the constraint is exploited to the fullest extent possible. This "unbalanced" system design allows all operations and improvements to focus on constraint's performance and therefore impacting the entire system (Cox et al., 2010).

Any variation in the system that is balanced according to takt time would impact throughput of entire system. Continued variation will dictate the need for elimination of variation in the entire line in a very quick manner, which would often be a very demanding and costly task. According to Goldratt (1990) this is not a rational act since: "Focus on everything, and you have not actually focused on anything". Therefore TOC suggests focusing of improvement initiatives on the constraint. This would result in direct impact on overall system performance.

Cox (2010) states that effort should be made to integrate best of both methodologies. Continuous improvement should still aim to eliminate variation. But the TOC perspective of unbalanced line, should set the direction of improvement focus toward constraint and therefore provides more rapid system improvement. This integration is then referred as Focused system improvement (FSI). FSI promotes efficiency and stability of the constraint as the important indicators. The non-constraints are measured on their effectiveness in keeping the constraint supplied. The output of the total system is the overall top indicator (Cox et al., 2010).

2.4. Discreet event simulation (DES)

Simulation is a tool that models a real system and its behaviour in a virtual environment. It is a powerful asset for engineers, designers and management in a decision process. By observing the model, the user can study, analyse and evaluate the real system since the model is mimicking the behaviour of the events over time. Both existing and future production systems can be modelled preliminary in planning or in the development stage (Shannon, 1998: 7). Another benefit of simulation is the ability to study changes in a virtual environment without having to change the real system. Changes in real system can be time consuming and expensive.

Discreet event simulation techniques consists of modelling concepts for abstracting a system's features into a coherent set of precedence. These features are linked with mathematical relationships. The computer executable code in a simulation software converts these mathematical relationships into requisite sample-path data. This data is then estimated in terms of system performance by procedures in the software. Methodologies for validation of these estimations compared to true, but unknown system behaviour is needed (Fishman, 2001: 4).

Advantages of simulation models compared to mathematic models are derived from easier comprehension and understanding of simulation models. Credibility is also better since simulation require less simplifying assumptions. Because of this, different experiments can be performed and hypothesizes tested without interfering and disrupting the real system. Time control of simulation enables analysis of system performance at a long time horizon or a detailed study of phenomena in short moments (Shannon, 1998: 8).

However, the quality of a simulation model depends on the skill of the modeller. Specialized training is required to master this skill. Even a high quality simulation model will not provide the user with an actual solution. The user has to keep in mind that simulation provides a tool for analysis of system under different conditions and will support the user in search for an optimal solution. Output of the system can at best only be as accurate as the input data. Gathering this data might be difficult and time consuming (Shannon, 1998: 7).

Skoogh and Johansson (2008) claims that DES projects rely heavily on the quality of input data. What they provide in their article is a guideline for handling input data which is further presented in chapter 3.3, Data collection.

Interaction with simulation model could be done through a user interface (UI). A key goal of a user interface is to simplify usage of simulation model for nonspecialists. This can be achieved by developing intermediate tools, between user and model, which can be easily used (Hamad, 1998). Simulation system can be viewed as structure of three parts, data input, simulation engine (model) and simulation results. Data input and results can be processed in separate modules without direct interaction with the complex engine. Numerous studies point out UI as a critical parameter to success of simulation. Those studies have shown significant effect of UI on factors such as learning time, performance speed, error rates and user satisfaction (Jones, 1988). The aim is to develop interface, which fulfil users' requirements, and accurately supports cognitive needs. The UI should be developed with consideration that it is easier to modify characteristic of a computer system than those of the users (Kuljis, 1993). A UI can be developed in form of sequential dialogue with request-response interaction (Hartson, 1989).

2.5. Requirements of integrated Theory of constraint and Continuous improvements

In order to benefit from integration between TOC and Continuous improvements the literature is suggesting that the following requirements should be met. They are formulated based on literature behind productivity increase.

2.5.1. Variation of input data

TOC and Continuous improvements are relying on conventional deterministic methods. These methods cannot take into account variations of input data such as product mix, demand, cycle times, disturbances etc. It is very arrogant to assume that input data is equal to its mean. This ignorance would produce invalid results with low credibility.

Mean value data assumption overlooks that longer downtimes exhaust downstream buffer stock and also creates unproductive time. Similar upstream operations will experience blockage and longer queue lengths (Williams, 1994).

Vincent and Law (1993) describe the use of existing data as an empirical density as unsustainable because it assumes that any data shorter than minimum or larger than maximum is impossible. Therefore according to Williams, appropriate density should be chosen with undertaking calculations, plotting a histogram of the available data and compare its shape with those of the candidate probability density functions.

2.5.2. Quantitatively identify improvement areas with high potential

According to McKinsey (2014) there is a risk that continuous improvement initiatives consume time and money without achieving a real success. This is dispiriting for employees and makes it even harder for leaders to get employees acceptance, motivate them and keep their faith (McKinsey, 2014: 25). A Case study from McKinsey also suggests the use of testing different indicators for improvements rather than static ones (McKinsey, 2014: 49). Instead of ignoring scepticism and resistance to change it is more productive to adhere to just a few improvements and implement them gradually. Therefore it is more important to choose the relevant improvement that really affects performance to perceive and excel employees' interest and participation (McKinsey, 2014: 99).

Organisation should spend less time on improvements that has low impact on total system performance (McKinsey, 2014; 141).

A framework for total organisation excellence is suggesting top down approach towards continuous improvements where opportunities for improvements are defined on system level and deployed on bottom level (Oakland, 2001). The main focus of stewardship leadership should be to establish that employees value the system, as a whole, more than their individual function (McKinsey, 2014: 30). It is dangerous to overlook system perspective and focus on achieving single target improvement. As a result Lean improvement without a holistic perspective would not reach desired increase in system performance (McKinsey, 2014: 32). Cross-functional connection is needed to see problems and design solutions that are beneficial for total system's performance (McKinsey, 2014: 61).

2.5.3. Perform structured experimentation

Testing changes in a risk-free environment, before implementing them in your organization has multiple benefits. Because TPS requires higher short-term costs for solving problems properly rather than quickly to get long-term benefits, it is beneficial to predict improvements' long-term outcome (Simul8, 2015).

Continuous improvement also increases the organization's capacity to acknowledge, learn and experiment. Learning is an important part of the improvement process since the employees must learn new ways to work and create ideas. Experimentation is the practical way to learn. Therefore, a tool that enables fast and accurate experiments is needed (Sasthriyar & Zailani, 2011).
It empowers employees by allowing their process improvement ideas to be tested with easy to understand visual and numerical feedback on the idea's effectiveness (Simul8, 2015).

2.5.4. Visualisation of the future state

Successful continuous improvement philosophy requires the buy in of management and other process stakeholders. There is a need to realistically predict outcome of the improvement project to reduce the gap between aspirational language and daily activities that may cause cynicism and demotivation among employees (McKinsey, 2014: 138). McKinsey has found out that visualisation is effective only if it is communicated effectively through the entire organization. Everyone should recognize and understand the desired future state. In that sense visualisation also gets the bottom-up credibility that it needs (McKinsey, 2014: 138).

2.6. The gap between requirements for FSI and current commonly used tools

The gap between requirements of FSI presented in section 2.5 and attributes of conventional commonly used tools like VSM includes (Marvel & Standridge, 2006):

- modelling and assessing the effects of variation,
- making use of all available data,
- identifying other possible improvements,
- validating the effects of proposed changes before implementation.

Attributes of the tools that are reason for this gap are presented below (Figure 2).

2.6.1. Deterministic method

The VSM is fundamentally a deterministic method. But production system parameters are random variables, for example customer demand, the time between machine breakdown and repair intervals, and operation times. Therefore VSM fail to address this variation that has high impact on the production system (Marvel & Standridge, 2006).

A more thorough analysis of the data includes an examination of the variability. Therefore an estimation of a probability distribution that fits the data is needed (Marvel & Standridge, 2006).

2.6.2. Qualitative method

The improved state in VSM is developed through a process performed by the Lean team. This team follows recommended questions which help to identify improvement opportunity. Since a VSM is a descriptive tool, there is no mechanism for analysing it to see if the desired improvement will achieve performance targets (Marvel & Standridge, 2006).

2.6.3. No structured experiments

The Lean method, VSM, use trial and error to address the achievements of proposed improvements. This tool cannot quantify and validate improvements before they are made. It is not possible to know if the Lean team has found the best future state with respect to desired levels of system performance (Marvel & Standridge, 2006).

DES simulation is identified to successfully address operational issues that the Lean approach could not resolve (Marvel & Standridge, 2006).

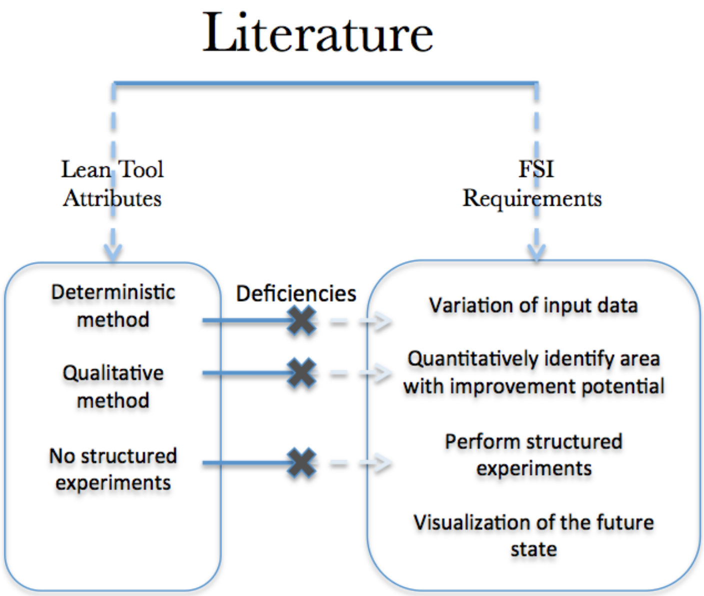

Figure 2 - Identification of gap

3. Method and work description

This section describes methodologies and how they were applied in order to achieve results for project goals. They are presented in a chronologic order. First the literature review was done in order to get understanding of existing knowledge about the subject. Purpose of literature review was to find DES attributes that could met FSI requirements, presented in section 2.5. This would fulfil the existing gap between requirements for FSI and current Lean tools.

Then an industry-based case study was done in order to make additional reasoning about use of DES for FSI. The attributes presented in literature were tested and evaluated. During the case study the simulation model was built in order to demonstrate possibilities for the use of DES to support FSI.

The work procedure for the industry-based case study is presented below. This procedure consists of several steps. The methodology behind the individual steps is then presented together with work description on how to perform the steps.

All methods were steered in an overall project plan. It was advised by experienced project managers to perceive the time plan as a document that should be constantly reviewed and updated accordingly. Since this is a research project, which means that when something new is about to be found, it is difficult to predict time distribution in advance. The time plan was designed to get an agreement with stakeholders about crucial milestones. The time plan can be found in appendix B.

3.1. Work procedure

Work procedure has followed methodologies that were proposed in literature. Literature review was done in order to get understanding of existing knowledge in this field of science. This understanding could highlight the gap between requirements of FSI and how existing continuous improvement and TOC tools can meet them. Further methodologies should be chosen in order to focus and try to close this gap. For that, a case study was chosen to be performed. In the case study DES was used to support use of FSI (*Figure* 3). Methodologies and work procedure used in a case study are presented afterwards.

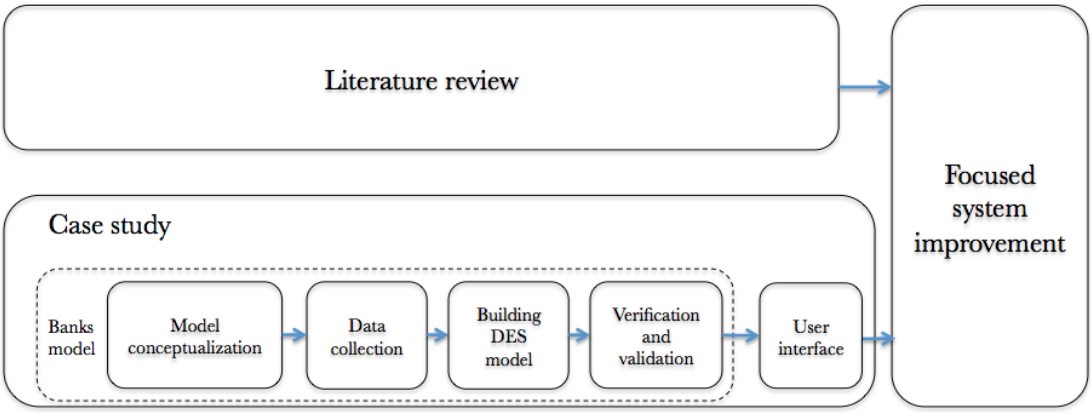

Figure 3 - Work procedure

3.2. Literature review

For the literature review the scientific articles from Access science, Scopus and Web of science databases were analysed. On the beginning of the literature review the terminology from DES theory was used for searching keywords in these databases. Later the references in the relevant articles were traced, to identify the most referenced authors in this respective field of science.

The purpose of the literature review was to identify requirements of FSI. Further it was evaluated which of those requirements cannot be met with conventional continuous improvement and TOC tools, especially value stream mapping was in focus. From literature was tried to conclude how DES attributes could meet those requirements. This was later evaluated in the case study.

3.3. Case study

The case study methodology is a combination of different sub-methodologies to get perspectives about it from different angles. These sub-methodologies are presented in the following sections. Triangulation of all these methodologies leads to the results (Groat &Wang, 2002).

3.3.1. Work description

The case study was performed at Factory A. The particular case study was chosen because of possible applications of research results. Therefore intrinsic interest was increased. Because the case study was performed for a single case, the generalisation cannot be done statistically. It was done analytically, based on reasoning, as recommended in the literature (Johansson, 2003).

The FSI was used during the case study to get additional understanding about the subject. Findings from the case study also enable additional reasoning, about the use of FSI and DES.

3.4. Banks model

Banks (2005) proposes a working procedure for simulation projects. Figure below is visualising his methodology with all necessary activities in a simulation project. Work description that has followed this method is explained in sections below.

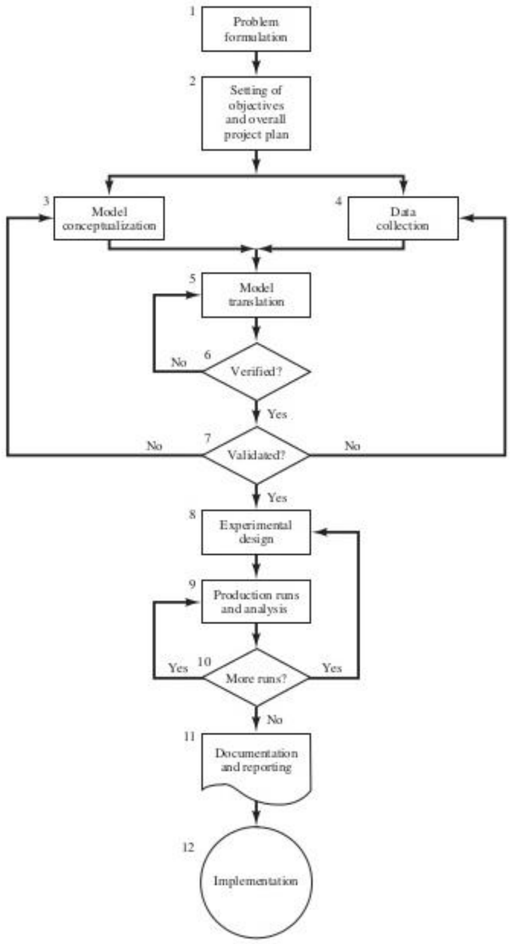

Figure 4 - Banks model methodology

3.5. Model conceptualization

A conceptual model is needed to describe the objectives, inputs, outputs, contents, assumptions, and simplifications of the model (Robinson, 2008). According to Law (1991), the conceptual model should contain an overview, including the objectives, performance measures of the model, system layout and/or process flow, detailed description of each subsystem, simplifying assumptions, and limitations of the model, summary of input data and sources of controversial information. Wang and Brooks (2007) have shown that the most widely used representation technique for a conceptual model is the flowchart.

Methods of model conceptualisation aim to simplify the model by reducing scope and detail in a model. Methods can also try to represent components more simply while maintaining a sufficient level of accuracy (Robinson, 2006).

Robinson's proposes five key activities for conceptual model: Understand the problem situation, determine the modelling and general project objectives, identify the model outputs (responses), identify model inputs (experimental factors) and determine the model content (scope and level of detail), and identifying any assumptions and simplifications (Robinson, 2008).

In short, the conceptual model defines what and how is to be represented in the simulation project.

3.5.1. Work description

Conceptualization of the system that is the target of simulation helped to initiate similar logic thinking that is required in the model. Process documentation from the plant was analysed to get an understanding in order to build the concept model. In addition to documentation, a visit to a plant with similar processes was done in order to visualise our perception of information about the simulating plant. Most of the entities were defined already in the conceptual model. They were represented in the flow chart. The conceptual model served as a base for building the simulation model. The conceptual model of the system cannot be presented due to confidentiality.

3.6. Data collection

In their article, Skoogh and Johansson (2008) provide a guideline for a data collection methodology for DES. The guideline consists of 13 activities and how they are connected. The aim of the guideline is to improve rapidity in the input data management and therefore also the rapidity of the whole DES project (Skoogh and Johansson, 2008).

Skoogh and Johansson (2008) divide input data in to three different categories, Figure 5 . Each category needs a different approach during collection. The categories reflect availability, they are:

Category A	Available
Category B	Not available but collectable
Category C	Not available and not collectable

Figure 5 - Input data chatagories (Skoogh et al., 2008)

Figure 6 is describing the proposed methodology steps together with explanatory text.

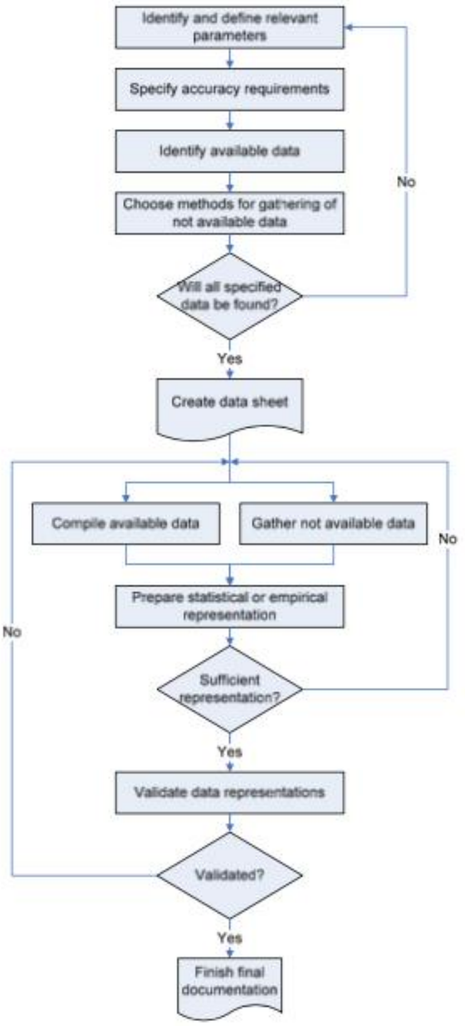

Figure 6 - Proposed methodology steps (Skoogh and Johansson, 2008).

A detailed explanation of the steps can be found in appendix A.

3.6.1. Work description

The data collection followed the steps presented in the flowchart above, to some extent. The categorization of available data mostly fell in category B and C. The methods of gathering not-available data consisted of studying a similar process and also through communication with an engineer on site at Factory A. Data sheets were then created in terms of raw data in Microsoft Excel. The engineer on site at Factory A was consulted for verification of the interpretation of raw data. This helped verify that the understanding of the processes was sufficient. The raw data was then used to calculate important factors for simulation such as cycle times, stop times, number of parts travelling together on pallets, etc. To represent data that would need stochastic distribution it had to be condensed. Condensation means that historic data was fit to a proper statistical distribution family, like for example normal or exponential distribution. This then get consensus about accepted level of validation (chapter 3.8) so that the simulation model would have a representation of the actual production system.

The details of this data collection work description will not be presented due to confidentiality.

3.7. Building the simulation model

A model translation is done from the conceptual model and the data collection, see figure 2 Banks model above. The logical relations from the conceptual model contribute how parts are moving through the model. Data collection provide information about where those parts go, how long time they spend in the process and other production characteristics. According to Banks (2005), the process of verifying a model is iterative. If the model does not run or operate as intended then more model translation is made.

There are numerous environments to build the simulation model in but they are similar in a broad perspective (Brunner & Schriber, 2005). The actual model building is done by programming in one of these environments. Depending on the environment, different perspectives and solutions to logical relationships are possible. The perspective and solutions chosen by the programmer should reflect the objective for the intended end-user of the model, so that the model can be verified (Banks, 2005).

3.7.1. Work description

Automod was used to build the DES model (Automod). The DES model was based on a complex plant with high variations in different areas such as customer orders, produced parts, breakdowns and maintenance. DES model has used input parameters that were collected according to methodology described in chapter 3.6. Data was inserted from the user interface. This is further explained in chapter 3.9 below.

The model was built so that the user can simulate variations through a user interface, and if the user wants to entirely remove a process or change a buffer capacity it is possible through the interface. At the start of every simulation, the model uses input data specified by the user in the interface and apply it to the simulation. After each verification process with the end-user, the programming code was revisited for further programming.

Since values were read from the UI, most calculations were done in the user interface and not in the actual simulation model. This helps make the DES more efficient since fewer calculations are made during simulation runs. That means faster execution of the code, which is crucial attribute to perform faster, and consequently, more experiment runs.

3.8. Verification and validation

Verification and validation follows the method as suggested by Sargent (2013), see figure 5 below. Sargent claims that the simulation model is to be built based on a conceptual model. The conceptual model defines the theories and assumptions needed to represent the production system for the intended purpose. The simulation model is then verified when correct implementation of conceptual model and execution of the programming is assured.
Operational validity determines satisfactory range of accuracy of the models output for the intended applicability (Figure 7). The needed accuracy has to be determined with consideration of value of higher confidence in the model and related higher costs. Absolute validity is too costly and time-consuming for intended applicability (Figure 8) (Anshoff & Hayes, 1973).

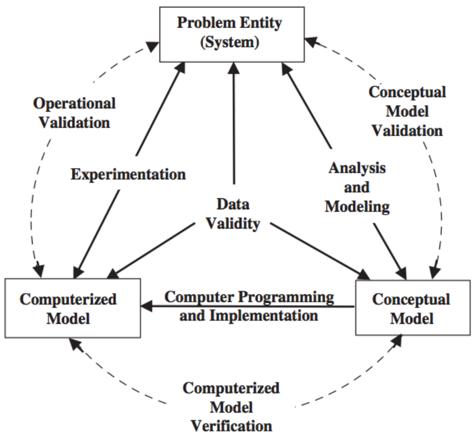

Figure 7 - Overall validity (Sargent, 2013)

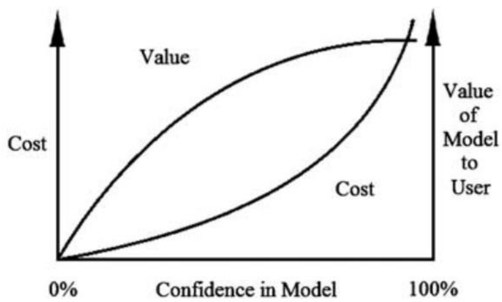

Figure 8 - Cost-value validation model (Anshoff & Hayes, 1973)

A model development team decides if the simulation model is within satisfactory range of accuracy. This decision is based on results of various tests and evaluations. As recommended in the literature, also the end user of simulation should decide about validity of the model (Sargent, 2013). Verification of both static and dynamic computerized model can be achieved through testing.

Static testing analyses computerized model with structured walkthroughs. In this technique, the developer presents the computer code to a peer group, line by line. In dynamic testing the computer program is executed under different conditions. Specific entities are traced through the model. Then results are analysed to determine accuracy (Sargent, 2013).
The validation method suggests following commonly used validation techniques. Animations graphically display the models behaviour through time. Operational graphic is used to measure various performance indexes while the code is executing. Event validity compares occurrence of events in the simulation model to the expected real system. Extreme condition tests check for the behaviour of the model in the event of any extreme and unlikely combination (Sargent, 2013).

If operational validity is not achieved, changes can be performed either in the conceptual model or in the computerized model.

3.8.1. Work description

Verification of the model was done by an experienced peer group, to which the code was explained line by line. As a dynamic test for model verification, tracing specific entities like for example parts, baseboards and articles was done. Meaningful messages were included in the code. Those messages were indicating code behaviour during execution in a message box. This technique enabled flexibility since entities that indicated suspicious behaviour could be traced.

Visualization of the model was achieved by animation and operational graphics during execution. Different states of the resources, like working, idle, setup, breakdown etc. were coloured differently in order to be able to observe their behaviour. Additional labels were included in the graphic interface, which provides information about load quantities and their flow through production. Extreme conditions with unlikely combinations were created in order check for unusual behaviour. Results of those tests were analysed and compared to proposed system theories. Those theories are developed from understanding of how such, not yet existing system, will operate.
Gradually, variations and unexpected behaviours were eliminated. Validation was done in cooperation with senior production engineers at the company to get consensus about sufficient level of confidence, described above.

3.9. User interface design

In order to design a user-friendly interface for generic use, Jones (1988) propose that the users needs should be identified. Semi-structured interviews can be used to identify these needs. The interviews can provide an understanding about what is expected from user interaction with the interface. Furthermore, usual working habits and data formats should be analysed to create a supportive interface. The main objective is to make it as efficient as possible by following existing work methods and to avoid duplication or changes to them (Jones, 1988).

3.9.1. Work description

The design of the user interface used in this project was done in collaboration with another master thesis with the title Generic user interface for simulation (Adelbäck & Malmgren, 2015). The authors of that thesis followed the semi-structured interviews proposed by Jones (1988). The interviews resulted in desired functions that were implemented in the user interface and also a layout that focused on user-friendliness.

The user interface was developed in Microsoft Excel. Presentation of data and calculations were done by the authors of this report. Communication between simulation model and UI was done by the collaborators, Adelbäck and Malmgren.

Since values were read from the UI, most calculations were done in the user interface and not in the actual simulation model. This helps make the DES more efficient since fewer calculations are made during simulation runs. That means faster execution of the code, which is crucial attribute to perform faster, and consequently, more experiment runs.

3.10. Focused System Improvement (FSI)

The method for FSI follows the logic presented in the picture below, see Figure 9. The most powerful way to integrate TOC and continuous improvements begins with *strategy*. The strategy sets the direction for improvements of business results.

Areas of the production system that benefit the total system the most are *designed*. These reconfigure the operational model, policies, roles and responsibilities, information system and measurements according to strategy.

Activation process makes the design operational. When required efficiency and stability is achieved an on-going system improvements are applied. Integration between TOC and Continuous improvement uses synergies to coherently achieve FSI instead of individual traditional continuous process improvement.

Improvement efforts are then applied in a focused way to provide even further improvements of total results. Key performance indicators (KPIs) are analysed to find gaps between present and desired performance. Further improvement techniques are determined.

Improvements must be *sustained* in a continuous way in order for the organization to achieve real bottom line results over time. All previous steps are documented and deployed through organization. KPIs are continuously reviewed and assessed to maintain progressive behaviour and to prevent achieved results degradation (Cox et al., 2010). The smaller loop from "Sustain" to "Improve" is through the report referred to as an improvement cycle, while the full cycle loop is referred to as an FSI cycle.

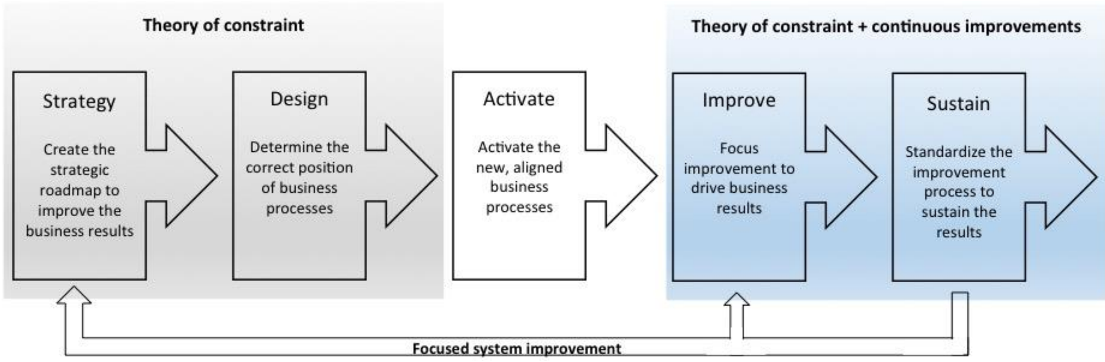

Figure 9 - Steps of FSI method (© The velocity approach, AvrahamY. Goldratt Institute. LP)

3.10.1. Work description

The work description of FSI is presented below. In each step, strategy, design, activation, improve and sustain it is shown how the attributes of DES can support FSI's requirements. They are presented in section 2.5. They are:

- *Variation of input data*
- *Quantitatively identify improvement areas with high potential*
- *Perform structured experiments*
- *Visualisation of the future state*

3.10.1.1. **Strategy**

Important objectives, such as utilization of resources or total output, were agreed upon to set the focus of improvements. They were chosen from the output data from the DES model.

Variation of input data

In order to enable updates and the use of stochastic input data, the UI was built in Microsoft Excel software. It is a widely used tool in the analysed company and it also works together with the simulation software, Automod. Additional macros are used for communication between Excel and Automod. No interaction between the user and Automod is required in order to perform experiments.
This UI was built according to data collected at the company.
In order to meet the users' requirements to support cognitive needs, the interface is:

- colour coded
- access to make changes is limited
- navigation tool is built

- instant data validation for preventing errors is performed
- help-section is integrated, which generically adopts to users' actions.

All of these features are suggested and implemented by Adelbäck and Malmgren (2015) to improve the user experience, and the tools are native to Microsoft Excel.

Data that is collected, imported and stored in the UI enables easier visualisation and management of data for end users, compared to simulation software. Macros in Visual basic were developed to enable communication between Excel and Automod simulation software.

Input data is divided into two parts. First part serves as a data basis with all the relevant information about material, products and processes. This data is expected to change with low frequency, not very often.
The second part of the input data serves as a template to enter highly variable data. This data is expected to be handled and changed often. Therefore it is important that it is presented in a user friendly way and is easy to operate with.

Formatting of data is focused on clear visualisation of data for good cognitive perception for the end user. The structure is also optimised with consideration of Automod logic. This dynamic input is predicted to be valuable later, when production is up and running, for usage during simulation for FSI. Prior to that, data is needed to perform experiments and improvements when production system is still at development phase.

Database is the static part of input UI. It contains data about products and processes. Spreadsheets contain data about raw material, parts and articles. This data includes relevant information for production processes like dimension, colour, amount etc. Cycle times are included for the all the processes with information which of them are required for each product.

Spreadsheets with breakdown, maintenance, set up and scrap rate data are used more regularly. To adjust data which is changing more often, the user experience is important. Therefore those spreadsheets were developed in a foolproof manner.

Each time more historic data is available to calculate stochastic input data the input should be adjusted in the UI. To ensure the correct format, which is readable in Automod, self-adjustable templates were created.
Because of market and demand uncertainties, production schedule is a very dynamic part of the data. Production schedule includes data about how many shifts the production will run, what batch size is to be produced and what is expected demand.

3.10.1.2. Design

After strategy for improvement work was conducted from understanding of current state the key performance indicators (KPIs) were set to monitor relevant performance. Those indicators were machine utilization, starved machines and buffers upstream and blocked machine and buffers downstream (Figure 10). Analysis of key performance indicators identifies constraints of the system. Previously described steps from verification and validation were done in order to assure that anomalies are not consequence of simulation error. Indicators were analysed in UI.

Figure 10 - KPI analysis UI

Quantitatively identify improvement area with high potential

At this step simulation is supporting FSI cycle with quantitative KPIs. Those KPIs are affected by system's dynamics that mimic the real system. By analysing them it is possible to deterministically identified constraint of the system and its dynamic through time. Constraints are the sensitive factors. Improvement of those factors results in higher yield, than improvement of non-constraint factors. Improvement of constraint has high potential since it will result in higher total output.

3.10.1.3. Activate

When constraints were identified the policies and process specification were analysed to identify possible improvements. At this step continuous improvement initiatives were suggested and tested in order to get effective results. Any improvement made at constraint station is expected to improve performance of overall system. Results of change were analysed in UI.

Perform structured experimentation

Simulation runs returned the KPIs results for each run when experimenting with multiple factors. In a short time and without risks many scenarios was tested, to assure anticipated behaviour of the system after improvement. Then it was possible to analytically and graphically determine the desired target level of sensitive factors, to which it should be improved. Continuous improvement efforts then strived to reach this target.

3.10.1.4. Improve

Output from the DES model was visualised and communicated through graphical representations that highlighted the change initiatives. Continuous improvements might not sufficiently exploit the constraint. Therefore effectiveness of different investments was analysed in order to elevate the constraint. DES provided needed support for quantitative evaluation of different options.

Visualisation of the future state

Simulation was used for visualisation and communication of future state. This future state is realistic estimation of improvement result. It is therefore used for explanation of the system perspective. It convinces process owners to appreciate improved system performance more than improvement of their individual interests.

Perform structured experimentation

Trial and error method was used to estimate investment possibilities with highest return. Many experiments were performed before investing and changing existing production. This was how simulation was used to reduce uncertainties and risk in the investment stage of FSI cycle.

3.10.1.5. Sustain

At this step, two choices were made. First, the constraint was not removed, and the process returned to the previous step, 4.3.4 improve. Then, analysis showed that the chosen key performance indicators were directing towards a new constraint. Therefore a new focus was determined by returning to the first step, 4.3.1, called strategy.

4. Results

In this chapter, results show how DES supports focused improvement work.
In the section 2.5 requirements for TOC and Continuous improvement were identified. Through this chapter, the following attributes of DES will be presented. They reflect the requirements of TOC and continuous improvement. They are:

- Ability to read and use stochastic input data
- Provide identifiable output data in terms of improvement potential
- Enabling structured experimentation of improvement potential
- Visualisation of future states

The theory has suggested the use of DES to meet these requirements. The DES model was built according to methodology and work description explained in chapter 3. Results of model conceptualization, data collection, verification and user interface has led to the resulted DES model. This model was used in the case study to test its value for closing the gap (*Figure* 11). Results of this closing are presented in two FSI cycles.

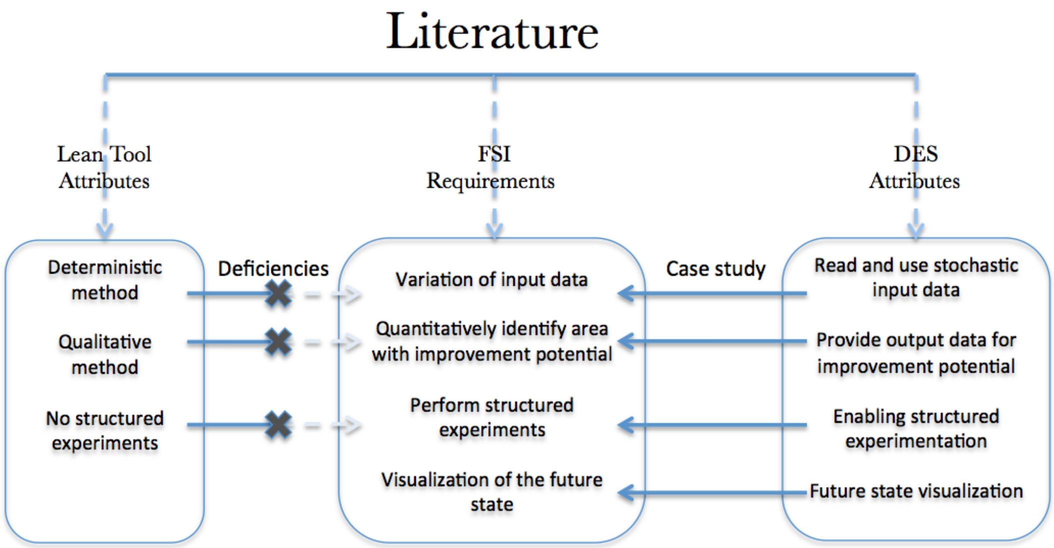

Figure 11 - Closing of the gap

4.1. Literature review

The results from literature review suggest that DES can fulfil the gap between requirements of FSI and current commonly used tools. Simulation is uniquely able to help achieving a corporate goal of finding a correct, solution that meets system design and operation requirements before implementation (Marvel & Standridge, 2006).

4.1.1. Variation of input data

DES can overcome this with use of stochastic data. Sensitivity analysis done with DES can provide information about impact of different parameters properties on the performance of the system. Bigger impact means greater attention to input data accuracy. Data input can accurately characterize empirical data sets and adapt usage of simulation software in modelling process accordingly (Law, 1991).

4.1.2. Quantitatively identify improvement areas with high potential

Simulation can be used to analyse the production system. Identification of constraints provides suggestions and feedback for process improvements. Sensitivity analysis can be performed. This analysis reveals the direction of improvements to the continuous improvement expert (Systemsnavigator, 2015).

4.1.3. Perform structured experiments

Simulation enables experiments with future system. Examination of a solution's result can be done with a carefully designed simulation experiment (Marvel & Standridge, 2006). The performance can be analysed before investing capital and without disrupting current operations (Systemsnavigator, 2015).

4.1.4. Visualisation of the future state

Simulation helps by presenting in a visual, interactive way support for evidence-based decisions (Simul8, 2015). Simulation also improves communication and visualization of the project outcome and therefore employees' involvement and motivation (Simul8, 2015). Simulation provides accurate projection about how the system behaves before and after implementing improvement change. It helps to accurately set short-term goal that effectively leads towards final goal because it enables prediction of performance improvement over time. It also helps to set objective time plans for responses that customers will see (Simul8, 2015).

4.2. DES model

The model and its code was built so that the user can simulate variations through a user interface, and if the user wants to entirely remove a process or change a buffer capacity it is possible through the interface. At the start of every simulation, the model uses input data specified by the user in the interface and apply it to the simulation. After each verification process with the end-user, the programming code was revisited for further programming. Code also enables manipulation of data, which is needed to be exported for experimenting.

The simulation model will not be explained in detail because of sensitive information. However, a picture of the simulation model is presented on Figure 12 below. In the picture, it is shown that the level of detail is chosen at the machine level. All 13 machines (coloured rectangles, Figure 12) in the factory A were simulated.

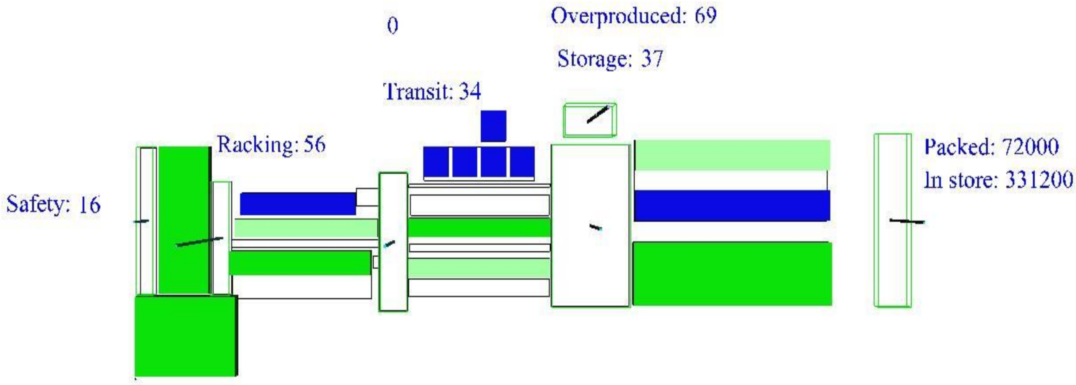

Figure 12 - Simulation model

4.3. First FSI cycle

After DES model was built it was used to support FSI cycles. The first FSI cycle has multiple improvement cycles, explained in chapter 3.10.

4.3.1. Strategy

The initial strategy is to utilise the FSI approach to reach a better response for a strategic KPI. This KPI is in line with what The Company in this case study aims to achieve by utilising the developed simulation model, which is a higher output of products in their system.

4.3.1.1. Variation of input data

DES supports the first step of the FSI cycle. Stochastic input data mimics the real system variations in order to present accurate KPI. This input data is visualised in the UI, see Figure 13, Figure 14 below.

DES was designed so that the user only needs knowledge about the UI to use the model. The UI, which is built in Microsoft Excel, utilizes macros to print raw data into text documents. From the UI, another macro can then be used to initiate a simulation from the model (Figure 13). The model then reads raw data from the text document. Based on this raw data, the simulation will run for a pre-determined amount of time, called run-time. After the run-time, the model will produce another text document with output from the simulation. This text document with output data can then with be read by the UI through another macro. This will provide the user with information about the system, ready to be analysed. Because of confidentiality concerns, the model will not be presented in this report.

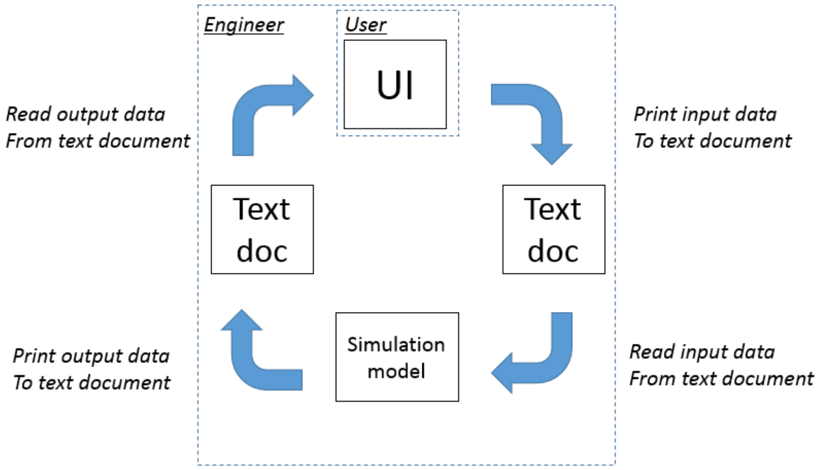

Figure 13: UI - Simulation model interaction

Data with high variety is entered in self-adjustable foolproof spreadsheets. Figure 10 shows UI for entry of stochastic breakdown data, both mean time to failure (MTTF) and mean time to repair (MTTR). Depending on which distribution is chosen from a "dropdown" list, required parameters are activated. If the chosen distribution is static, then only one cell will be activated. If the chosen distribution instead is normal, then two parameters will be activated. Other cells that are not required for this type of distribution are coloured grey and locked, see Figure 14 below. The DES code is optimised for this behaviour in the UI and will only read activated parameters.

Breakdowns									
MTTF (h)					MTTR (h)				
Distribution	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Distribution	Parameter 1	Parameter 2	Parameter 3	Parameter 4
	Mean μ	Standard deviation σ				Mean μ	Standard deviation σ		
Normal	0,69	0,09			Normal	0,12	0,03		
	Shape parameter α	Scale parameter β				Mean μ	Standard deviation σ		
Gama	1,17	0,31			Normal	0,15	0,05		
	Minimum	Mode	Maximum			Mean μ	Standard deviation σ		
Triangular	1,17	0,31	2,10		Normal	0,15	0,05		

Figure 14: UI for stochastic input data

4.3.2. Design

A high utilization for some machines can be observed in Figure 15 below. This indicates that point to point and single edge machines are constraining the system with their long manual cycle times.

4.3.2.1. Quantitatively identify improvement area with high potential

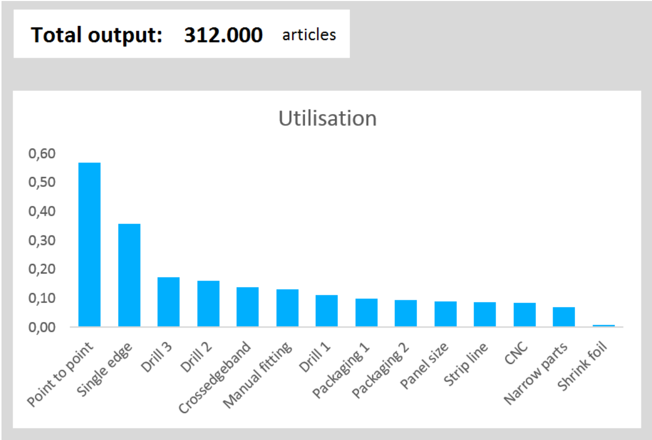

Figure 15: Utilisation

Utilisation of the machines was analysed. Figure 15 indicates that they are theoretically maxed out. Their inability to supply needed parts at the right time renders the downstream processes starved. Therefore the total output of the process could not meet the demand, which is higher than 312.000 articles.

4.3.3. Activate

When the constraint was identified, DES enabled experimentation of reduced cycle-times with many different scenarios presented below.

4.3.3.1. Perform structured experiments

A preselected range of factor values were selected based on approximation (Figure 16). Experiment for each value was executed. Desired responses were analysed for each experiment, to find the optimal value from pre-assumed range of data.

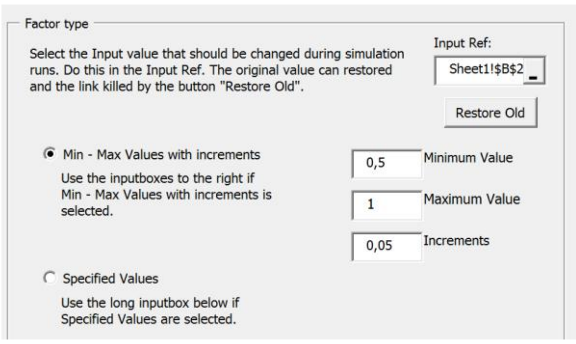

Figure 16: Vary factors UI

The constraint at the manual machines needed elevation. It was needed to find required productivity improvement on those machines. Then continuous improvement initiative will have clear goal how to improve method on operational level in order to make effect on overall system performance. The graph in Figure 17 is steeper from 0 to 25%, revealing a higher output increase in that area. Higher productivity increase than 25% results in a slower output increase. It is possible to assume that it is easier to achieve improvements on the beginning of the continuous improvement initiatives, under 30%, by collecting "low hanging fruits". Improvement initiatives for productivity increase above 30% might require more sophisticated and complicated methods. Therefore productivity increase of 30% was selected as a target for continuous improvement initiative (Figure 18), since it results in the best yield on overall output.

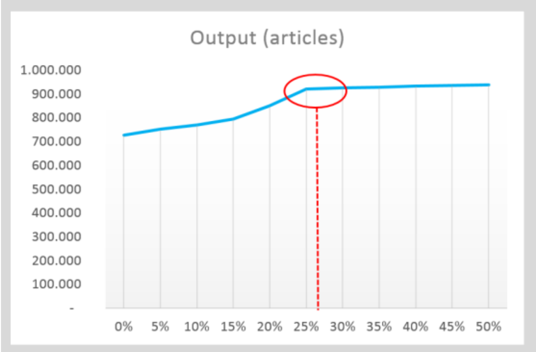

Figure 17: Output - productivity improvement

Run number	Productivity improvement	Output (batches)	Output (articles)
1	0%	303	727.200
2	5%	313	751.200
3	10%	321	770.400
4	15%	331	794.400
5	20%	354	849.600
6	25%	384	921.600
7	30%	386	926.400
8	35%	387	928.800
9	40%	389	933.600
10	45%	390	936.000
11	50%	391	938.400

Figure 18: Productivity improvement experiment

This has resulted in a better flow of products through production system. Downstream machines were supplied sufficiently in order to produce according to demand. But productivity improvement has still not shifted the constraint from manual machines, see Figure 19. Utilisation of those machines was still the highest, which indicates that they were still constraining the system. Further steps were therefore required.

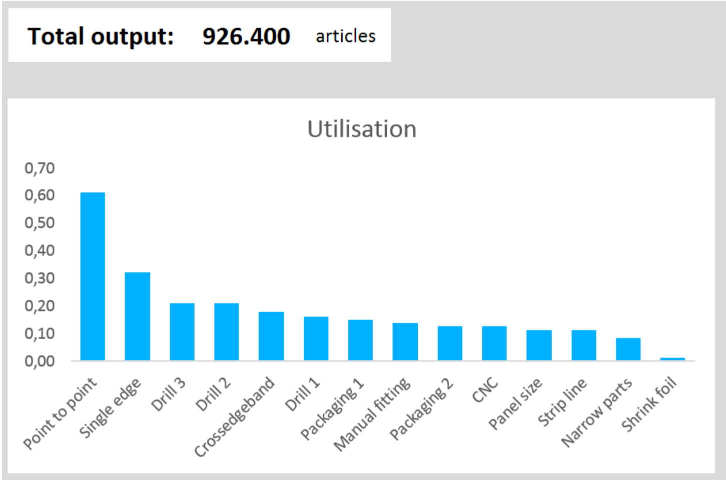

Figure 19: Utilization after manual machines productivity improvement

4.3.4. Improve

This step of FSI can benefit from two attributes of DES. First, different scenarios of subordination can be tested. Then results of those experiments can be used for visualization and communication to get acceptance.

Lunch breaks are affecting the available utilisation of the constraint. Since an hour saved on constraint is an hour saved in entire system, it might be possible to allocate lunch breaks from other machines in a manner that constraint would always be up and running. From workers perspective this might be a delicate solution. Therefore it is very important to pre-test it to avoid later cynicism and demotivation for improvements.

4.3.4.1. Perform structured experiments

It was simulated how change of timing of lunch breaks would affect output. Now the constraint has never stopped during lunch, operators from other stations operated it during the lunch break. Result of this change in policy has resulted in slightly better utilisation of constraint. Accordingly this has increased better utilisation of overall system. Utilisation of Point to point machine has increased from 61% to 64%, see Figure 20.

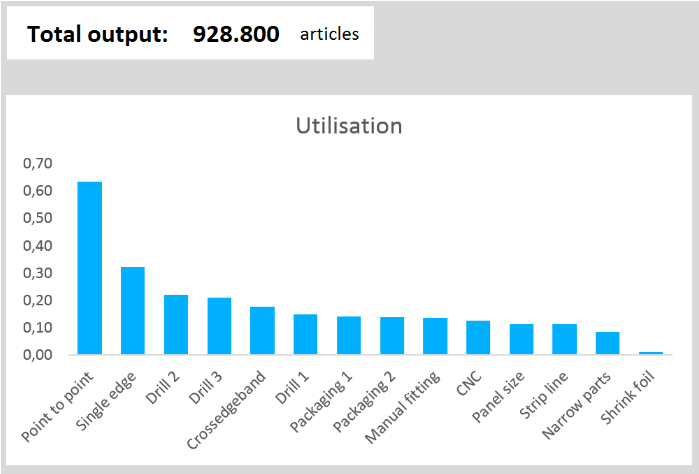

Figure 20: Utilisation after lunch break rescheduling

4.3.4.2. Visualisation of the future state

Graphic interface and KPIs presentation can be used to get acceptance for this delicate improvement. More importantly, it makes management optimistic and involved during implementation of a new policy, since it will have a clear target. Graphic interface (Figure 12) can be used as a visual tool during training of new policy to improve understanding of how policy will be executed.

4.3.5. Sustain

At the end of the first FSI cycle, results indicate that the constraint has not shifted. According to the method presented in chapter 4.3.5, more cycles of improvement are necessary.

4.3.6. Improve, second improvement cycle

At this stage of FSI, DES enables experiments with different investment possibilities in order to elevate the constraint.

4.3.6.1. Perform structured experiments

Cost-free improvements were not sufficient to shift the constraint. An investment possibility was therefore analysed. A scenario with an additional parallel point to point machine was assessed.

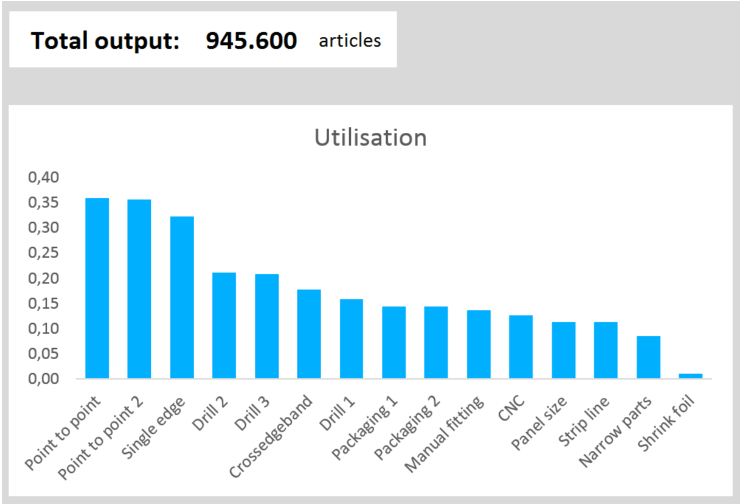

Figure 21: Utilisation after new Point to point machine

As seen from the performance indicator chart, see Figure 21, the utilisation of the point to point machine has halved. However this was still not sufficient for a constraint-shift. Therefore further investments were analysed.

4.3.7. Improve, third improvement cycle

Lean philosophy is recommending the use of levelled workload throughout the process in order to prevent machine and operators burden. To reach this level production schedule was reviewed. High workload on manual machines was identified. Since manual machines have high operational costs in production and since they do not add much value to the product, different alternatives were analysed. Revision of product design, possibility of outsourcing and lower service level can be analysed. In this case-study, outsourcing of demand was chosen. Outsourcing must follow predefined limitations about quantities and deliveries. Therefore experiment was focused towards analysis of effect of outsource rather than outsourcing specification revision, which might be a simulation project on its own. It was found that after outsourcing of some articles that generate high workload on manual machines, the constraint has moved away from those machines, see Figure 22.

Figure 22: KPIs after outsourcing

4.3.8. Sustain

Since the demand for the system was reduced, output is not a valid KPI anymore. A new KPI was introduced, throughput time. After outsourcing, the average throughput time has decreased by 27, 2%. Constraint has shifted on to Drill machines, see Figure 22.

4.4. Second FSI cycle

According to the method presented in 4.3.5, a full FSI cycle should be initiated after a constraint has shifted.

4.4.1. Strategy

The need for additional KPIs has emerged during improvement in chapter 5.1.7. This need originates from the fact that production capacity has improved to the point where the demand can be reached. Therefore the output of the system has stagnated at the maximum demand that cannot be increased. A KPI that describe other parameters than output were needed. Those were then analysed to set the strategy for a second improvement cycle.

4.4.2. Design

Analysis has revealed a low utilisation of machines. Therefore the design of the second cycle has focused on identification of reasons for low utilisation.

4.4.2.1. Quantitatively identify improvement areas with high potential

As seen from Figure 23 below, the utilisation of drill machines is now the highest. This indicates the shift of constraint to drill machines. This was further evaluated with graphic analysis of simulation. Behaviour of upstream and downstream buffers has proven the shift of the constraint.

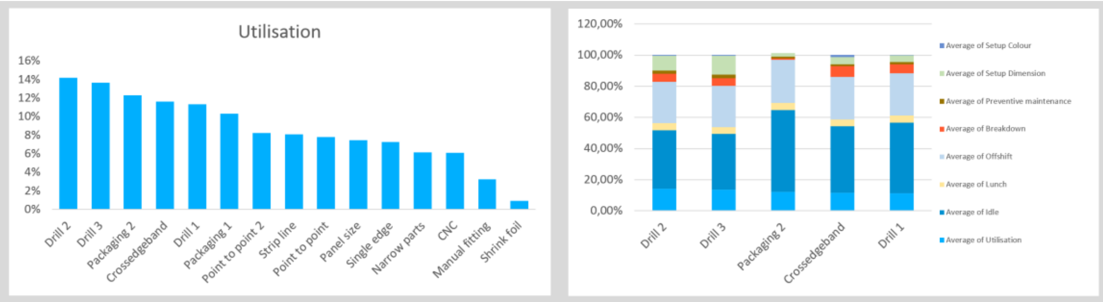

Figure 23: Utilisation, left, and division of machine-states to the right

The Figure 23 on the right shows how machines with the highest utilisations were analysed. Percentages of different machine-states that have affected utilisation were examined. It was identified that drill machines have high percentages of setup time. A setup is needed if a new product type is to be machined. Drill 3 had setup time of 12% and Drill 2 was occupied 9% of total available time for setups (green). This was very high, since the current utilisation was at around 14% (light blue). Two practical ways of reducing the amount of time that machines are in a setup-state were identified. The first one was to continuously improve setup methodology by reducing time spent on setup between product types. The second way aimed to reduce the number of total setups that all machines experience by introducing a batch-oriented production plan.

The first option requires investments, while the second option involves a re-structuring of production planning. Since the investment level of the second option is lower, it was analysed first. Focus was directed at the trade-off between setup times and buffer utilization.

4.4.3. Activate

After the improvement was designed, activation was performed by changing the batch size policy. Existing batch size policy promote fragmentation of batches in order to keep the machines running, which means that parts of the same batch did not get machined together, resulting in more setups. Possibility of changing this policy was analysed with experiments. Effect of different routing of parts on system performance was analysed.

4.4.3.1. *Perform structured experiment*

The improvement meant that if a part belonged to a batch, it would travel and be machined together with other parts of the same batch. Experiment has shown that this improvement would result in significant reduction of setup time, see Figure 24.

Set up before	Set up after	Difference
9,47%	3,22%	-66%
12,14%	3,32%	-73%

Figure 24: Setup time comparison

This has resulted in higher idle time of drilling machines, because of longer times for waiting for entire batch sizes from upstream machines (dark blue, Figure 25).

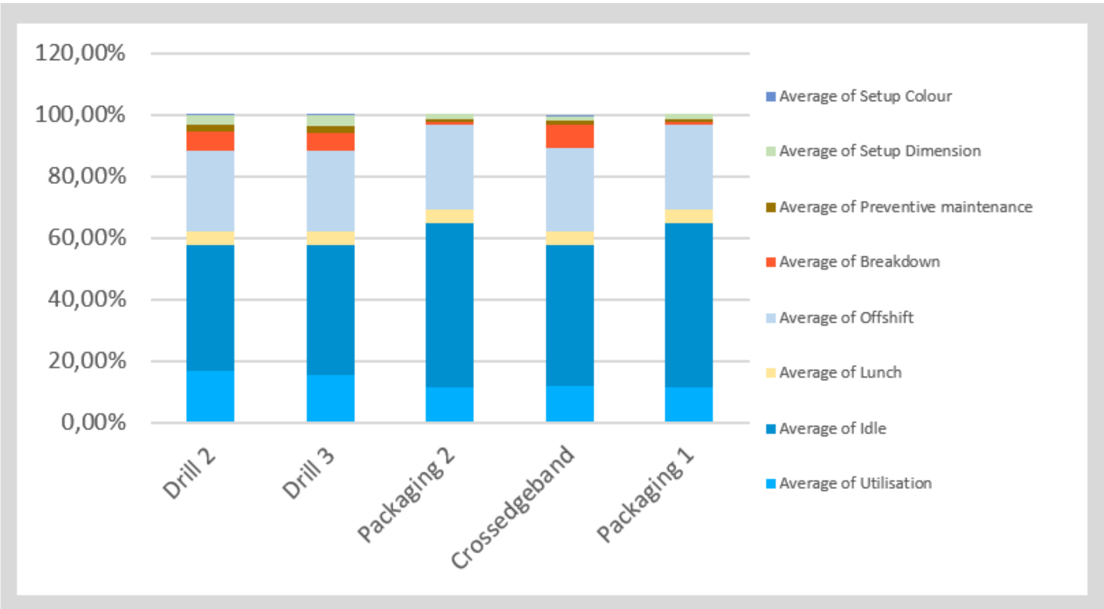

Figure 25: Closer look of division of machine-states. The machines with the highest utilisation are highlighted here

There was no indication that a batch-production policy resulted in starved or blocked machines. No decisive trade-off between setup times and buffer utilization was detected.

4.4.4. Improve

As stated before, the improved system can produce more than the demand. Long idle times indicate this. Since demand cannot be increased, the opportunity for reducing production schedule from three to two shifts was analysed.

4.4.4.1. *Visualisation of the future state*

The production demand was met even though fewer shifts were scheduled for production. Reduction of number of shifts would still result in sufficient running time to produce according to demand. Figure 26 below shows increased off-shift time (grey area). Idle time is reduced accordingly.

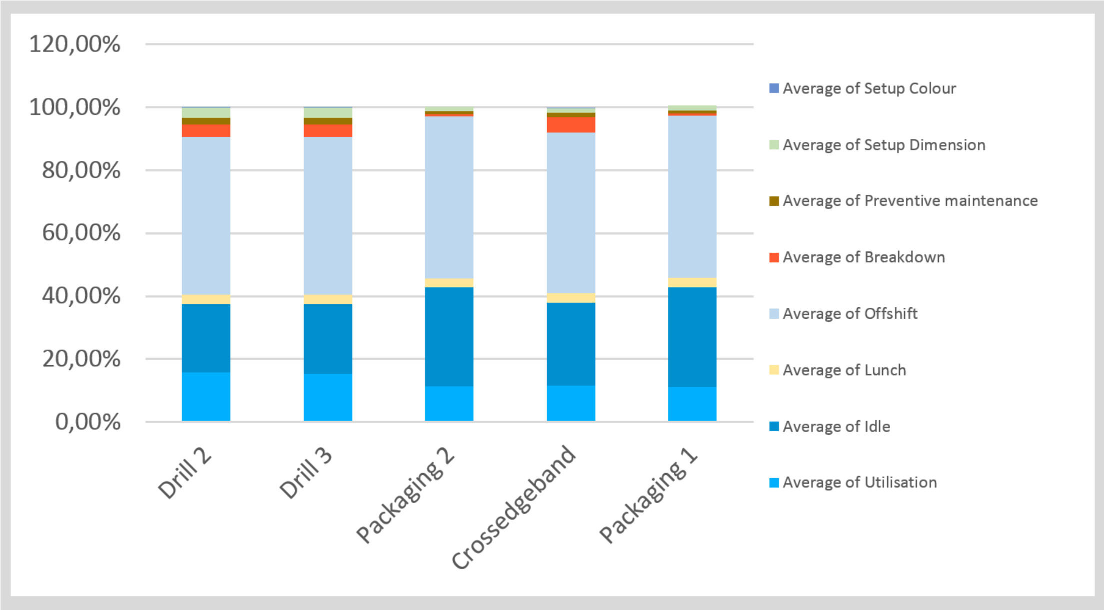

Figure 26: Machine-states after 2-shift production

4.4.5. Sustain

The second FSI cycle resulted in increased performance since the same output was reached with lower scheduled production time. In terms of utilization, which was the focus of this FSI cycle, the differences between utilization and idle states have reduced.

5. Discussion

The observed factory in the case study claimed to follow Lean, a philosophy which is strongly engaged with continuous improvements. It was therefore unexpected to see the extent of the improvement potential. Therefore we consider the results as a valuable contribution.

Our reasoning from the literature has concluded that there is a possibility to achieve this potential by combining DES and FSI as oppose to the factory's current methods. This was further confirmed with the results from the case study.

5.1. Method

To reach the conclusions that might provide new knowledge to production engineering field of science, some reasoning based on the literature review was done. In order to validate the reasoning, a specific case study was performed. Time limitations of the project did not enable more case studies to cross check the results. Since the literature did not suggest any case specific characteristics of evaluated methods we were confident that DES could support integration of TOC and continuous improvements throughout entire manufacturing industry.

The results of FSI cycles, presented in this report are practical for the case study. But the literature suggests that FSI can be applicable anywhere where constraint exists. No steps in the FSI cycles are dependent on practical case, which means that the method is applicable in other situations as well. If the targeted production system has a well-defined strategy, the first step in FSI, then the method presented in this report should be applicable.

By using FSI method, this master thesis has shown possibility to combine best of TOC and continuous improvements. Results show how improvements can continuously be focused towards effective improvements of system's productivity. Literature review highlights the gap between requirements of FSI method and current tools in Lean. Literature has suggested DES as a tool that can meet these requirements. Therefore this report does not convey other methods than DES to fill the gap.

As presented in chapter 4, Figure 11, requirements were identified from the literature review. The requirements were not questioned during case study. It might be beneficial to refine the requirements also through the case study. This could be done by interviewing stakeholders, relevant people, in the case study.

Because of confidentiality, a real production schedule was not used during the experiments. However, the results were used to, as stated in the project purpose, assess to which extent DES can support FSI to increase the system's productivity. Even though a real production schedule is not used, the simulation model is still built on a true industry-based case study. A statement about to which extent DES can support the integration mentioned above can still be made by observing the outcome of changes made in each FSI cycle.

5.2. Variations of input data

To meet the requirement for variation of input data literature review has presented an attribute of DES that can accurately use stochastic data. One of the aspects of the case study was that a user, with no prior knowledge of DES, should be able to vary input data through the UI.

In the result section above, many variations are experimented with to highlight this function in DES. In the light of these experiments, DES manages to account for the gap. See chapter 4.3.1.1 for an example of this solution. The extent of this function still relies on the nature of the input data, where good data will provide the model with a more realistic behaviour. A realistic behaviour will support FSI, so that focus for improvement is placed where it should. The variation of input data is crucial for all experiments in the different steps of FSI, providing a stronger focus for where improvements should be made.

5.3. Quantitatively identify areas with improvement potential

One of the requirements is that focus for improvement should be placed where it is needed the most. The literature promotes use of DES to meet this requirement.

The results from the case study contain numerous graphs and tables that are derived from the DES model. These visualisations point out directions for where improvements will be experimented with in further steps. Therefore, the function of DES to provide output data that can be represented in graphs and tables is important for FSI to succeed in providing that focus. This finding agrees with the theory presented in chapter 2.5.2, about DES revealing the direction of improvements.

5.4. Perform structured experiments

The literature encourages use of DES for experiments during FSI method. The avoidance of real system disturbance and wrong investment decision are explained as the main benefits.

In addition, the case study has shown an important feature of combined DES and a user friendly UI. This is the possibility to perform high number of practical experiments in a short time. Result section shows how experiments are done to support the decisions made in FSI. This supports the theory presented in chapter 2.5.3, that simulation enables assessment of future systems before investments are made (Systemsnavigator, 2015). All experiments performed in the previous chapter are done without disrupting operations on site, which is an important element in DES modelling.

5.5. Visualisation of the future state

This feature has not been presented in the literature as a gap. Anyway the literature is recommending use of DES to support visualisation during FSI. It is stated that simulation improves communication and visualisation of the FSI throughout the entire cycle.

Figure 12 shows a visualisation made in Automod software. What this visualisation provides is a way to communicate the scope and importance of results to stakeholders and others. The DES together with FSI manages to convey how the system change from the original state until two FSI cycles has been implemented. This result is in line with the theory of DES, to realistically predict the outcome of improvements (McKinsey, 2014: 138).

5.6. The FSI cycles

The result section presents results from two full cycles of FSI, and two additional improvement cycles. The results clearly show possibility of FSI supported by DES to increase the productivity of the system.

The first FSI cycle focused on maximizing the output. Improvements made in that cycle has resulted in meeting the demand, see results above. The second cycle changed focus towards an increase in productivity without compromising the first focus of maximizing output. Finally, the FSI cycles leads to a reduction of production shifts.

By following the method presented in chapter 3.10, the results have demonstrated the possibility of productivity increase through integration between Theory of constraint and Continuous improvements.

6. Conclusions and recommendations for future work

The research has shown that DES can support integration between Theory of constraint and Continuous improvements by following a method for Focused system improvements. The experiments are based on stochastic input data that a user can implement through an interface. As supported in the theory of DES, these experiments are then presented visually. A focus for continuous improvements can then be chosen with TOC, and applied through a DES model. The DES model will assess the changes and visually present a future state without ever interrupting production at the real production system. This is the utility of DES supported FSI. New focal points can be assessed right away, without having to wait for the real system to present new constraints.

This project has provided experiments of DES supported FSI in an industry-based case study. Deficiencies of traditional tools have been highlighted and solved, and therefore helped prove that the theory behind DES and its attributes are sound.

The field of DES is growing together with the rest of the IT-market. New tools for simulation may provide paradigm shifts that change how DES is performed in production systems. This study adds to that field in terms of visual presentation and future state estimations. The DES model is the tool to turn stochastic input data into reliable output data. Even if the tool changes, the FSI approach can still be applied.

The following recommendations are for future work:

- Develop and implement an FSI tool into a user interface

If there exists a method behind an approach like FSI, then a user could utilise this in the user interface. The outcome could be that operators at the site where the simulation has been made can test their own improvement ideas and evaluate future states with the benefits of FSI.

- Develop and implement design of experiments into a user interface

DES supported FSI enables many experiments to be done. Design of experiments provides the user with a strong method to ensure that the experiments investigate important factors.

- Provide the target production plant with input-data gathering tools that support DES and FSI

Engineers and operators on site might not know what DES is. Strong input data results in a more reliable result. Investigating possibilities to a qualitative approach for gathering of input data is therefore of interest. The simulation engineer could therefore benefit from providing the production plant with input-data gathering tools. These tools could measure the range of products that are produced in a time interval, reasons behind breakdowns etc. Some of these tools already exist, usage of them is advised.

- Introduce a financial aspect to FSI

Results in this report do not account for the financial impact they carry. This was part of the delimitations. Introduction of this aspect can result in different focus from the FSI.

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Appendix A

Step 1 – Identify and Define Relevant Parameters
The important parameters to include in the model are identified. The effort to identify parameters increases with higher system complexity and level of detail (Skoogh and Johansson, 2008). This process can be done together with development of conceptual model.
There are numerous methods to perform step 1. Core manufacturing simulation data, integrated computer aided manufacturing definition, are among them (Lee et al. 2007, Perera and Liyanage, 2000).
When identification is done, all parameters are described in terms of measurement and model representation. This will help avoid confusion when the actual modelling takes place.

Step 2 – Specify Accuracy Requirements
For each parameter, an accuracy requirement can be defined. If a parameter has a large impact on the model performance, accuracy requirements should be higher. An example of parameters with high impact is possible constraints (Skoogh and Johansson, 2008).
System knowledge is the only source to understand which parameters needs the highest accuracy before the model is built. There are analyses to compliment step 2, performed when the model is built to validate parameter importance.
Expected variability of parameters can influence accuracy requirements. An example of attributes that are not expected to vary are conveyor speed and cycle times for automated processes (Skoogh and Johansson, 2008). A high variability is usually handled with more samples for a good representation in the model.

Step 3 – Identify Available data
In accordance to figure 3, available data is categorised as Category A. For the data that a company has gathered, it is important to review it and see if it is possible to use for the simulation project. The result from step 3 is category A data together with sources for the parameters. Example of sources are from Resource planning systems, Lean efforts etc. (Skoogh and Johansson, 2008).

Step 4 – Choose Methods for Gathering of Not Available Data
Category B and C data needs to be either estimated or gathered. A common way is to study the production and manually measure the data. The methods used for the manual gathering reflects the detail requirements. For high detail, methods such as Methods-Time Measurement, Sequence-based activity and Method analysis (Skoogh and Johansson, 2008).

Category C, see figure 3 above, is mainly present in factories that are not yet built (Skoogh and Johansson, 2008). For data in category C to be gathered, Skoogh and Johansson write about three different approaches:

- Discussion with experts, i.e machine vendors, or in-house production engineers
- Review of historical data from similar systems within the same organization
- Standardized data stored in process libraries

Step 5 – Will All Specified Data Be Found?
This step aims to make sure that the parameters specified are also possible to collect in some way. If some parameters turn out to be impossible to collect, then this should affect accuracy and relevance reevaluation (Skoogh and Johansson, 2008).

Step 6 – Create data sheet
All data regarding the project should reside in the same place. This could be in a spread sheet or a database. This aim for coherent structure will make future steps easier to perform and also prevent data from being lost or misplaced (Skoogh and Johansson, 2008).

Step 7 – Compile Available Data
All category A data is collected for analysis. Some category A data is previously analysed and ready to use in a simulation model, after validation in step 11. Raw data is extracted from the data sheet according to accuracy requirements and compiled together with, usually, additional calculations (Skoogh and Johansson, 2008). Filtering is used when extracting data from databases or sheets, to remove data that is not representative of a normal process. Finally, an analysis will be carried out on the sets of extracted data for step 9 in this methodology.

Step 8 – Gather Not Available Data
In this step, measurements of unavailable data and estimations are carried out. Category B and C data can be changed to category A in this step. For category B, this process might be time consuming. Category C may not take as long time. Gathering of this data can be based on assumptions of an expert on the process. If the data is gathered through historical data from a process that is similar, the gathering might be more time consuming. The result from step 8 is just sets of raw data, like step 7, ready for analysis.

Step 9 – Prepare statistical or Empirical Representation
Variability in gathered data needs to be presented. There are different methods for this: traces, empirical distributions, bootstrapping or statistical distributions (Robinson, 2004).
Statistical representation is a popular approach. To support this method, tools such as ExpertFit and Stat::Fit are used. There also exist manual modelling of statistical distribution.
The result from this step is data representations that can be used for the simulation model (Skoogh and Johansson, 2008).

Step 10 – Sufficient Representation
The representation from the previous step is evaluated in this step. Statistical distributions can be justified with different tests, though it is difficult for representations to pass these (Skoogh and Johansson, 2008). It is essentially up to the engineer to decide if the representation is strong according to the accuracy specified for each parameter. Later in the project a sensitivity analysis can be performed on representations with weak comparison to real world data. Based

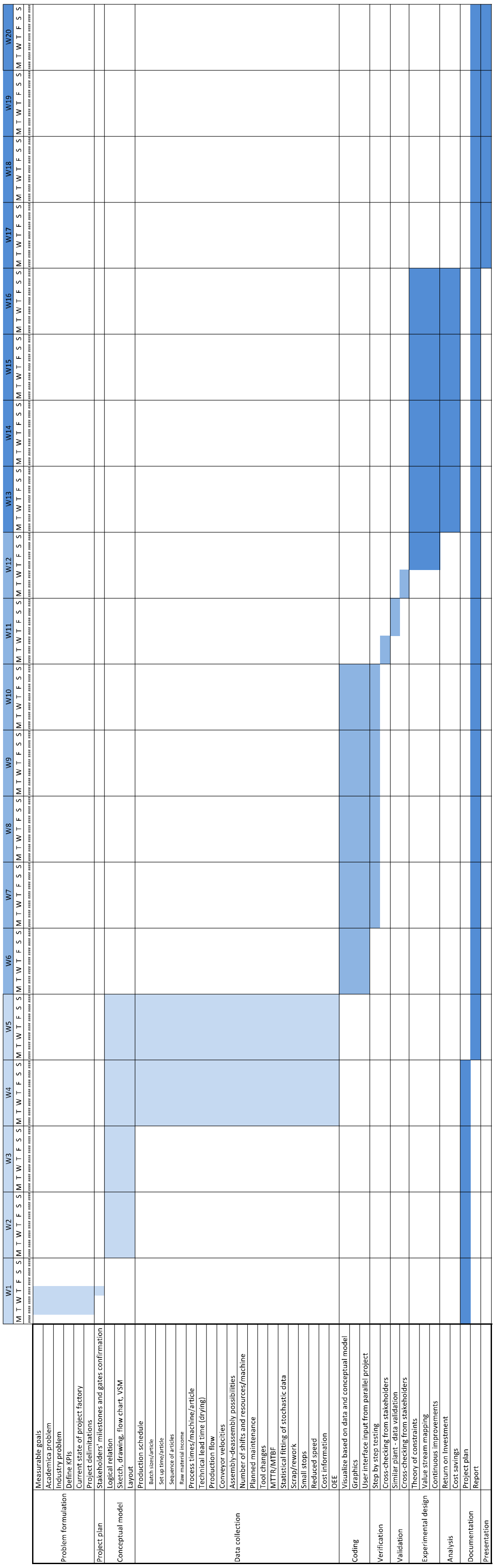
on this analysis, additional investigation can be performed on different factors (Skoogh and Johansson, 2008).

<u>Step 11 – Validate Data Representations</u>
A face validity is achieved through cooperation with process experts during input data phase. There are other methods for validation, for example: data evaluation comparison and sensitivity analysis. Additional validation is performed later during model validation process (Skoogh and Johansson, 2008).

<u>Step 12 – Validated?</u>
If all parameters are validated in the last step then they are ready to be used in the model. If validation fails for parameters, then stepping back and identifying the issues is necessary (Skoogh and Johansson, 2008).

<u>Step 13 – Finish Final Documentation</u>
Documenting is a continuous process during the whole project. When it comes to parameters, the following are important to document: sources of data, gathering methods, validation results and assumptions made regarding the parameters. Finally, a data report together with a data sheet is completed to be implemented in project report.

Appendix B



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Problem formulation
Measurable goals
Academica problem
Industry problem
Define KPIs
Current state of project factory
Project delimitations
Project plan
Stakeholders' milestones and gates confirmation
Conceptual model
Logical relation
Sketch, drawing, flow chart, VSM
Data collection
Layout
Production schedule
Batch sizes/article
Set up time/article
Sequence of articles
Raw material income
Process times/machine/article
Technical lead time (drying)
Production flow
Conveyor velocities
Assembly-deassembly possibilities
Number of shifts and resources/machine
Planned maintenance
Tool changes
MTTR/MTBF
Statistical fitting of stochastic data
Scrap/rework
Small stops
Reduced speed
Cost information
OEE
Coding
Visualize based on data and conceptual model
Graphics
User interface input from parallel project
Verification
Step by step testing
Cross-checking from stakeholders
Validation
Similar plant - data validation
Cross-checking from stakeholders
Experimental design
Theory of constraints
Value stream mapping
Continuous improvements
Analysis
Return on Investment
Cost savings
Documentation
Project plan
Report
Presentation