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# Optimizing a production line of packaging material by the use of discrete-event simulation

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# Preface

This Master's Thesis is a part of the examination of a Master's degree in Mechanical Engineering, finished at the Department of Design Sciences at Lund University, Faculty of Engineering.

First of all we would like to thank Peter Öhman, our supervisor, for all the help and tutoring we have received during the long hours working with our thesis and his interest in our work, without it this thesis would never have seen its end.

We would also like to thank all employees at PM Production for all the information they have been sharing with us and all the help and support we have received when problems have arisen.

Finally, we would like to thank course supervisor Mats Johnsson, Associate Professor at the Division of Packaging Logistics at Lund University, for all the help we have received during the thesis.

17th of January 2010, Lund
Sebastian Ferrada
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# Abstract

Title: Optimizing a production line of packaging material by the use of discrete-event simulation

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Problem Definition: A packaging company is currently evaluating their production and searching for development opportunities to make the production more effective. At the facility for packaging materials there is a production line with two machine-groups consisting of two printers and one laminator. In the present situation the two machine-groups are disconnected from each other by the use of an inventory.

Purpose: The purpose with the thesis is to make the production of packaging material more effective by mapping the production process and finding ways to reduce the buffer between the two machine-groups, in order to reduce lead time and achieve a streamline flow through the production line. A discrete-event simulation model will be developed by using the software Simul8 that enables the company to test different setups and scenarios.

Restrictions: The study is limited to examine one production line that consists of two machines, a printer and a laminator.

Methodology: First a discrete-event simulation model of the production line as it is today will be developed. After a satisfactory model of the real production line has been developed a new model will be developed consisting of one printer and one laminator. This model will be the first scenario and the base model throughout the study and other scenarios will be tested and evaluated based on this model.

Conclusion: During the period that the study covers the total production was approximately 12 500 km of paper material. The output of the simulation model representing the real world process is 12 100 km. In scenario 1, one of the printers is removed and one printer and one laminator are left running continuously which yields an output of 9 800 km. In scenario 2, the average run speed in the printer is increased, by benchmarking a facility of the same complexity as the one covered in this study, which yields an output of 10 500 km. In scenario 3, the variation and mean time of two setups in the printer, the sleeve change and the creasing tool change, is reduced which yields an output of totally 10 000 km. In scenario 4, the stops Lack of Resources time, Waiting for Approval time, Cleaning time and Force Majeure time in the machines are removed which yields an output of 10 100 km. In scenario 5, scenarios one through five are all included simultaneously which yields an output of 11 200 km.

From the simulations it can be concluded that by improving different parameters the total output of the production line can be increased. However, the improvements made in this study are not sufficient to compensate for the output loss resulting from removing one of the printers. The study’s purpose is to provide an understanding of the production line and find important parameters that result in a more effective process, that can be seen as a base and help to the company if they want to continue working with these suggestions.

Key words: Discrete-event simulation, Simul8, input analysis, statistical process control.

# Sammanfattning

Ett förpackningsföretag ser för närvarande över hur de kan effektivisera produktionen i olika avdelningar inom verksamheten. I företagets fabrik av pappersmaterial för förpackningar finns en produktionslinje med två maskingrupper, tryck och laminering, som består av två tryckpressar och en laminator. I dagsläget frikopplas maskingrupperna från varandra genom ett mellanlager. Studien avgränsas till att undersöka en produktionslinje med två maskiner, en tryckpress och en laminator. Syftet med examensarbetet är att effektivisera produktionen av pappersmaterial för förpackningar genom att kartlägga hur man kan minska mellanlagret mellan maskingrupperna för att korta ledtiden och få ett rakare flöde. Ett simuleringsverktyg ska utvecklas i mjukvaruprogrammet Simul8 som ger företaget möjligheten att testa olika scenarier i produktionen.

All input data som ingår i modellen är baserad på en månads produktion, augusti 2009, och är tagen från produktionsdata som rapporteras automatiskt till en databas inom företaget. Den första simuleringsmodellen som utvecklas är en modell av produktionen som den är idag. När en tillfredställande modell av produktionslinjen som den är idag har utvecklats är nästa steg att utveckla en ny modell som består av en tryckpress och en laminator. Denna modell kommer att utgöra det första scenariot och fungera som en basmodell för hela studien. Olika scenarier kommer att testas och utvärderas baserat på denna modell.

Under den period som studien avser, augusti 2009, var den totala tillverkningen i den verkliga produktionslinjen ca 12 500 km pappersmaterial. Tillverkningen i simuleringsmodellen som avbildar den verkliga processen är 12 100 km. I scenario 1, avvecklas en av tryckpressarna och den kvarvarande tryckpressen och laminatorn körs kontinuerligt vilket resulterar i en tillverkning på 9 800 km. I scenario 2, höjs den genomsnittliga hastigheten i tryckpressen, genom att jämföra fabriken i studien med en annan fabrik med samma komplexitet, vilket resulterar i en tillverkning på 10 500 km. I scenario 3, reduceras variationen och medelvärdet i två setup i tryckpressen, klichébyte och verktygsbyte, vilket resulterar i en tillverkning på 10 000 km. I scenario 4, avvecklas stoppen Resursbrist, Väntan på godkännande, Städning och Force Majeure i maskinerna vilket resulterar i en tillverkning på 10 100 km. I scenario 5, inkluderas alla scenarier samtidigt vilket resulterar i en tillverkning på 11 200 km.

Slutsatserna som kan dras från simuleringarna, är att tillverkningen i produktionslinjen kan höjas genom att förbättra olika parametrar som påverkar produktionslinjen. De förbättringar som har genomförts i denna studie är inte

tillräckliga för att kompensera för förlusten av tillverkat material som uppstår vid avvecklingen av en av tryckpressarna. Studiens syfte är att kartlägga produktionslinjen och hitta viktiga parametrar som resulterar i en effektivare process, som ska utgöra ett underlag till företaget om de skulle vilja utveckla förslagen.

# Table of Contents

1. Introduction ....- 1 -
  1.1. Background ....- 1 -
  1.2. Discussion of the problem ....- 2 -
  1.3. Task and purpose ....- 3 -
  1.4. Delimitations ....- 3 -
2. Methodology....- 5 -
  2.1. Data collection ....- 5 -
  2.2. Validity ....- 6 -
  2.3. Reliability....- 7 -
  2.4. Objectivity ....- 7 -
3. Frame of reference ....- 9 -
  3.1. Production layout....- 9 -
  3.2. Materials flow and Lead time analysis....- 11 -
  3.3. Production line....- 11 -
    3.3.1. Availability....- 12 -
    3.3.2. Dependability and utilization rate ....- 13 -
    3.3.3. Importance of maintenance ....- 16 -
    3.3.4. The importance of quality....- 17 -
  3.4. Dimensioning of buffers....- 17 -
  3.5. Input Analysis....- 18 -
    3.5.1. Kolmogorov-Smirnov test ....- 20 -
    3.5.2. Autocorrelation....- 20 -
  3.6. Output Analysis....- 21 -
  3.7. Lean Manufacturing....- 22 -
  3.8. Six Sigma ....- 26 -
  3.9. Statistical Process Control....- 27 -
  3.10. Control Charts ....- 28 -
    3.10.1. Mean Charts....- 30 -

3.10.2. Range Chart - 30 -
3.11. Process capability - 31 -
3.12. Simulating manufacturing systems - 32 -
3.12.1. Introduction to Simulation - 32 -
3.12.2. Simulation models - 34 -
3.12.3. Discrete-Event System Simulation - 37 -
3.12.4. Steps in a Simulation study - 38 -
4. Empirical data - 43 -
4.1. The production - 43 -
4.2. Materials flow and Lead time analysis - 44 -
4.3. Production line - 45 -
4.3.1. Printer - 45 -
4.3.2. Laminator - 48 -
4.4. Variance - 51 -
5. Analysis - 53 -
5.1. The production - 53 -
5.2. Materials Flow and Lead time analysis - 53 -
5.3. Production line - 53 -
5.3.1. Printer - 53 -
5.3.2. Laminator - 54 -
5.4. Input Analysis - 54 -
5.5. Variance Analysis - 58 -
6. Simulating the production - 63 -
6.1. Simulation models - 63 -
6.2. Scenarios - 68 -
6.3. Results of simulation - 69 -
7. Discussion and conclusions of simulations - 71 -
7.1. Further possibilities - 72 -
References - 75 -

Appendix 1 ........................................................................................................- 77 -

Appendix 2 ........................................................................................................- 79 -

Appendix 3 ........................................................................................................- 81 -

Appendix 4 ........................................................................................................- 83 -

Appendix 5 ........................................................................................................- 88 -

Appendix 6 ........................................................................................................- 90 -

Appendix 7 ........................................................................................................- 92 -

# 1. Introduction

## 1.1. Background

A packaging company is currently evaluating their production and therefore searching for development opportunities to make the production more effective. At the moment certain production processes and flows are out-of-date which makes improvement and development necessary in order to meet global competition and achieve excellence.

In order to evolve a company must continuously find new ways of creating growth and reducing costs. A more effective production process can create a higher growth by reducing total costs, tied up capital and lead times. Hence, all companies are in the need of continuous development. A continuous production development by constantly improving is a condition for the company to maintain its competitiveness on the market.

Making the production more effective can be accomplished based on, among other theories and concepts, *Lean Manufacturing* and *Six Sigma*. Lean Manufacturing is a method that tries to eliminate waste in the production while the idea behind Six Sigma is to identify and reduce causes of variation in production processes. Many companies have combined Six Sigma and Lean Manufacturing practices where they have realized that the two concepts complement each other very well, i.e. Lean Manufacturing addressing process flow and waste whereas Six Sigma addresses variation and design[1].

In this Master's thesis a packaging company is examined. At the company facility for packaging materials there is a production line that consist of two machine-groups, printing and lamination. In the present situation the two machine-groups are disconnected from each other by the use of an inventory. The inventory is managed by AGV-vehicles that transport the semi-finished products to the inventory and collect material from this inventory when it's time for use in the other machine-group. By reducing the inventory and introducing a small buffer between the two machines the company hopes to achieve a streamline flow through the production

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[1] Magnusson et al, *Six Sigma The Pragmatic Approach* (2003), pp. 302.

line, which could ultimately lead to a reduction in lead time and higher profit-margins. This is however not certain due to the scheduled downtime – which is a reason to have an inventory – can depend on whether the packaging company often uses the production line for small batch production or not. This puts a great demand on the changeovers which in turn lowers the availability for the machines.

In order to reduce the inventory and dimension different levels of a buffer, the packaging company requires a computer-based simulation model. With the help of a simulation model there is an opportunity to virtually reproduce an event, in order to evaluate the effects and consequences of having different buffer capacities, without making actual physical changes which makes the simulation model a powerful tool for optimizing and developing manufacturing processes[2].

## 1.2. Discussion of the problem

A production line is very sensitive to interferences due to production stop in one of the components results in the whole line stopping. This is why buffers exist - to improve the availability for the whole line. A buffer results in more tied up capital within the company and a lowers the lead time, which according to the Du-Pont model leads to a lower profitability ratio[3], hence the necessity to construct a system with high availability, low costs and short lead times.

The packaging company wants to make their production more effective by reducing the buffer and analyzing the production process in order to identify and eliminate waste. By doing this the company hopes to avoid unnecessary expenditure of resources.

During the work with this study some important questions will be in focus of attention. How big is the need of a buffer? How big should the buffer be? Where are the critical factors in the production that results in stops and how can these be modified in order to avoid the need of a buffer? Which parameters can be modified that give the biggest effect concerning the process flow and lead time? Is it worth making these changes in relation to the improvement they give?

By developing a simulation model of the production process the company wishes to have a simulation model that is simple and user-friendly.

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[2] Ståhl, Jan-Eric, *Industriella Tillverkningssystem del II – Länken mellan ekonomi och teknik* (2009), pp. 325.

[3] Aronson et al., *Modern logistik – för ökad lönsamhet* (2004), pp. 197.

## 1.3. Task and purpose

The purpose with this Master's thesis is to make the production of packaging material more effective - by mapping the production process and finding ways to reduce the buffer between the two machine-groups - in order to reduce lead time and achieve a streamline flow through the production line.

The goal is to develop a simulation model for the production line that can be used to analyze different setups and test various scenarios for the production planning. The expectation is that this will result in the finding of critical factors in the production that the company can continue to work with. The aim is that the tool will be of great assistance in testing different scenarios in the production planning

## 1.4. Delimitations

The study is limited to examine one production line that consists of two machines, one for printing and one for lamination. The purpose is not that this study will result in final solutions on how the production should be carried out more efficient and what critical factors that should be eliminated and/or changed. The purpose is to map and give suggestions to feasible improvements and find important parameters in the production that result in a more effective process. This study should be seen as a base and help to the company if they want to continue working with these suggestions.

A simulation model will be developed in the software program Simul8. The tool will be able to simulate different setups where various levels of the buffer can be modeled and tested.

# 2. Methodology

There are two extreme types of methodology when realizing a study[4]; the inductive and the deductive. The inductive method starts from gathering empirical data and later comparing the empirical data to the frame of reference, while the deductive works the other way around. In this Master's thesis the authors choose the abductive methodology, which is a mixture of both the inductive and the deductive. First, a frame of reference will be written and afterwards it will be compared to the collected empirical data. In order not to get locked to certain theories the authors will return to the frame of reference to get a deeper knowledge within the relevant fields and compare these to the empirical data.

During the project the approach will be to first start with the collection of relevant theories, in order to build up a frame of reference, and the learning of the software Simul8. Afterwards data will be collected and an analysis will be made by both analyzing the empirical data against the frame of reference and by using the previously developed simulation model. This will end up in a couple of feasible suggestions for improvements.

The frame of reference will first of all be taken from the course literature that the authors have used during their education and if needed the authors will go deeper into relevant literature.

## 2.1. Data collection

Data that is collected can be of the type qualitative or quantitative data. Quantitative data is data that can be quantified while qualitative data cannot be quantified and is often of the type values, ideas or attitudes. Focus will be on processing quantitative secondary data in order to enable the development of a simulation model.

Further, data that is collected can be divided in two groups[5]: Primary- and secondary data. Primary data is collected with the purpose of being used in the study while secondary data is data that has not been collected primarily for the study.

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[4] Björklund et al., *Seminarieboken – att skriva, presentera och opponera* (2003), pp. 62.

[5] Lundahl et al., *Utredningsmetodik för samhällsvetare och ekonomer* (1999), pp. 52.

**Primary and secondary data**

In this study primary data will primarily be collected during the mapping of the production line, but also continuously during the project, which will be carried out at the packaging company's production site. Primary data will be collected from observations and interviews but if necessary measurements will be carried out.

Observations will be the base for improved understanding of the production line and for the secondary data that has been collected by the packaging company. The observations are going to be of the type open and with certain amount of interaction, which means that the authors will be working at the production line during the time of two weeks. Observations can be of the type standardized or unstructured where the unstructured type will be used.

The interviews will be of the type free interviews, which are interviews that are not standardized or structured. These types of interviews are common and important in qualitative studies[6].

In this project the secondary data will be primarily data about the processes in the production line that is already available and that covers the month this study covers, August 2009. This data constitutes a database with production feedback that is automatically reported by the company's business management software.

In order for the secondary data to be able to be processed it will be analyzed using a suitable method. First autocorrelation will be checked and afterwards a theoretical distribution function will be chosen. The level for autocorrelation will be set to 0.5, that is, if any pair of data points has a autocorrelation value of above 0.5 or below -0.5 the pairs will be considered autocorrelated. The theoretical distribution function will be tested by a Kolmogorov-Smirnov test with a confidence interval of 95 %. The input analysis will be double-checked by doing the same analysis using a software for input analysis, Stat::Fit.

## 2.2. Validity

With validity one looks at to what extend the study measures what is intended to be measured. The validity in this study is considered to be high due to the data consist of real production data, thus what the authors intend to measure is what has been measured. As for example where the authors aimed to measure and model the

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[6] Lundahl et al., *Utredningsmetodik för samhällsvetare och ekonomer* (1999), pp. 115-116.

setup times for August 2009 the data collected was the real setup times for the month and thus the authors were able to measure what they intended to measure.

## 2.3. Reliability

With reliability one looks to which extend an instrument measures the same way each time it is used. The reliability in this study is considered high due to the measures done in this study are measures done automatically by the business management software the company uses and thus the instrument will measure the same each time.

## 2.4. Objectivity

With objectivity one looks at to what extend the values and ideas of people has affected the result of the study. In this study objectivity is considered to be high due to a big part of the result is based on production data that is automatically reported to a database giving the values and ideas of certain people to have low impact on the result.

# 3. Frame of reference

## 3.1. Production layout

In order to best design a production process it is of importance to have a thorough understanding of what is produced and how it is being produced. Depending on the products batch size and the amount of products being produced the production can be divided into[7]:

- One-of-a-kind production
  The production of one-of-a-kind production is characterized by small volumes with large variation in the product. The production is often based on customer specified orders which sets high demand on flexibility. Airplanes, ships and larger machines are example of products that are produced with one-of-a-kind production.
- Batch production
  Characteristic for batch production are medium sized batches of one type of product where the production is often inventory-based. Examples of batch production are semi-finished goods and tools.
- Mass production
  Mass production is characterized by a continuous production of one sort of product where the production speed is high. Often special tools are used to produce the product. An example of mass production is the well known production of the T-Ford.

The production can further be divided depending on how the material is handled during the production and how the production equipment is arranged[8]:

- Product oriented layout
  In the product oriented layout the manufacturing and assembly is carried out in one spot. The production is often of the type one-of-a-kind production or short batches where the amount of manual work is large,

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[7] Ståhl, Jan-Eric, *Industriella Tillverkningsystem del II – Länken mellan ekonomi och teknik* (2009), pp. 26.

[8] Ibid, pp. 27.

which makes the time of production long. The products are often large, heavy and difficult to move. The layout is most common in the one-of-a-kind production.

- Functional oriented layout
  In the functional oriented layout the machines are placed after the type of manufacturing operation i.e. milling machines stand at one place and turning machines at another, this means that a large variety of products can be manufactured. The drawbacks with this type of layout are complicated materials handling, long internal transportations and long waiting time between the machines. This layout is most common in the batch production.
- Line production layout
  In the line production layout the machines are placed after manufacturing and process order which gives a foreseeable production flow and high production speed. The drawbacks are less flexibility and long setup times. This layout is suitable for large batches or continuous production. The line production layout can further be divided into: rate based assembly line and floated line[9]. The rate based assembly line has a buffer between the assembly cells while the floated line has none.

The floated line is the most sensitive to disruptions hence a stop in one of the stations means a stop for the whole line, while the rate based assembly line continues to operate as long as there is buffer left. Though all type of buffer and inventory means larger tied up capital and longer lead times.

Table 3.1. Properties for a functional and a line production layout (Ståhl 2009:29)

| | Functional layout | Line production layout |
|---|---|---|
| Lead time for a batch | High | Low |
| Work in progress, WIP | High | Low |
| Disorder sensibility | Low | High |
| Capacity utilization | High | Low |
| Need of planning | High | Low |

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[9] Aronson et al., *Modern logistik – för ökad lönsamhet* (2004), pp. 85.

Batches can be produced both in a Functional and Line production layout but the total utilization will be lower in a Line production layout[10], see table 3.1 for a summarizing of properties for the functional and the line production layout.

## 3.2. Materials flow and Lead time analysis

The purpose of a lead time analysis is to analyze information and materials flow in a structured way. Lead time analysis may range from flow between different production machines to flow within the company. The goal is to reduce the total time information and materials spend in a flow. According to studies a small amount – between 0.05 to 5 percent – of the total amount that is spent on performing a service, producing and delivering is directly value adding while the rest of the time is unproductive time[11].

The time a product spends in a flow can be divided into active and passive time. Active time means that some sort of activity is carried out while no activity is carried out during the passive time. Active time may for example be machine tooling, assembly or input into a computer system while passive time can for example be when material is in inventory or waiting in front of a machine in order to be processed. Often the passive time is the longest which means that it is suitable to first start reducing the passive time in order to reduce the total time[12].

## 3.3. Production line

A production line is often associated with large volumes or mass production as for example the line production sites in the car manufacturing business. A characteristic for a line production is that a certain amount of machines are connected with some sort of handling or transportation equipment. Further, a line production can be divided into one or multiple steps where there can be a buffer between the steps. A line with one step is a floated line and a line with multiple steps is a rate based line. The line can be fully automated or mechanized where the mechanized is the most common. The feeding to and from the line can be fully or partly mechanized.

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[10] Ståhl, Jan-Eric, *Industriella Tillverkningsystem del II – Länken mellan ekonomi och teknik* (2009), pp. 29.

[11] Larsson et al., *Processbaserad verksamhetsutveckling* (2001), pp. 284.

[12] Aronson et al., *Modern logistik – för ökad lönsamhet* (2004), pp. 208.

Pro- and cons for production lines are:

| **Pro** | **Cons** |
|---|---|
| Higher production rate | Lower flexibility |
| Lower throughput time | Long SETUP times |
| Lower amount of work-in-process, WIP | |

Buffers are used to reduce the effects of downtime by increasing the availability for the whole line. Buffers can also be used to even out variations in cycle time at the respective station. The down time in a line can happen due to:

- scheduled stops
- maintenance
- refilling of materials
- unscheduled stops
- tool failure
- mechanical or electrical failures

Depending on the characteristics of the feeding process between the stations a production line can be divided into:

- Synchronous line – the details are moved at the same time through the line and all stations take the same time to process.
- Asynchronous line – details are moved through the line at different opportunities.

In the asynchronous line the handling equipment will work as a buffer with one detail of capacity and the station that takes the longest time to process will decide the speed of the production.

### 3.3.1. Availability

The availability in a production system can, depending on if it is a series- or parallel system, see figures 3.1 and 3.2, be calculated as:

$$R_S(t) = R_1(t) * R_2(t) * \dots R_n \qquad (1)$$

$$R_P(t) = 1 - \big(1 - R_1(t)\big) * \big(1 - R_2(t)\big) \dots \big(1 - R_n(t)\big) \qquad (2)$$

where R(t) describes the components reliability functions. Equation 1 is for series systems where the different components are strictly depending on each other. Equation 2 is for parallel systems.

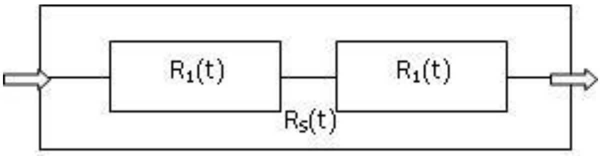

Figure 3.1. Reliability block diagram for a series system (Bergman et al. 2007:158)

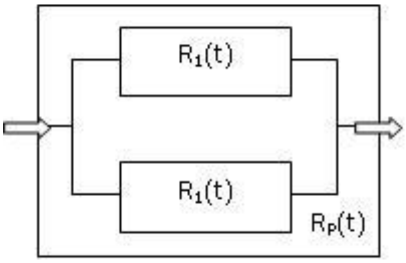

Figure 3.2. Reliability block diagram for a parallel system (Bergman et al. 2007:159)

Large series systems will require high dependability requirements on the components while parallel systems will have lower requirements. Thus to increase the total availability for a series system buffers are used between the components.

### 3.3.2. Dependability and utilization rate

The meaning of dependability is that resources should be activated when needed, that is machines and other equipment should be able to work properly when they are needed. A unit's dependability, see figure 3.3, is decided by[13]:

- Reliability and reliability function
  Reliability is a qualitative property in a system that decides the risk for failure and disturbs while the reliability function is a quantitative measure. Reliability can be defined as;”*the ability to perform a required function under given conditions”*[14]. The numerical value is MTTF.
- Maintainability
  Maintainability is a qualitative property in a system and it expresses the systems degree of adaption to the maintainability. Maintainability can be defined as;”*a measure of how easy it is to detect, localize and remedy failures”*[15]*.* The numerical value is MTTR.

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[13] Nilsson et al., *Kvalitets- och underhållsstyrning – Kurskompendium* (2009), pp. 16.

[14] Bergman et a.l, *Kvalitet från behov till användning* (2007), pp. 149.

[15] Ibid.

- Maintenance support
  Maintenance support is a qualitative property in the maintenance resources. Maintenance can be defined as; “*the ability of the maintenance organization to mobilize maintenance resources when needed”*[16]. The numerical value is MWT.

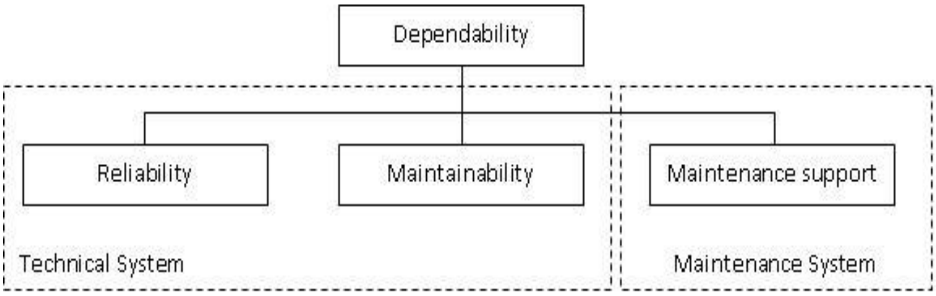

Figure 3.3. The relationship between dependability and its components (Nilsson et al. (2009:15)

Dependability, A, is given by the equation:

$$A = \frac{Used\ uptime}{Total\ available\ time} = \frac{MTTF}{MTTF + MTTR + MWT} \qquad (3)$$

where:

- MTTF (Mean Time To Failure) also called MTBF (Mean Time Between Failure) is a measurement for the reliability measured in hours and can be calculated as used uptime divided by amount of stops.
- MTTR (Mean Time To Repair) is a measurement for maintainability measured in hours and can be calculated as total time to repair divided by amount of stops.
- MWT (Mean Waiting Time) is a measurement for maintenance support measured in hours and can be calculated as total waiting time divided by amount of stops.
- A (Availability) is a measurement for availability measured in percentage.

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[16] Bergman et a.l, *Kvalitet från behov till användning* (2007), pp. 149.

Capacity Utilization, U, describes how well a production system is being used and is defined as”*the ratio between total amount of produced details and the total production capacity”*[17]. Capacity utilization can be described by the relation:

$$U = \frac{\sum_{i=1}^{n} N_{0i}}{P_{Cap}} \qquad (4)$$

where:

- n = amount of produced batches during the period
- $N_{0i}$ = the size of the series in the respective batch
- $P_{Kap}$ = total production capacity during a given time of period

When working with dependability one can either work with reliability techniques or dependability techniques. Reliability techniques are concepts that are frequently used within the work with quality while dependability techniques are a new branch. Within this branch the workability and dependability of a production system are reviewed. By this, maintenance will constitute as a part of the work with dependability. [18]

In all type of production there will be a need of maintenance, hence each production system will constitute of two concurrent subsystems: a technical- and a maintenance system. The optimal is that both subsystems give a positive contribution to the total performance of the production system, therefore the systems total performance will constitute of the technical- and dependability performances, see figure 3.4.

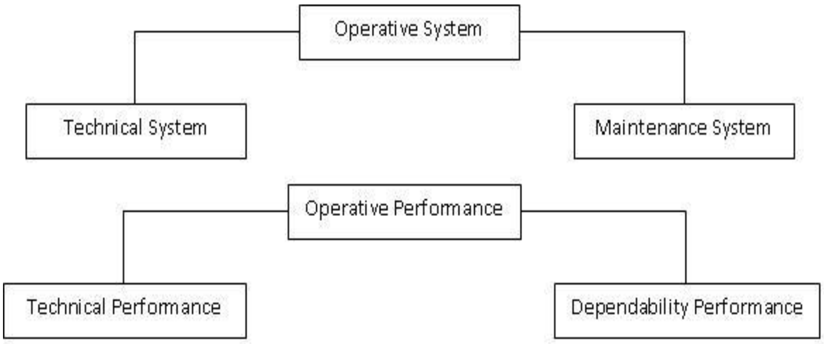

Figure 3.4. Relationship between the components to the operative system and the operative performance (Henriksson et al. 2009:13)

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[17] Ståhl, Jan-Eric, *Industriella Tillverkningsystem del II – Länken mellan ekonomi och teknik* (2009), pp. 77.

[18] Nilsson et al., *Kvalitets- och underhållsstyrning – Kurskompendium* (2009), pp. 11.

### 3.3.3. Importance of maintenance

The traditional view on maintenance has been more of a technical perspective where the centre of interest has been on the technical competence of the personnel and a high readiness for remedy maintenance. The assessment of maintenance has mostly been based on the rapidness in the repairmen work rather than the ability to prevent technical stops. However, during a long time it has been known within the personnel working with maintenance that it is better to prevent a technical stop rather than waiting for failure to occur and then repairing it. Therefore, large efforts have been made to switch focus on the maintenance from constituting of unplanned measures to more planned and systematic effort[19].

The maintenance effort can be a much faster and more flexible measure to increase the capacity when having availability losses than what new investments can offer. Well used maintenance efforts may therefore be considered as a value added feature of the facility's capacity that will both prolong the life time and also improve the performance. Maintenance may also affect the company's sales, both by increasing the amount of products the company can sell - this depends on the amount that can be produced - and by the price the company can charge - depends on the quality of the product). Maintenance may also affect the capability of the machines and therefore the ability to produce products with the desired quality and also affect the delivery precision.

A feasible way to calculate the total amount of products that a company can produce is the TAK model[20]:

$$n_{tot} = n_{max} * T * A * K \qquad (5)$$

where:

- $n_{tot}$ = amount of products a company can produce
- $n_{max}$ = the theoretical max production
- T = Availability
  Availability is calculated as the share of the total time that a machine is producing and is the factor that traditionally has been seen as the one thing that is affected by maintenance. Availability is, among other things, affected by failure in the equipment, interruption, changeovers and adjustments.
- A = facility utilization

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[19] Nilsson et al., *Kvalitets- och underhållsstyrning – Kurskompendium* (2009), pp. 20.

[20] Ibid, pp. 22.

The facility utilization is calculated as real production speed divided by maximal production speed. This is affected by, among other things, idle running, small interruptions and lower production rate.

- K = Quality interchange
  The quality interchange is calculated as how much of the produced products are of correct quality. This can be affected by, among other things, defects in the process and reduced interchange.

### 3.3.4. The importance of quality

Improved quality can impinge the profitability of a company in many ways, for example[21]:

- lower employee turnover and absence due to illness
- shorter lead times
- lower scrap and rework costs
- higher productivity

Quality is not all about producing products with high quality but also lowering the costs for the resources being used in the production, by for example lowering the amount of flaws and defects. Low internal quality can lead to a series of problems in the production which ultimately will lead to high inventory levels and buffers so that problems in one component will not lead to larger problems further on in the line. By increasing the internal quality one may lower the needs of keeping high inventory- and buffer levels. Therefore it is of importance for a company to have high internal quality when working with production programs as Lean Production and Six Sigma.

There is also a reverse relationship; by reducing the inventory level and other buffers, quality problems will be brought up to the surface, and when these are eliminated more inventory reduction can be made which will lead to further quality improvements. This relationship is called the Japanese lake.

## 3.4. Dimensioning of buffers

To dimension an ordering policy for an inventory when the demand is stochastic, it is of importance to first start with deciding a suitable demand distribution. When the demand during a period is low then it can best be modeled with a discrete stochastic variable. With large demands it is more practical to use a continuous stochastic

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[21] Bergman et al., *Kvalitet från behov till användning* (2007), pp. 56.

model[22]. Discrete models can be Poisson-, geometrical- or binomial distributions. With large demand it is often more suitable with a continuous distribution. The most common is the normal distribution due to the central limit theorem, which states that; if the amount of independent stochastic variables is large one can approximate the distribution with the normal distribution.

If the relationship $\sigma/\mu \ll 1$ – much smaller than one 1 – is true, the risk for negative demand is large when using the normal distribution and it may in these cases be better to use the gamma distribution. Another property of the gamma distribution is that the probability for large demands is larger for the normal distribution. The Weibull- and exponential distribution are other feasible alternatives for continuous systems.

If $S_1$ is defined as the *probability to run out of stock during the cycle time C* and we have an (R,Q)-system, which means that we place and order Q when the inventory level is at R, $S_1$ may then be described by the relationship:

$$P(D(L) \leq R) = S_1 = \Phi\left(\frac{R-\mu}{\sigma}\right) = \Phi\left(\frac{SS}{\sigma}\right) \qquad (6)$$

here it is assumed that the lead time for the demand is following a normal distribution. Put different, we will decide the level R so that we have the probability $S_1$ that the demand during the lead time will be lower than R. For a given $S_1$ the relationship $\frac{SS}{\sigma} = k$ is chosen to be large enough. The variable *k* - titled as the safety factor *k* – is easiest chosen from a table. After a safety factor *k* has been chosen, the safety stock and the order point can be calculated from the equations:

$$SS = k\sigma \qquad (7)$$

$$R = SS + \mu \qquad (8)$$

## 3.5. Input Analysis

After the data has been collected it must be processed. An approach for processing collected data is[23]:

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[22] Axsäter, Sven, *Inventory Control* (2006), pp.97.

[23] Ståhl, Jan-Eric, *Industriella Tillverkningsystem del II – Länken mellan ekonomi och teknik* (2009), pp. 145.

- One can start by calculating the MDT, Mean Down Time, and the MTBF, Mean Time Between Failure:

$$MDT = \frac{\sum DT}{k} \qquad (9)$$

$$MTBF = \frac{\sum TBF}{k} \qquad (10)$$

where $k$ is the amount of stops during the time of measurement, DT is the down time and TBF is the time between failure.

- Afterwards one can assume a distribution function for TBF and DT, for example the exponential distribution function:

$$F_{TBF}(t) = 1 - e^{\frac{-t}{MTBF}} \qquad (11)$$

$$F_{DT}(t) = 1 - e^{\frac{-t}{MDT}} \qquad (12)$$

- At last a follow up of the chosen distribution function can be made by fitting the collected data into a theoretical distribution function. How well the chosen and the empirical data fits will depend on the amount of data one has and if one has chosen the correct distribution function.
- The empirical function is calculated as:

$$S(t_j) = \frac{j}{k+1} \qquad (13)$$

Other approaches for calculating an empirical function are[24]:

$$S(t_j) = \frac{j}{n} \qquad (14)$$

$$S(t_j) = \frac{j}{n+1} \qquad (15)$$

$$S(t_j) = \frac{j-0.5}{n} \qquad (16)$$

When both the empirical and theoretical distribution functions have been calculated and plotted it has to be decided whether the fit is good or not. A feasible way to do

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[24] Kelton et al., *Simulation Modeling & Analysis* (1991), pp. 375.

this is to make a goodness-of-fit test for example the Kolmogorov-Smirnov Test. Other possible goodness-of-fit tests are the Chi-square and Anderson-Darling test.

### 3.5.1. Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test compares the empirical distribution function with the theoretical distribution function by a comparison of the closeness between the two distribution functions. This is done by calculating the largest vertical distance between the empirical and theoretical distribution function for all collected values. This is formally defined as:

$$D_n = sup\{\left|F_n(x) - \hat{F}(x)\right|\} \qquad (17)$$

where $D_n$ is the distance between the empirical and the theoretical distribution function. $D_n$ may be computed by calculating:

$$D_n^+ = \max_{0 \leq i \leq n}\{\frac{i}{n} - \hat{F}(X_i)\}, \quad D_n^- = \max_{0 \leq i \leq n}\{\hat{F}(X_i) - \frac{i-1}{n}\} \qquad (18)$$

where one finally gets the value from:

$$D_n = \max\{D_n^+, D_n^-\} \qquad (19)$$

The test latter rejects the null hypothesis $H_0$ – that the data follows the chosen distribution function - if $D_n$ exceeds some constant $d_{n,1-\alpha}$, where α is the specific level of the test. α of 5 % gives a test with 95 % confidence values. Critical values for the Kolmogorov-Smirnov test can be found in Appendix 1.

The KS-test is quite sensitive when having large data series, it is suggested not using the KS-test for data series larger than 30 points and instead it is recommended using the Chi-square test[25].

### 3.5.2. Autocorrelation

In order to be able to assume a suitable empirical distribution function the input data must be controlled for independency which is done by calculating the autocorrelation for the data series. This is due to the assumption of the data being *Identical Independent Distributed*, IID, in order to fit a distribution function.

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[25] Laguna et al., *Business Process Modeling, Simulation and Design* (2005), pp. 337.

The autocorrelation can be calculated as[26]:

$$\hat{\rho}_j = \frac{\widehat{C}_j}{S^2(n)} \qquad (20)$$

where $\rho_j$ is the estimated autocorrelation, $C_j$ is the estimated autocovariance and $S^2$ the estimated standard deviation. Se further Kelton et al.(1991) for different approaches on calculating the autocovariance.

It is difficult to use the estimator $\rho_j$ due to the fact that the estimator is biased and correlated with other correlation estimators, thus a "good" estimates of the $\rho_j$ will be difficult to obtain unless n is very large and j is small relative to n, where n is the total amount of data points and j is the j:th pair of data.[27] For this reason the software Stat::Fit uses only 1/5 of length of the calculated $\rho_j$ for the data series with length n.

Independency in the data series is achieved when the autocorrelation is between -0.5 and 0.5. For values above/below 0.5 and -0.5 and close to +/- 1 it is assumed that the data is autocorrelated.

## 3.6. Output Analysis

A feasible way to establish a models output data is by comparing it to the actual system. If the data of both systems closely resemble one could say that the model is fairly valid, thus the greater the commonality between the two systems the greater is the confidence on the simulation model.[28]

An intuitively approach to compare the output data and the data from the real-world system is to use one of the classical statistical test such as the t-student, two-sample chi-square, two-sample Kolmogorov-Smirnov tests. This comparison is made in order to determine whether the simulated model resembles the real-world model, but the major drawback of using these kind of statistical tests is that one assumes IID – Identical Independent Distributed – for the data but output data of almost all simulated models and real-world models are both non-stationary and autocorrelated thus none of these tests can be used directly.[29]

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[26] Kelton et al., *Simulation Modeling & Analysis* (1991), pp. 385.

[27] Ibid, pp. 286.

[28] Ibid, pp.311.

[29] Ibid, pp. 315.

**Correlated inspection approach**

The Correlated inspection approach is used when one wants to compare the output data of a model with the one from the real-world system[30]. The idea is to compare both the model and the real-world system using historical system input data rather than samples from the input probability distribution. This would mean that the model and the real-world system would experience exactly the same observations from the input random variables. Ultimately this results in a statistically more precise comparison.

If we let $Y_1,Y_2\ldots$ be an output stochastic process from a single simulation run and we let $y_{11},y_{12},\ldots y_{1m}$ be a realization of the random variables $Y_1$, $Y_2,..Y_m$ resulting from making a simulation run of length m observations using the random numbers $u_{11},u_{12},..$ where the i:th random number used in the j:th run is denoted $u_{ji}$. By running the simulation with a different set of random numbers $u_{21},u_{22},\ldots$ then we will obtain a different realization $y_{21},y_{22},\ldots y_{2m}$ of the random variables $Y_1,Y_2,\ldots Y_m$. If we now make n independent runs with different random numbers with the length m we would get a matrix:

$$\begin{array}{ccccc}
y_{11}, & \ldots, & y_{1i}, & \ldots, & y_{1m} \\
y_{21}, & \ldots, & y_{22} & & y_{2m} \\
 & & , & & \\
\cdot & & \cdot & & \cdot \\
\cdot & & \cdot & & \cdot \\
\cdot & & \cdot & & \cdot \\
y_{n1}, & \ldots, & y_{ni}, & \ldots, & y_{nm}
\end{array}$$

The observations from a particular replication, row, will clearly not be IID but the columns are IID observations of the random variable Y, for i = 1,2,…,m. This independence across runs is the key to output-data analysis methods.[31]

## 3.7. Lean Manufacturing

In a modern manufacturing environment, companies must be responsive to the needs of the customers, their specific requirements and to varying global market demands[32]. The manufacturing activities must, at the same time, be carried out with

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[30] Kelton et al., *Simulation Modeling & Analysis (1991),* pp. 316.

[31] Ibid, pp. 523.

[32] Kalpakjian et al., *Manufacturing engineering and technology* (2006), pp. 1227.

a minimum amount of wasted resources in order to ensure competitiveness. This has lead to the development of the concept Lean Manufacturing.

A broad description of the term Lean Manufacturing is that the main goal is to focus on activities within the manufacturing process that create value for the customers[33]. All activities and all expenditure of resources within the process that does not create value to the customers are considered to be wasteful, and are therefore a target for elimination.

Lean Manufacturing is a structured methodology to identify and eliminate waste in all areas of manufacturing through continuous improvement and by emphasizing product flow. This requires a thorough assessment of each of the activities of a company in order to minimize all non-value-added activities and optimize processes to maximize added value. This is made from the viewpoint of the customer. Activities include the efficiency and effectiveness of all its operations, the efficiency of the machinery and equipment, the number of personnel involved in each operation, and the possible dispensing of some of its operations and managers[34].

The process flow should correspond to a value stream which consists of all specific actions required to produce a specific product that meets the customer requirements. This viewpoint is critically important, because it helps identify whether or not an activity clearly adds value, adds no value but cannot be avoided or adds no value and can be avoided.

**Waste analysis**

To be able to focus on the activities that create value to the customer companies has to understand how to identify and eliminate waste and unnecessary expenditure of resources. The focus of Lean Manufacturing is on the entire process flow and not just the improvement of one or more individual operations[35].

Typical wastes to be considered and either reduced or eliminated include the following: [36]

**Overproduction** – Producing over customer requirements, products that do not reach the customers or products that are produced early for which there are no orders. It is the most serious waste, as it discourages smooth flow and hides defects.

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[33] Bergman et al., *Kvalitet från behov till användning* (2007), pp. 622.

[34] Kalpakjian et al., *Manufacturing engineering and technology* (2006), pp. 37.

[35] Magnusson et al., *Six Sigma The Pragmatic Approach* (2003), pp. 447.

[36] Bergman et al., *Kvalitet från behov till användning* (2007), pp. 623.

Overproduction results in handling damage and undetected defects. It requires extra handling, extra space, extra interest charges, extra machinery and extra labor.

*Examples:* Producing product to inventory based on sales forecasts, producing more to avoid setups or batch process resulting in extra output.

*Causes*: Producing unnecessary materials, parts, components, or products before they are needed or manufacturing items for which there are no orders. Forecasting, long setups, lack of communication or focus on keeping busy rather than meeting customer needs.

*Countermeasures*: Pull system scheduling or setup reduction.

**Waiting** – occurs whenever products are not moving or being worked on. Time during which value is not added to the product, created when material, information, people, or equipment is not ready. Or it can be because of late delivery of raw material, work in process, capacity bottlenecks and equipment downtime.

*Examples*: Waiting for parts, prints, inspection, machines, information or machine repair.

*Causes*: Push production, work imbalance, centralized inspection, order entry delays, lack of priority, lack of communication, time delays, inconsistent work methods or long setup times

*Countermeasures*: Maximize the efficiency of workers at all times or rate time production.

**Transport** – any movement in the factory could be viewed as waste as it does not create value. If it is possible to eliminate movement without creating other problems by reorganizing the value stream then waste is eliminated.

*Examples:* Unnecessary transportation of material, work in process, parts, finished goods or information from place to place and/or into or out of storage between processes or over long distances.

*Causes*: Batch production, push production, storage, multiple handling, delay in materials handling, unnecessary handling, lack of co-ordination of processes, poor workplace organization or multiple storage locations.

*Countermeasures*: Minimizing or eliminating product transportation because it represents an activity that adds no value. Flow lines, pull system, Kanban, better plant layout or forming machining cells.

**Inappropriate processing** – complex processes should be absent and simplicity installed. A process that creates incorrect products has to be corrected immediately to avoid waste. Unnecessary, incorrect or redundant processing of a task, processing higher-quality products than is necessary or processing with poor tools or improper product design.

*Examples*: Multiple cleaning of parts, paperwork, over-tight tolerances, awkward tool or part design, longer than necessary heat treatment, too many coats of paint, unnecessary or inefficient inspections, too many standards to hold on to.

*Causes*: Delay between processing, push system, unnecessary steps or work elements/procedures (non added value work), inappropriate tooling or equipment, poor tooling maintenance or failure to combine operations.

*Countermeasures*: The elimination of unnecessary processes and steps, because they represent costs. Flow lines or Lean Design.

**Unnecessary inventory** – unnecessary inventory increases lead time and takes space. Producing, holding or purchasing unnecessary inventory which can take up space.

*Examples*: Raw materials, work in process, finished goods, consumable supplies, purchased components.

*Causes*: Supplier lead times, lack of flow, long setups, long lead times, paperwork in process, lack of ordering procedure, unreliable equipment, unbalanced flow, inaccurate forecasting or large batch sizes.

*Countermeasures*: Using just-in-time production approaches to eliminate inventory, because inventory represents cost, leads to defect, and reduces responsiveness to changing market demands. One-piece flow lines or setup reduction.

**Defects** – the bottom line waste is defects, production of a part that is scrapped or requires rework.

*Examples*: Scrap, rework, defects, correction, field failure, variation, missing parts.

*Causes*: Failure to inspect and catch human and machine-made quality problems, having to fix an error already made, or fixing it repeatedly. Process failure, misloaded part, batch process, inspect-in quality or incapable machines.

*Countermeasures:* The elimination of part defects.

**Unnecessary motion** – motions that cause poor ergonomics and effectiveness. Actions of people or equipment that do not add value to the product. Faults in the safety system increase the risk of injuries and create insecurity and a worse and less effective working environment.

*Examples*: Searching for parts, tools, prints, etc., sorting through materials, reaching for tools, lifting boxes of parts. Wasting human activity on watching machines.

Causes: Workplace disorganization, missing items, poor workstation design, unsafe work area or inconsistent work methods.

*Countermeasures:* Performing time and motion studies to identify inefficient workers or unnecessary product motions.

## 3.8. Six Sigma

Six Sigma is an improvement methodology with the purpose of reducing costs and providing increased customer satisfaction[37]. The main focus is on reducing unwanted variation. Unwanted variation is a critical factor in the production and a source of costs and dissatisfied customers. The basic idea is to collect and process data to try to reduce or eliminate the variation in production focusing on the parameters that affects properties that are important to the customers. The variation in processes creates problems like varying lead times and varying quality, which can lead to delays and scraps. A good process control brings opportunities to find optimal process data, which leads to shorter run times, reduced downtime and better quality[38].

The Greek letter "sigma", σ, is a notation of a standard deviation. The distance from the process mean to the nearest tolerance limit, for a manufacturing process that is

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[37] Bergman et al., *Kvalitet från behov till användning* (2007), pp. 622.

[38] Ståhl, Jan-Eric, *Industriella Tillverkningssystem del II – Länken mellan ekonomi och teknik* (2009), pp. 304.

in statistical control, should be at least six times the standard deviation of the process[39].

Besides the random variation that exists, when the process in statistical control, the process is often disturbed by long term variation. However, the causes for this long term variation are, in general, assignable and unless this variation is too big it can be accepted. According to the Six Sigma approach this variation is acceptable as long as the process mean deviates at the most ±1.5 $\sigma$ from the target value. This means that the distance from the mean value to the nearest tolerance limit is at least $4.5\sigma$. The probability of incorrect results under these circumstances, assuming a normally distributed output, is at most 3.4 defects per million. This means that an important property to the customer should rarely be of dissatisfaction, no more on average than 3.4 times per million opportunities.

The measurement system used is simple and consistent. The measure is defects per million opportunities, written as dpmo. In every activity of a sub-process, the total number of defect opportunities is estimated and put in relation to the total number of actual defects. By adopting the same measurement scale to all characteristics that are important to the customers, the dpmo of the various processes can be weighted together to produce a single dpmo for the entire organisation.

The standard order of improvement within Six Sigma is (1) eliminate special causes of variation, (2) reduce variation, and then, (3) improve location (mean).

## 3.9. Statistical Process Control

The main purpose of Statistical Process Control is to find as many assignable cause of variation as possible and then eliminate them[40]. These variations can be all from variation in run speed to variation in inhomogeneous materials, thus independently of what type of variation it is it should be reduced. In the Six Sigma program this reduction of variation is an essential element.

Variation can be of two types; *Assignable variation* and *Random variation*. The assignable variation is due to variation occurring from assignable causes and the random variation is caused by common causes.

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[39] Bergman et al., *Quality – from customer needs to customer satisfaction* (2003), pp. 542.

[40] Bergman et al., *Quality – from customer needs to customer satisfaction* (2003), pp. 207.

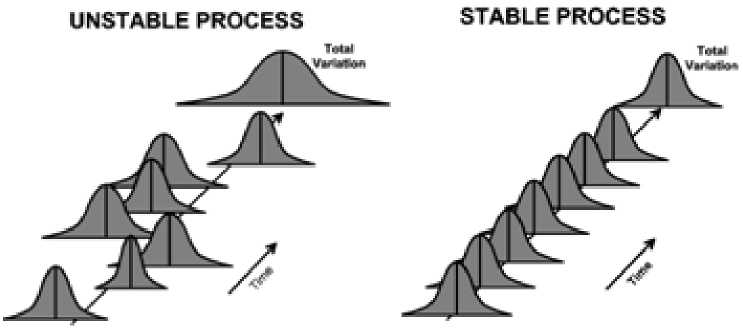

Figure 3.5. Example of a stable and unstable process (www.variation.com)

When the assignable variation has been eliminated or at least reduced only the random variation remains in the process. When only the random variation contributes to the variation and no systematic variation occurs the process is said to be in statistical control and thus we have a stable process, see figure 3.5.

The purpose of Statistical Process Control is, on the basis of data from the process, to

- Identify assignable causes in order to eliminate them and create a stable, predictable process.
- Supervise the process when it is in statistical control so that no further assignable causes are introduced without the knowledge of the operator.
- Continuously give information from the process, so that new causes of variation can be identified as assignable and eliminated.

## 3.10. Control Charts

Control charts were first introduced by Walter. A Shewart, as the prime tool to find if assignable causes of variations exist. Control charts are also an excellent tool to graphically show the process output in time order[41].

The basic idea is to take out a number of observations from the process at certain time intervals and by using these observations calculate some form of process quality indicator. The quality indicators can for example be the arithmetic mean and the standard deviation. After this is done the indicators are plotted in a diagram. If the plotted indicators are within the prescribed limit it can be said that the process is in statistical control or that the process is stable. These prescribed limits are called control limits and often a central limit is used to indicate an ideal level, see figure

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[41] Bergman et al., *Quality – from customer needs to customer satisfaction* (2003), pp. 231.

3.6. UCL is the upper control limit and LCL is the lower control limit. Also plotted in the figure is an upper tolerance limit. It is important to notice the difference between a control limit and a tolerance limit. The control limits are used in the control chart as an indicator of the stability of the process and is calculated by the use of actual production data, while the tolerance limit are set to determine whether a single unit fulfils stipulated productions requirements and is not dependent of the actual production data.

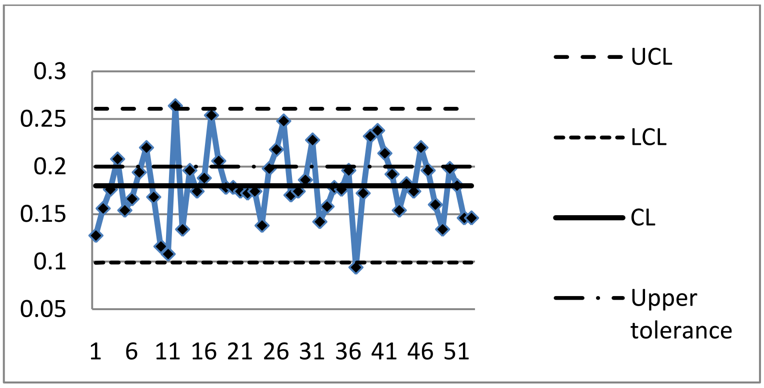

Figure 3.6. Control chart with upper- and lower control limit, central limit and a tolerance limit.

The choice of control limits must be made in such a way that the chance for false alarms is small. This limit is often chosen as:

$$\mu \pm \frac{3\sigma}{\sqrt{n}} \qquad (21)$$

With this limit the probability that the arithmetic mean, $\bar{x}$, of a sample of size n deviates more than $3\sigma/\sqrt{n}$ from the process mean, μ, is approximately 0.3 %, and thus considered to be a reasonable risk. This is under the assumption that the distribution of the sample mean is normally distributed. Control charts designed with these limits are sometimes called Shewart charts.

When working with control chart one will plot different charts depending on the quantity that is being supervised. However, the most frequently used charts for variables are Mean and Range Charts[42].

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[42] Oakland S., John, *Statistical Process Control – A practical guide* (1986), pp. 70.

### 3.10.1. Mean Charts

When working with a Mean Chart one first start with taking *k* sample of *n* units each. A common rule is that *k* should be at least 20-25, preferably 40, and *n* is by tradition taken as 5.

As a point estimator of μ the mean value $\bar{\bar{x}}$ of the mean values of the samples $\overline{x_1},\ \overline{x_2}, \dots, \overline{x_k}$ is chosen, thus giving:

$$\bar{\bar{x}} = \frac{1}{k}(\overline{x_1} + \overline{x_2} + \cdots + \overline{x_k}) \qquad (22)$$

If the standard deviation, σ, is known UCL and LCL can be calculated according to equation 22.

$$UCL = \bar{\bar{x}} + 3\frac{\sigma}{\sqrt{n}}\ and\ LCL = \bar{\bar{x}} - 3\frac{\sigma}{\sqrt{n}} \qquad (23)$$

If the standard deviation is unknown it must be estimated by either the *s-method*, equation 23, or the *R-method*, equation 24.

$$\sigma_{estimated} = \frac{s_1 + s_2 + \cdots s_k}{k} * \frac{1}{c_4} = \frac{\bar{s}}{c_4} \qquad (24)$$

where $\bar{s}$ is the standard deviation of the various samples, *k*, and $c_4$ is a constant that depends on the sample size, n.

$$\sigma_{estimated} = \frac{R_1}{d_2} + \frac{R_2}{d_2} + \cdots + \frac{R_k}{d_k} * \frac{1}{k} = \frac{\bar{R}}{d_2} \qquad (25)$$

where R is the range in each sample, that is the difference between the largest and the smallest value in each sample, n.

Values for the constants $c_4$ and $d_2$ can be found in Appendix 2.

### 3.10.2. Range Chart

The range is the difference between the largest and the smallest value in each sample, n. The UCL, CL and LCL are given by equations 25, 26 and 27.

$$UCL = D_2 * \sigma \qquad (26)$$

$$CL = d_2 * \sigma \qquad (27)$$

$$LCL = D_1 * \sigma \qquad (28)$$

If σ is unknown it can be estimated by the use of equation 24. UCL and LCL can then be calculated according to equations 28 and 29.

$$UCL = D_4 * \bar{R} \qquad (29)$$

$$LCL = D_3 * \bar{R} \qquad (30)$$

Interesting is that if the sample size, n, is chosen to be 5 it yields that's $D_3$=0 and thus the reason of why n has traditionally been chosen to be 5.

Values for the constants $D_1$,$D_2$,$D_3$ and $D_4$ can be found in Appendix 2.

## 3.11. Process capability

The main goal of statistical process control is to reduce variation in the process and then supervise the process so that no new assignable causes appear. By the use of information obtained from statistical process control and the ability of the process to produce within the tolerance limits – also called the capability of the process - one can define various measures of this capability.

Figure 3.7 shows two processes, where the lower one is a process that is outside the specification limits while the upper one is within the specification limits. The specification limits are often set as the lower and upper tolerance limits.

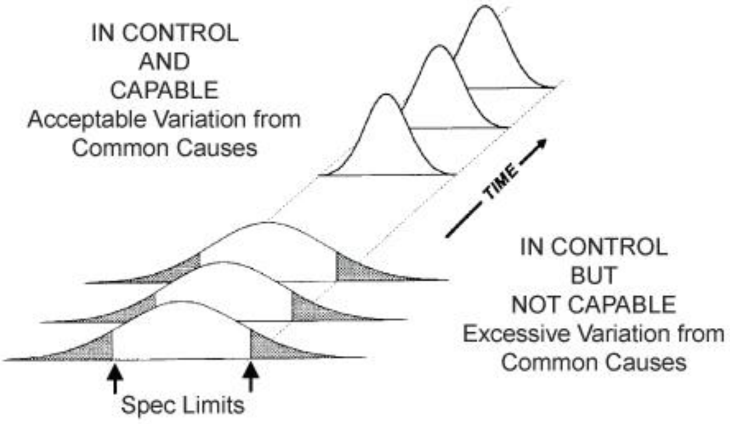

Figure 3.7. Process capability (www.drc.com)

One of the various measures of the process capability that can be defined is the capability index, cp, and is defined according to equation 30.

$$C_p = \frac{T_U - T_L}{6 * \sigma} \qquad (31)$$

where $T_u$ is the upper tolerance limit and $T_L$ is the lower tolerance limit.

A large value of $C_p$ yields that the process, if well-centered, will produce within the tolerance limits, and a low value yield a process producing outside the tolerance limits. A drawback of the capability index is that it only takes into account the dispersion of the process and not its centering, thus the index measures the possibilities provided by the process if it is centered correctly rather than the capability of the process. Another measure of the process capability that takes into account both the dispersion and the centering is the $C_{pk}$ – *the adjusted capability index.* This index is calculated according to:

$$C_{pk} = \min\left(\frac{T_U - \mu}{3 * \sigma}, \frac{\mu - T_L}{3 * \sigma}\right) \qquad (32)$$

Thus, the adjusted capability index measures the distance between the mean, μ, and the nearest tolerance limit in relation to 3σ.

Common requirement for the capability indices of a process is that $C_p$ is 1.5 and $C_{pk}$ is 1.33. For example the target according to the Six Sigma program is a $C_p$ of 2.0.

## 3.12. Simulating manufacturing systems

### 3.12.1. Introduction to Simulation

Many systems in the manufacturing industry are so complex that models of these systems are almost impossible to solve mathematically. In these cases, numerical, computer-based simulation can be used. A simulation is the reproduction of the operation of a real-world process or system and its behavior as it evolves over time[43]. First a simulated history of a system is created and then from the simulation, data is collected as if a real system was being observed. This simulation-created data is used to estimate the measures of performance of the system. A simulation model takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical, and symbolic relationships between the objects of interest, of the system.

Once developed, a simulation model can be used to investigate a broad variety of scenarios concerning the real-world system. Potential changes to the system can first be simulated in order to evaluate their impact on system performance. Another

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[43] Banks et al., *Discrete-event simulation* (1984), pp. 2.

use of simulation is to study systems that are still in the design state, before they are built. Therefore, simulation modeling can be used both as an analysis tool for evaluating the effect of changes to existing systems, and as a design tool to forecast the performance of new systems under various conditions.

**Advantages**

Advantages with using simulation[44]:

- Usually simulation data are much less costly to obtain than similar data from the real system[45]. The most frequently used argument is that it is cheaper to create a model in the computer than it is to build a physical model to perform tests.
- The object does not exist in reality or it is too big or small.
- The process goes too fast or too slow or it has some other unwanted effects.
- Experiments are too expensive, too dangerous or take too long time.
- Simulation provides the opportunity to test every aspect of a planned change without spending any resources on purchases. By changing simulation inputs and observing the resulting outputs, important insight may be obtained into which variables are most important and how variables interact.
- A great benefit of using simulation in a manufacturing environment is that it gives the opportunity to obtain a *system-wide view* of the effect of “local” changes to the manufacturing system[46]. If a change is made at a particular work station, its impact on the performance of *this* station may be predictable. On the other hand, it may be difficult to determine ahead of time the impact of this change on the performance of the *overall system*.
- Identify constraints. Bottlenecks are an effect rather than a cause. By using simulation to perform bottleneck analysis, the cause of the delays in work in process, information, materials, or other processes may be discovered. Simulation is capable of uncovering inefficiencies that usually go undetected until the system is in operation.

**Disadvantages**

Possible disadvantages with using simulation:

- Simulation modeling and analysis can be time consuming and expensive.

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[44] Banks, Jerry, *Handbook of Simulation – Principles, Methodology, Advances, Applications, and Practice* (1998), pp. 10.

[45] Banks et al., *Discrete-event simulation* (1984), pp. 4-5.

[46] Kelton et al., *Simulation Modeling & Analysis* (1991), pp.697.

- Model building requires special training that is learned over time and through experience.
- Simulation results are difficult to interpret. Since most simulation outputs are random variables, it may be difficult to determine whether an observation is a result of system interrelationships or randomness. Further, most output data is autocorrelated and thus cannot be treated with the usual statistical techniques assuming IID – Identical Independent Distributed – data.

**Areas of Application**
Areas where simulation can be applied include:

- Simulation of large-scale distribution and inventory control systems to improve the design of these systems[47].
- Simulation of the operation of a production line to determine the amount of in-process storage space that should be provided.
- In complex systems, where it is impossible to find solutions to optimizing problems, simulation models can be an alternative of use[48]. A few examples are product flows in a manufacturing facility or vehicles in traffic.
- The need for and the quantity of equipment and personnel: location and size of inventory, buffers and evaluation of the effect of a new piece of equipment on an existing manufacturing line.
- Performance evaluation: throughput analysis and bottleneck analysis.
- Evaluation of operational procedures: Production scheduling (choosing batch sizes), policies for material inventory levels, reliability analysis and quality-control policies.

### 3.12.2. Simulation models

Two concepts used when modeling a system, are the system and the system boundary. A *system* is defined as a group of objects which act and interact together toward the accomplishment of some purpose[49]. An example is a production system manufacturing automobiles. The machines, component parts, and workers operate as a group along an assembly line to produce a vehicle. A system is often affected by changes occurring outside the system. These changes occur in the *system environment*. It is necessary to decide on the *boundary* between the system and its environment when modeling systems.

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[47] Banks et al., *Discrete-event simulation* (1984), pp. 5.

[48] Ståhl, Jan-Eric, *Industriella Tillverkningssystem del II – Länken mellan ekonomi och teknik* (2009), pp. 327.

[49] Banks et al., *Discrete-event simulation* (1984), pp. 6.

In order to understand and analyze a *system*, for example a production process, a number of terms are defined. An entity is an object of interest in the system. An *attribute* is a property of an entity. An *activity* represents a time period of specified length. If a production process is being studied, machines might be one of the entities, their speed, capacity or breakdown rate might be an attribute, and welding and stamping might be activities.

The *state* of a system is defined to be that collection of variables necessary to describe the system at any time, relative to the objectives of the study. In the study of a machine breakdown, possible state variables are the status of machines (busy, idle or down). An *event* is defined as an instant incident that may change the state of the system. The term *endogenous* is used to describe activities and events occurring within a system, and the term *exogenous* is used to describe activities and events in the environment affecting the system. In the production process study, the arrival of a new work item is an exogenous event, and the completion of process of a work item is an endogenous event.

A *model* is defined as a representation of a system for the purpose of studying the system[50]. For most studies, it is not necessary to consider all the details of a system; a model is a simplification of the system. However, the model should be sufficiently detailed in order to allow valid conclusions to be drawn about the real system. Depending on the purpose of the study different models can be developed for the same system. Models are represented in a similar way as a system, consisting of entities, attributes and activities. However, a model contains only those components that are relevant to the study.

Simulation models can be classified as being *static* or *dynamic*, *deterministic* or *stochastic*, and *discrete* or *continuous*[51]. A *static* simulation model represents a system at a certain point in time and is used when time does not play a role in a system. *Dynamic* simulation models represent a system as it changes over time. A deterministic model does not contain any random variables. The outputs are determined after the inputs are known and the relationships in the model have been established. However, sometimes it is required that a system is modeled as having at least a few random input variables. These models are called *stochastic* simulation models and generate output that is itself random; therefore they are only an approximation of the real characteristic of a model. In real processes, variability will always exist in the time it takes to complete a particular task. If the variability is

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[50] Banks et al., *Discrete-event simulation* (1984), pp. 7.

[51] Ibid, pp. 10.

small, it might be enough to use deterministic models to describe the process. In processes with more elements of variability, stochastic models are better used to fully describe the process, since the variability is often one of the most important characteristics to capture in the model of a process[52].

An example that can be used to illustrate the importance of using a stochastic model is the checkout process at a grocery store where one of the main purposes of the study is to avoid long lines. Customers arrive at the checkout stations with their items so they can pay and leave. Each cashier scans the items, bags them, and collects payment from the customer. The time it takes to service a customer depends on the amount and type of groceries and the form of payment used; therefore, it varies from customer to customer. In addition, the number of customers per time unit that arrive at the cashier's station is highly uncertain and variable. Applying a deterministic model to describe this process, using only the average service time and the average number of customer arrivals per time unit, fails to capture the variability and explain why queues are forming. This is because the deterministic model assumes that it always takes exactly the same amount of time for a cashier to serve a customer, and that customers arrive at constant intervals. But the fact that queues often form at a cashier's station indicates that this is too simplistic of a way to describe the complex reality. Variability makes it difficult to match demand and capacity in such a way that queues are avoided.

The difference between a *discrete* model and a *continuous* model lies in how the state variables change over time. In a discrete model the state variables change only at a discrete set of point in time, while in a *continuous* system the state variables change continuously with respect to time[53].A manufacturing process is an example of a discrete system, since state variables – e.g. the number of items that are currently in production – change only when a new item arrives or when an item finishes production. An airplane moving through the air is an example of a continuous system, since state variable such as position and velocity can change continuously with respect to time.

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[52] Laguna et al., *Business Process Modeling, Simulation, and Design* (2005), pp. 171.

[53] Kelton et al., *Simulation Modeling & Analysis* (1991), pp. 4.

### 3.12.3. Discrete-Event System Simulation

Discrete-event simulation systems are discrete, dynamic and stochastic[54].

*Discrete-event simulation* is the modeling of systems as it evolves over time in which the state variables change at a discrete set of points in time. In mathematical terms, this means that the system can change at only a *countable* number of points in time. These points in time are the ones at which an event occurs. A discrete-event simulation model studies the dynamics of the system from one event to the next, since the state variables change as a result of an event happening in the system. That is, the simulation moves the “simulation clock” from one event to the next and considers that the system does not change in any way between two following events. Discrete-event models focus only on the time instances when discrete events occur. This allows for major time compression because it makes it possible to skip through all time segments between events when the state of the system remains unchanged.

**Concepts in discrete-event simulation**[55]

The concepts in discrete-event simulation can be summarized as following:

System – A group of entities (e.g., people and machines) that interact together over time to achieve common goals.

Model – An abstract representation of a system, including logical and/or mathematical relationships which describe a system in terms of state, entities and their attributes, sets, events, activities, and delays.

System state – A group of variables that include all the information necessary to describe the system at any point in time.

Entity – Any object or component in the system which requires explicit representation in the model (e.g., a server, a machine).

Attributes – The properties of a certain entity (e.g., the priority of a waiting customer, the routing of a job through a job shop)

Set – A group of associated entities, ordered in some logical fashion (such as all customers currently in a waiting line, ordered by first come, first served, or by priority).

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[54] Banks et al., *Discrete-event simulation* (1984), pp. 10.

[55] Banks et al., *Discrete-event simulation* (1984), pp. 10.

Event – An instant occurrence that changes the state of a system (such as an arrival of a new customer).

Activity – A duration of time of specified length (e.g., a service time or interarrival time), which length is known when it begins.

Delay – A duration of time of unspecified length, which length is not known until it ends (e.g., customer's delay in a last in, first out waiting line, which when it begins, depends on future arrivals).

### 3.12.4. Steps in a Simulation study

Typical steps that can be included in a simulation study are shown in figure 3.8.

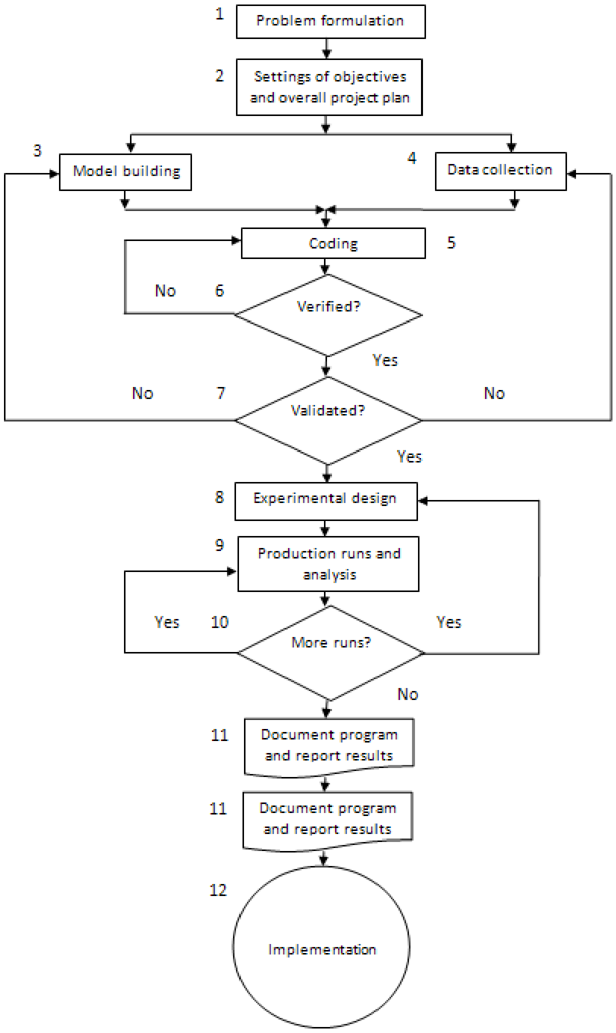

Figure 3.8. Steps in a simulation study (Banks et al. 1984:12)

A discussion of each step[56]:

1. *Problem formulation*. At the beginning of each study a statement of the problem should be established. It is of great importance that everyone involved in the simulation, for example the analyst or the policymaker, clearly understand the problem and agree with the formulation of it. During some occasions the problems must be reformulated as the study progresses.
2. *Setting of objectives and overall project plan*. The objectives specify which questions are to be answered by simulation. The overall project plan includes a statement of the alternative systems to be considered, and a method for evaluating the effectiveness of these alternatives. It should also include the plans for the study in terms of the number of days required to accomplish each phase of the work with the expected results at the end of each stage.
3. *Model building*. In modeling it is of great importance to be able to capture the essential features of a problem as a model designer, to select and modify basic assumptions that describe the system, and then to improve the model until a useful approximation results. It is best to start with a simple model and continuously develop the model toward greater complexity. The model complexity does not need to exceed what is required to achieve the purposes for which the model is intended. Not following this principle will only add to model building and expenses. It is not necessary to have a one-to-one mapping between the model and the real system. Only the most important parts of the real system need to be included.
4. *Data collection*. As the complexity of the model changes, the required data elements may also change. It is required to begin as early as possible, often together with the early stages of model building, since data collection takes a large part of the total time required to perform a simulation. The objectives of the study determine what kind of data to be collected.
5. *Coding*. Most real-world systems results in models that require a great deal of information storage and computation, so the model must be programmed for a digital computer.
6. *Verified*? Is the computer program performing correctly? With complex models it is difficult to code a model successfully without spending a lot of time on debugging. If the input parameters and logical structure of the model are correctly represented in the code, verification has been completed.
7. *Validation*? Validation is the determination that a model is an accurate representation of the real system. Validation is achieved through the calibration

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[56] Banks et al, *Discrete-event simulation* (1984), pp. 12.

of the model, an iterative process of comparing if the model accuracy is viewed as acceptable. Validation is something that should be done throughout the entire simulation study. During step 3, when building the model, it is very important for the modelers to involve people in the study who are closely familiar with the operations of the actual system. It is also useful for the modelers to interact with the decision maker (or the model's intended users) on a regular basis. The accuracy of the probability distributions specified for generating input random variables should be tested using goodness-of-fit tests. Pilot runs can be used to test the sensitivity of the model's output to small changes in an input parameter. If a system similar to the one of interest currently exists, output data from pilot runs for a model of the *existing* system can be compared with those from the actual existing system (collected in step 4).

8. *Experimental design*. The alternatives that are to be simulated must be determined. Often, the decision concerning which alternatives to simulate may be a function of runs that have been completed and analyzed. For each system design that is simulated, decisions need to be made concerning the initial conditions for the simulation runs, the length of the warm-up period, the length of the simulation runs, and the number of independent simulation runs to make for each alternative.
9. *Production runs and analysis*. Production runs are made to provide performance data for the system designs that are being simulated. Statistical techniques are used to analyze the output data from the production runs. Typical goals are to construct a confidence interval for a measure of performance for one particular system design or to decide which simulated system is best relative to some specified measure of performance.
10. *More runs*? Based on the analysis of runs that have been completed, the analyst determines if additional runs are needed and what design those additional experiments should follow.
11. *Document program and report results*. If the program is going to be used again by the same or different analysts, it may be necessary to understand how the program operates. This will allow confidence in the program so that model users and policymakers can make decisions based on the analysis. If the program is to be modified by the same or different analyst, this can be made easier by satisfactory documentation. Another reason for documenting a model is so that model users can change parameters of the model in order to determine the relationship between input parameters and output parameters of performance, or to determine the input parameters that optimize some output measure of

performance. The result of all analysis should be reported clearly and concisely. This will enable the model users to review the final formulation, the alternative systems that were addressed, the criterion by which the alternatives were compared, the results of the experiments, and the recommended solution to the problem.

12. *Implementation.* The success of the implementation phase depends on how well the previous 11 steps have been performed. It is also dependent upon how thoroughly the analyst has involved the ultimate model user during the entire simulation process. If the model user has been thoroughly involved during the model-building process and if the model user understands the nature of the model and its outputs, the implementation is likely to go well. But if the model and its underlying assumptions have not been properly communicated, implementation will probably suffer.

A simulation study is not a simple sequential process. Not all studies will necessarily contain all these steps and in the order stated. As one proceeds with a study and a better understanding of the system of interest is obtained, it is often desirable to go back to a previous step. For example, new insights about the system obtained during the study may necessitate reformulating the problem to be solved.

# 4. Empirical data

## 4.1. The production

The production at the packaging company's facility produces orders from 4 000 up to approximately 90 000 meters. The product variety is large and the technical difference when it comes to producing the package material depends on the type of print being used , the size, volume, package system and shape. There are four different print methods where each method has some sub-methods. The four main printing methods are:

- Flexo Print – The classic printing method that offers good economy and is easy to print.
- Flexo Process – A higher quality print method.
- Offset – The best print quality available for chilled liquid food packages.
- Metallised – A metallised print method that gives the package a metallised surface.

The package system defines what type of package it is, for example if it is a package where as the size defines the size of the package and the volume the packages volume. Finally the shape decides if it is for example a slim package or a square.

During the month the study covered the total amount of produced material in the printer P14, categorized by print method, can be seen in table 4.1.

Table 4.1. Produced material in printer P14 during August 2009

| | **P14** | | |
|---|---|---|---|
| **Materials Input** | **Frequency** | **Total (m)** | **Avg (m)** |
| FP CD | 218 | 3 531 551 | 16 200 |
| F D | 115 | 2 911 887 | 25 321 |
| F CD | 37 | 655 795 | 17 724 |
| **Sum** | 370 | 7 099 233 | |

Here the materials produced are divided into:

- FP CD – Flexo Process Clay coat Duplex
  The Flexo Process Clay coat Duplex is a print type used when the paper material is coated.

- F D – Flexo Duplex
  The Flexo Duplex print type is used when the paper to be printed is not coated.
- F CD – Flexo Clay coat Duplex
  A print type used when the paper material is coated. The difference between Flexo Process Clay coat Duplex and Flexo Clay coat Duplex is that the first one offers a better print quality.

For the printer P12 there was only one type of print produced in August, which can be seen in table 4.2.

Table 4.2. Produced material in printer P12 during August 2009

|  | P12 |  |  |
|---|---|---|---|
| **Materials Input** | **Frequency** | **Total (m)** | **Avg (m)** |
| FP CD | 344 | 5 095 557 | 14 813 |

When producing different types of prints there will be a need for an Anilox setup. This setup will occur every time there is a change in print method, for example if the printer is currently printing Flexo Process and the following order is Flexo Print an Anilox change will be needed.

For the laminator the production was not divided into print type thus the total amount of material produced by the laminator was 12 538 910 meters in August 2009.

## 4.2. Materials flow and Lead time analysis

The material to be processed, consisting of paper rolls, is brought to the printer by AGV-vehicles. At the printer the material spends time queuing before being processed. This queue varies from 1 – 3 paper rolls and the time depends on the cycle and down time of the printer. The paper rolls are loaded manually into the printer. After being processed the paper rolls are removed from the printer manually and AGV-vehicles takes the rolls to an inventory.

When an invoice is received the materials are brought to the laminator where they are placed in a queue before being loaded manually to the laminator. The queue before the laminator varies from 1-3 paper rolls. After being processed the materials are unloaded from the laminator manually and AGV-vehicles pick the materials up and take them directly from the laminator to the slitter.

Inputs to the line are taken by trucks to the corresponding line and are loaded manually when needed.

The material flow is shown in figure 4.1.

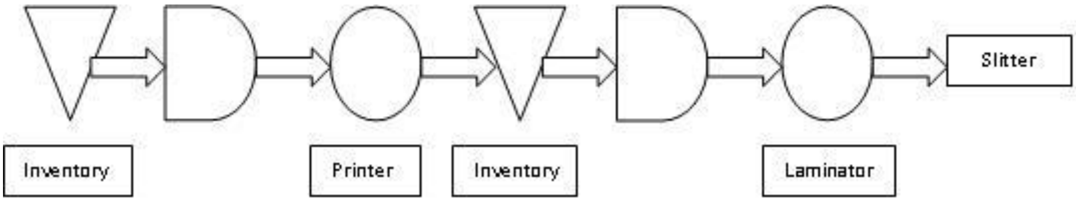

Figure 4.1. Materials flow for the production line studied

## 4.3. Production line

The production line of packaging materials consists of four parts; pre-print, printer, laminator and slitter. At the production site there are two printers at one spot and two laminators following, though only one laminator is mostly used. There is an inventory between the printer and laminator that is physically disconnected from the production facility.

The production line covered in this study consists of two steps; the first step is the printer and the second is the laminator. The feeding to and from the printers and laminators are carried out manually. Further, the material is moved to and from the printer at different times than the material to and from the laminator.

The printer and the laminator are separated from each other by a brick-wall. The organizational structure is that different teams work at the prints and laminators. These teams work different shifts during the year.

### 4.3.1. Printer

The current max speed of the printer is 600 m/min and for the month covered in this study the average speed was 463.74 m/min. The printer is built up of seven printing stations where a different color is loaded in each section. Not all seven sections are necessary to use in every order – this depends on the complexity and quality of the print, hence if it is a Flexo Print, Flexo Process, Offset or Metallised. Also depending on what type of print, if it is a photographic print or a regular print the speed is decided. A print that covers the whole paper cannot be printed at full speed due to there will be no time for the print to cool down – though theoretically it should not be necessary. Further, the last roll in each order is printed at a lower speed.

During August 2009 the manned hours in the printer were 440, the utilized hours 399 and the run time 244 hours. The quality interchange was 98 %.

Before each order a dummy-roll is printed in order to get the correct color tone. A lot of time it is orders of just one paper roll and the length of this roll can vary from 4000 to 6000 meters. An idea developed in Lund is to put setup material on the paper roll containing the print paper in order to avoid/lowering the setup time, hence the machines does not have to be loaded with a dummy-roll.

#### *4.3.1.1. Production feedback*

There are different codes that are used to describe different events that occur in the printer. These events are reported automatically to a database where technicians later can analyze the production data. The production data recorded in the database are among other things setup, Planned and Unplanned stop data.

**Setup**

Setups are carried out each time a new order is to be processed, but not all setups are needed for each order. There are seven different setups:

- 12-01 – Sleeve change
  This setup is carried out every time there is a different order being processed, and it is the clichés that defines the moisture of the print.
- 12-02 – Sleeve and Anilox change
  The Anilox setup is carried out every time there is a change in the print method, hence a change from Flexo Process to Offset will lead to an Anilox change.
- 12-03 – Creasing tool change
  The Creasing tool setup is carried out every time there is a change in the package system, volume, size or shape.
- 12-04 – Anilox and Creasing tool change
  This setup is used when both an Anilox and a Creasing tool is changed at the same time.
- 12-05 – Width and Creasing tool change
  The setup is used when the size of the package is changed. Though, this code should not be used since there is no need to stop the machine when carrying out this setup. This is due to the width change is mostly carried out as a flying setup. For this reason the setup 12-05 will be used together with setup 12-03 and from now on called setup 12-03.

- 12-06 – Sleeve and Chamber change
  Normally the Chamber change is carried out during a planned stop of one hour each morning, but when there's no time for the planned stop it is coded as a 12-06 setup.
- 12-07 – Start up
  This setup is used when the printer is started again after a longer stop. For example in August 2009 this code was used after a holiday but also after a preventive maintenance.

In August 2009 the amount of setups, total time and average time in the printer is seen in table 4.3.

Table 4.3. Setup for the printer

| Setup | Frequency | Total time (h) | Avg (min) |
|---|---|---|---|
| 12-01 | 266 | 42.62 | 11.12 |
| 12-02 | 9 | 5.64 | 33.84 |
| 12-03 | 22 | 8.39 | 22.88 |
| 12-04 | 13 | 7.16 | 33.05 |
| 12-05 | 30 | 13.81 | 27.62 |
| 12-06 | 5 | 1.12 | 13.44 |
| 12-07 | 6 | 1.43 | 14.3 |
| **Sum** | 316 | 80.17 | |

**Planned stop**

During the month the study covers there were a total of 33 planned stops. The frequency, total and average time per type of planned stop can be seen in table 4.4, where the planned stop 17 is a Shift End stop. This stop is used at the end of one shift and when there is following shift planned, for example the end of one working week. The event code 17 is also used when D&E – Development and Engineering – runs tests in the printer. The event code 28 is used when a planned maintenance is carried out. There are two types of planned maintenance for the printer; one carried out daily during the first shift and it takes approximately one hour, the other one is a longer maintenance stop that is carried out once a week and it takes a whole shift. Event code 31 is a Force Majeure stop. This code is used when there is a stop in the printer due to reasons out of control as for example fire or electricity cut.

Table 4.4. Planned stops for printer

| Planned Stop | Frequency | Total time (h) | Avg (h) |
|---|---|---|---|
| 17 | 13 | 230.07 | 17.70 |
| 28 | 19 | 38.03 | 2.00 |
| 31 | 1 | 2.45 | |
| **Sum** | 33 | 270.55 | |

There are other planned stops that did not occur during August 2009; stop 29 which is a planned stop event code and 30 which is used for stop related to education.

**Unplanned stop**

During August 2009 there were a grand total of 137 unplanned stops. In table 4.5 the frequency, total time and the average time per unplanned stop is presented. Unplanned stop 21 is a repair stop. This event code is used when the printer is out of function due to mechanical or electrical failure and personnel from the technical-division is called to repair the failure. Event code 23 is used when there is lack of resources as for example lack of personnel at the printer or lack of material. Event code 25 is used when there is need for approval as for example when a new creasing tool is being tested or when there is a need for approval from the customer or design department. Event code 26 is used when there is a short stop in the production.

Table 4.5. Unplanned stops for printer

| Unplanned Stop | Frequency | Total time (h) | Avg (h) |
|---|---|---|---|
| 21 | 12 | 34.36 | 2.86 |
| 23 | 15 | 9.23 | 0.62 |
| 25 | 26 | 5.34 | 0.21 |
| 26 | 84 | 20.50 | 0.24 |
| **Sum** | 137 | 69.43 | |

There is one more event code for the printer that was not used during August 2009; event code 27 which is used during cleaning. Thus, all the cleaning that is carried out in the printer is coded as a planned maintenance.

### 4.3.2. Laminator

The current max speed of the laminator is 500 m/min and for the month covered in this study the average speed was 483.56 m/min. The laminator consists of different stations and depending on the amount of layers and the width of the paper different setups are needed. Orders are processed so that the similar orders are processed after each other, for example orders with same width are produced after each other and if there is a new order with a different width the production is planned such that the width change is not so big that a width change setup is needed, thus the setup can be carried out as a flying setup. Also of interest is the different layers that the material constitutes of, for example packaging material for milk are all produced after each other and when the production is switched to producing packaging material for tomato juice a setup is needed. Hence, the production planner tries to place orders with similar width and amount of layers after each other.

During August 2009 the manned hours in the laminator were 626, the utilized hours 553 and the run time 445 hours. The quality interchange was 98.9 %.

#### *4.3.2.1. Production feedback*

The production feedback that is automatically reported to the database is the same for the planned and unplanned stop, however the setups are different.

**Setup**

The setups for the laminator are different from the ones in the printer. But as for the printer some are carried out more frequently than others.

- 12-01 – Heating
  Setup used during the start up of the laminator. During August this code was used two times where both of the times it was due to lack of orders.
- 12-03 – Width change – From Wide to Narrow
  Setup used when the width of the material changes from wide to narrow.
- 12-04 – Width change – From Narrow to Wide
  Setup used when the width of the material is changed from narrow to wide.
- 12-05 – Grammage Change
  Setup used when there is a change in the grammage of the material.
- 12-06 – Specification Change – Adhesive
  Setup used when there is a change in the adhesive polymer.
- 12-07 – Lami Material setup
  Setup used when there is a start of lami material production.
- 12-09 – PLH setup
  Setup used when there is a start and end of a PLH production.
- 12-11 – Specification Change – 2nd Inside
  Setup used when there is a start of K/R film production.

In table 4.6 all of the setups carried out during the month the study covers are presented ordered after setup type.

Table 4.6. Setup for the laminator

| Setup | Frequency | Total time (h) | Avg (h) |
|---|---|---|---|
| 12-01 | 2 | 0.13 | 0.65 |
| 12-03 | 20 | 10.52 | 0.46 |
| 12-04 | 13 | 11.30 | 0.87 |
| 12-05 | 17 | 2.51 | 0.15 |
| 12-06 | 8 | 2.38 | 0.30 |
| 12-07 | 1 | 0.21 | |
| 12-09 | 5 | 4.99 | 1.00 |
| 12-11 | 2 | 0.55 | 0.28 |
| **Sum** | 68 | 32.59 | |

The setups that occur most frequently are the change from narrow to wide, wide to narrow and the grammage change. This is consistent with the production cycle for the laminator; these setups are the ones used most frequently and hence the importance to reduce the amount of setup needed.

**Planned stop**

The event codes for the planned stops in the laminator are the same as the ones for the printer. Event code 17 stands for shift end, 28 for planned maintenance and 31 is used when a force majeure has occurred. Event code 29 is used when there is a planned stop, which in the case of the laminator is when there is lack of orders. Table 4.7 shows the planned stop for August 2009.

Table 4.7. Planned stops for the laminator

| Planned Stop | Frequency | Total time (h) | Avg (h) |
|---|---|---|---|
| 17 | 6 | 100.82 | 16.81 |
| 28 | 3 | 12.52 | 4.17 |
| 29 | 1 | 55.98 | 55.98 |
| 31 | 4 | 4.57 | 1.14 |
| **Sum** | 14 | 173.89 | |

**Unplanned stop**

The event codes for the unplanned stops in the laminator are the same as the ones for the printer. Event code 21 stands for repair, 23 for lack of resources, 25 for waiting for approval and 26 is used when a short stop has occurred. Table 4.8 shows the unplanned stops for the laminator during August 2009.

Table 4.8. Unplanned stops for the laminator

| Unplanned Stop | Frequency | Total time (h) | Avg (h) |
|---|---|---|---|
| 21 | 10 | 11.26 | 1.13 |
| 23 | 2 | 10.52 | 5.26 |
| 25 | 1 | 1.37 | |
| 26 | 111 | 51.31 | 0.46 |
| **Sum** | 124 | 74.46 | |

## 4.4. Variance

Values of variance were taken for setup 12-01 and 12-03 in the printer. These values constituted of all the setups 12-01 and 12-03 carried in August 2009 ordered in groups of 5. Thus, the first five setups 12-01 constitutes sample group 1 and sample group 2 constitutes of the following five setups and so on. Setup 12-03 follows the same pattern and can be found in Appendix 3 together with the sample groups for setup 12-01.

For setup 12-01 there is a limit of 12 min when carrying out a setup of one sleeve change + change of 2 colors. When it takes more than 12 minutes it is recorded and analyzed. For setup 12-03 there is no such limit.

# 5. Analysis

## 5.1. The production

The production is a *batch production* type where each batch is one order and the orders vary from 4000 up to 90000 meters. The production layout is a *Line production layout,* where the production starts with a printer and following is a laminator. Due to there is an inventory between the two machines the line can further be categorized as a *rate based assembly line.*

## 5.2. Materials Flow and Lead time analysis

The printer and the laminator are, due to the materials flow, visually and organizational structure, disconnected from each other. The materials from the printer are moved to an inventory that is physically disconnected with the production and the two machines are disconnected visually by a brick wall. Further the organizational structure is such that different teams work different shifts at the laminator and printer. This has made the production line to be disconnected. The theoretical cycle time for the printer is 600 m/min and for the laminator 500 m/min and the lead time for an A-type order is 2 weeks while the lead time for a B-type order is 3 weeks, hence the passive time is much larger than the active time.

## 5.3. Production line

The production line is a *multiple step production line* where it is partly mechanized due to the material being loaded manually. Further the materials are moved independently of each other thus it is an asynchronous line.

Effort has earlier been made on connecting the printer and laminator to get a streamline flow, that is moving the material directly from the printer to the laminator. This was not successful due to the production layout and the fact that the printer had a maximum speed for 400 m/min while the laminator was operating at 500 m/min.

### 5.3.1. Printer

The TAK-value for August 2009 is calculated according to equation 5:

$$n_{max} = 720\ h * 36000\ m/h = 25\ 920\ 000\ m$$

$$T = \frac{244}{440} = 0.5545$$
$$A = \frac{29385}{36000} = 0.816$$
$$K = 98\ \%$$

This yields a TAK-value of 25 920 000 * 0.5545 * 0.816 * 0.98 = 11 493 512.76 m. Thus the maximum amount of packaging material that the printer can produce is roughly 11 500 km. In order to increase the capacity either the availability or the facility utilization, or both, should be improved. If for example the run speed would be increased to 31 000 m/h this would yield a facility utilization of 86 %, which ultimately give a max production of roughly 12 200 km.

### 5.3.2. Laminator

The TAK-value for the laminator in August 2009 can be calculated as:

$$n_{max} = 720 * 30000\ m/h = 21\ 600\ 000$$
$$T = \frac{445}{626} = 0.711$$
$$A = \frac{28169}{30000} = 0.933$$
$$K = 98.9\ \%$$

This yields a TAK-value for the laminator of 21 600 000 * 0.711 * 0.933 * 0.989 = 14 171 025.75 m. Thus, the maximum amount of packaging material that the laminator can produce is roughly 14 200 km.

## 5.4. Input Analysis

In order for a simulation to be valid it is necessary to make a thorough input analysis. For the purpose of this thesis the input analysis was made in Excel where empirical and theoretical distribution functions where plotted. A Kolmogorov-Smirnov test was later made in order to see if the chosen distribution was the proper one. Further, the input data was checked for autocorrelation due to the assumption that the data is IID – Identical Independent Distributed. For validity the same test was carried out using the software Stat::Fit.

Following is two examples of the input analysis, one for the time setup 12-01 takes and one for the amount of downtime of the unplanned stop 26 in the printer P14. The result of the input analysis for the rest of the input data can be seen in Appendix 4.

**Setup 12-01**

The data for the setup 12-01 constitutes of 266 data points. The autocorrelation plot, which can be seen in figure 5.1, shows that the data for the setup 12-01 is not correlated.

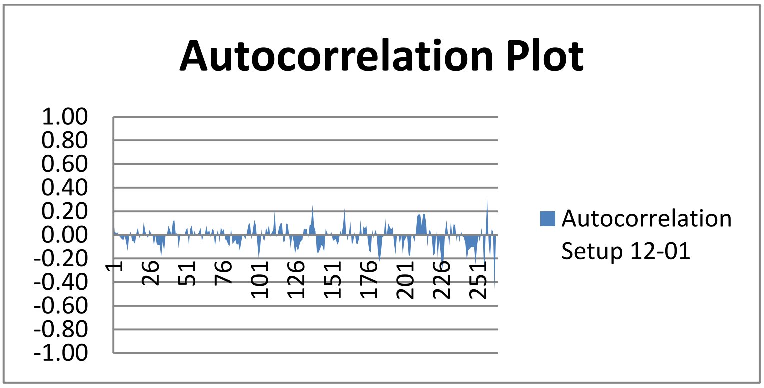

Figure 5.1. Autocorrelation plot for setup 12-01

Further, given the fact that the closer to the end of the data series one gets the less accurate is the calculated autocorrelation. It is therefore of interest only to look at the start of the data series, which in the case of setup 12-01 shows that the data has correlation values lower than 0.20 and therefore is not autocorrelated.

Once the autocorrelation could be ruled out the empirical distribution function was plotted. A theoretical distribution function was assumed – for this setup the assumed distribution function was chosen to be the lognormal distribution. Figure 5.2 shows the empirical and the assumed theoretical distribution function.

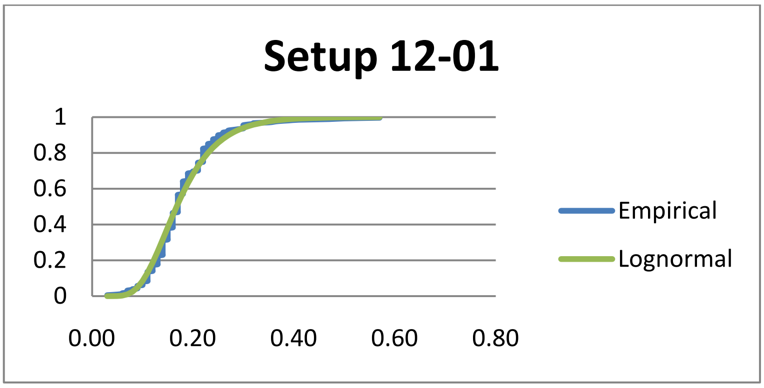

Figure 5.2. Empirical and Theoretical distribution functions for setup 12-01

In table 5.1 data for setup 12-01 can be found. The total time that the setup 12-01 was carried out during August 2009 was 47.76 hours with an average of 10.77 minutes. The setup was carried out 266 times and the standard deviation was 4.19 minutes.

Table 5.1. Statistics for setup 12-01

| **Total(h)** | **Avg(min)** | **Frequency** | **Standard deviation** |
|---|---|---|---|
| 47.76 | 10.77 | 266 | 4.189711168 |

The chosen distribution function was tested with a Kolmogorov-Smirnov test. Table 5.2 shows the result of the KS-test.

Table 5.2. KS-Test for setup 12-01

| **KS-Test** | | | | **Reject** |
|---|---|---|---|---|
| D+ | D- | D=max{D+,D-} | KS Value for $D_{0.05}$ | |
| 0.065343873 | 0.0909252 | 0.090925242 | 0.08338695 | |

The KS-test rejects the hypothesis that the setup 12-01 is lognormal distributed. But, the D level is 0.091 which is fairly close to the critical KS-value of 0.084 for a 95 % confidence.

Thus, running the data series in Stat::Fit the hypothesis of setup 12-01 being lognormal distributed is accepted by the KS-test and the Anderson-Darling test. Given the fairly good fit in figure 8, the fact that an Anderson-Darling test accepts the hypothesis and the knowledge that the KS-test is sensitive when having large data series, the hypothesis that the setup 12-01 is lognormal distributed is accepted.

### Unplanned stop 26 in P14

The data for the unplanned stop 26 in the printer P14 constitutes of 84 data points. In figure 5.3 the autocorrelation plot for the unplanned stop 26 is shown.

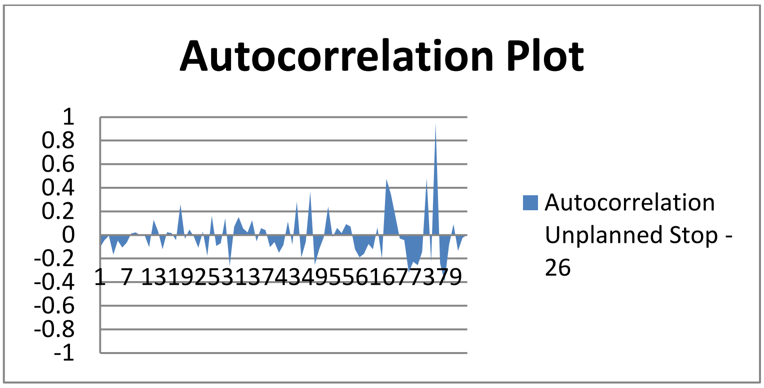

Figure 5.3. Autocorrelation plot for the unplanned stop 26 in the printer P14

The plot shows that for the length of 1/5 of the data series the highest value is roughly 0.20 but for values close to the end of the data series the highest value is close to 1 thus it is clearly autocorrelated at the end of the data series. But, given the fact that Stat::Fit only calculates autocorrelation up to 1/5 of the length of the data series and the fact that the closer to the end of the data series the less accurate is the autocorrelation calculation it is feasible to conclude that the input data for the unplanned stop 26 in the printer P14 is not autocorrelated.

Figure 5.4 shows the empirical and the assumed theoretical distribution function for the unplanned stop 26 in the printer P14.

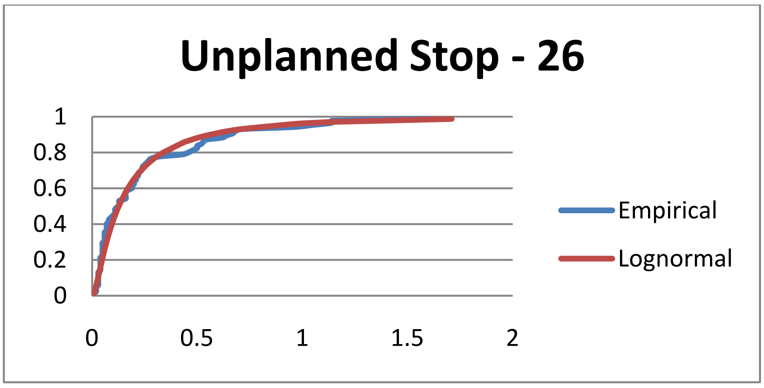

Figure 5.4. Empirical and theoretical distribution functions for the unplanned stop 26 in the printer P14

Table 5.3 shows statistics for the unplanned stop 26. The total amount of downtime was 20.50 hours in August 2009, the average downtime 14.64 minutes and the standard deviation 18.57 minutes.

Table 5.3. Statistics for unplanned stop 26 in the printer

| Total(h) | Avg(min) | Frequency | St. Deviation |
|---|---|---|---|
| 20.50 | 14.64 | 84 | 18.569571468 |

The KS-test for the unplanned stop 26 in the printer P14 accepts the hypothesis that the downtime is lognormal distributed, which can be seen in table 5.4.

Table 5.4. KS-test for unplanned stop 26 in the printer P14

| KS Test | | | | |
|---|---|---|---|---|
| D+ | D- | D=max{D+,D-} | $D_{0.05}$ | **Accept** |
| 0.097046598 | 0.078170396 | 0.097046598 | 0.148388165 | |

The D-level is 0.097 where as the critical KS-value for a 95 % confidence is 0.148, thus the hypothesis should be accepted. This is also confirmed by a Chi-square test made in Stat::Fit.

## 5.5. Variance Analysis

For each of the sample groups for the setup 12-01 and 12-03 the sample mean, standard deviation and range were calculated using the values of all of the setup 12-01 and 12-03 during August 2009, see table 5.5.

Table 5.5. Mean, Range and standard deviation values for the setups 12-01 and 12-03+12-05

| | 12-01 | 12-03 |
|---|---|---|
| Mean | 0.18 | 0.4 |
| Range | 0.14 | 0.38 |
| Standard deviation | 0.057 | 0.152 |

Below follows the analysis for the setup 12-01. The result of the analysis for setup 12-03 can be found in Appendix 5. For this analysis it is important to note that the upper tolerance limit for setup 12-01 is only for a setup of one sleeve change + two colors. For the setup 12-03 no such upper tolerance limit exists, thus in this analysis it is assumed to be equal to the mean of the values during August 2009.

**Setup 12-01**

The UCL, CL and LCL for the Mean Chart are calculated according to equations 21 and 22.

$$UCL = 0.180 + 3\frac{0.057}{\sqrt{5}} = 0.260$$
$$CL = 0.180$$
$$LCL = 0.180 - 3\frac{0.057}{\sqrt{n}} = 0.104$$

The upper tolerance limit is set to 0.2 hours, according to the limit where the setups 12-01 are recorded.

From the Mean Chart, see figure 5.5, we can see that there are 3 values close to the UCL and 3 values close to the LCL. There are 11 values above the upper tolerance limit and the sample mean varies from below 0.1 up to 0.25 hours. For the sample means around sample number 7 there is a trend of decreasing mean down to 0.1 hours where something is changed and the following sample mean is 0.25 hours. A similar pattern can be seen for the sample means around sample number 35.

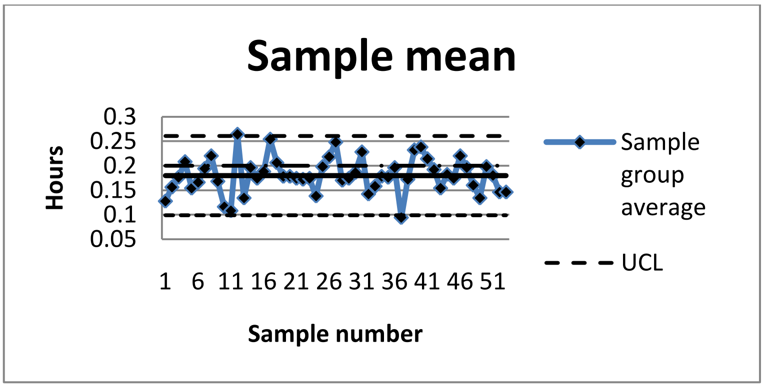

Figure 5.5. Sample mean chart for setup 12-01

A feasible reason for the 11 values above the tolerance limit is that this limit is set to the limit of 0.2 hours where setups 12-01 are recorded and analyzed. This limit is for setup with one sleeve change + 2 colors, thus the ones above might be setups with more color changes. When it comes to the patterns around sample number 7 and 35 a deeper analysis should be made.

For the Range Chart the UCL, LC and LCL are calculated according to equations 28, 29 and 26.

$$UCL = 2.11 * 0.14 = 0.298$$
$$CL = 0.14$$
$$LCL = 0 * 0.14 = 0$$

From the Range Chart in figure 5.6 we can see that there are 5 values above the upper control limit.

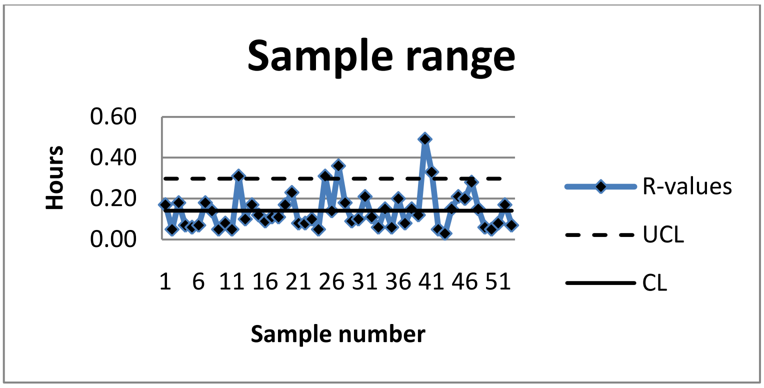

Figure 5.6. Sample Range chart for setup 12-01

For the process the $C_p$ and $C_{pk}$ values are calculated accordingly to equations 30 and 31, yielding a value of 0.477 for $C_p$ and 0.048 for $C_{pk}$. Thus, the $C_p$ value is not close to the recommended value of 1.33 and even more from the value of 2.0 that the process should have according to the Sig Sigma program.

**Variance and Mean reduction to Six Sigma level**

As stated above, a process capability according to a Six Sigma level requires a $C_p$ of 2.0. With this value as a target the standard deviation is solved from equation 30, where the upper tolerance limit is set to 0.2 hours.

The first reduction is only a variance reduction thus the mean is the same, 0.18 hours, but the standard deviation is $\sigma = 0.0167$ hours. The second reduction is a mean reduction, under the assumption that a variance reduction in a program of Six Sigma would ultimately also give a mean reduction due to no process values above the upper tolerance level would be accepted. Thus, for the mean reduction all values above the upper tolerance level was set to the value of the tolerance level, 0.2 hours. This mean reduction yielded a new mean of $\mu = 0.159$ hours.

With the new standard deviation and mean the function Random Number Generator in Excel was used to create a normal distributed series of 266 data points with $\sigma = 0.0167$and $\mu = 0.159$. The normal distribution was chosen due to that Excel does not generate random numbers following a lognormal distribution, and given the *Central Limit Theorem* the assumption of normal distribution is considered to be acceptable.

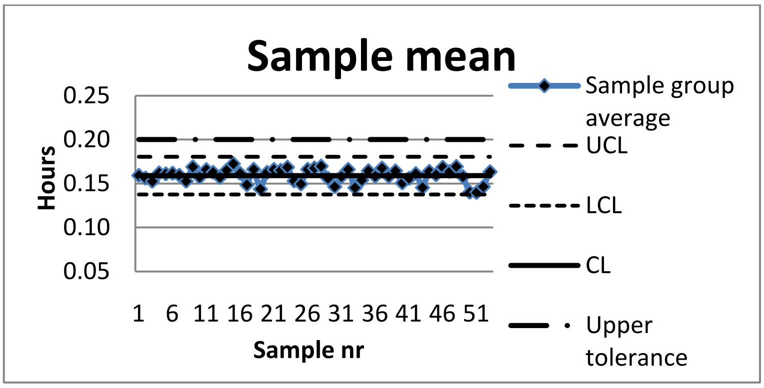

Figure 5.7. Mean Chart using Six Sigma levels for process capability

From figure 5.7 it can be seen that the sample values are centered around the central limit and none is above the upper control limit or below the lower control limit. Further the distance from the UCL to the LCL is lowered. Given the new mean and standard deviation none of the sample values are close to the upper tolerance limit.

From the Range Chart, see figure 5.8, it can be seen that the range of the sample values is decreased and below the upper control limit.

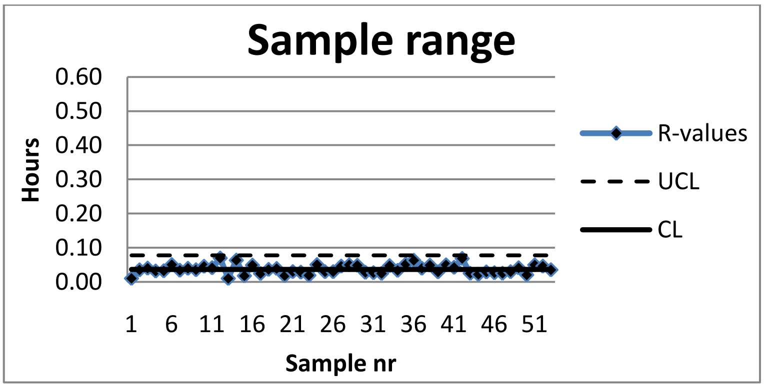

Figure 5.8. Range Chart using Six Sigma levels for process capability

The above analysis is made under the assumption of the setup 12-01 following process capability values used in a Six Sigma program. These values are considered to be extremely hard to achieve due to the high requirements on the process, hence this analysis should only be seen as a feasible scenario of an idealized process.

# 6. Simulating the production

## 6.1. Simulation models

A simulation model, in this study called the current model, of the production line as it is today has been developed. The production line in the current model consists of two printers, P12 and P14, and one laminator, P22, with an inventory between the printers and the laminator. After a satisfactory model of the real production line has been developed certain modifications will be made to the model where different sets of parameters and objects in the simulation model are removed or modified. Afterwards, a new model will be developed consisting of one printer, the P14, and one laminator, the P22. Thus, the printer P12 has been removed from the model. This model, in this study called the basic model, will be the base model throughout the study and different scenarios will be tested and evaluated based on this model.

Based on the modifications made in the model various scenarios are developed and modeled for the production line. These scenarios have then been tested by running the models at the maximum amount of production runs possible in the software used. The simulation software used in this study is the discrete-event simulation software, Simul8 Educational Edition. The maximum amount of production runs that can be made in this edition of Simul8 is 30 000 runs, each run with a new set of random variables. The data used in the model is the data that has been collected and previously presented in chapter 4.3.

In table 6.1 all input data that has been collected for the printers and laminator has been summarized. The data that is not used in the model has been marked with an *.

Table 6.1. Input Data

| **Order Size** [P12, P14, P22] | **Run Speed** [P12, P14, P22] |
|---|---|
| **Setups**<br>**P14**<br>12 – 01 Sleeve change<br>12 – 02 Sleeve and Anilox change<br>12 – 03 Creasing tool change<br>12 – 04 Anilox and Creasing tool change<br>12 – 05 Width and Creasing tool change | **P22**<br>12 – 01 Heating*<br>12 – 03 Width change – From Wide to Narrow<br>12 – 04 Width change – From Narrow to Wide<br>12 – 05 Grammage Change<br>12 – 06 Specification Change – Adhesive* |

| | |
|---|---|
| 12 – 06 Sleeve and Chamber change*<br>12 – 07 Start up* | 12 – 07 Lami Material SETUP*<br>12 – 09 PLH SETUP*<br>12 – 11 Specification Change – 2nd Inside* |
| **Stops**<br>**P12, P14 & P22**<br>**Planned**<br>17 Non working time<br>28 Maintenance time<br>29 No orders time*<br>30 Education time*<br>31 Force Majeure time | **Unplanned**<br>21 Repair time<br>22 Speed loss time*<br>23 Lack of Resources time<br>25 Waiting for Approval time<br>26 Short stop time<br>27 Cleaning time |

The clock properties of the model are as follows; the model runs for 24 hours a day 7 days a week for 4 weeks, yielding a simulation run for a period of 40 320 minutes. The clock properties are the same for all models and have not been modified through the study.

In figure 6.1, a snapshot of the current model developed for the production line as it is today is shown.

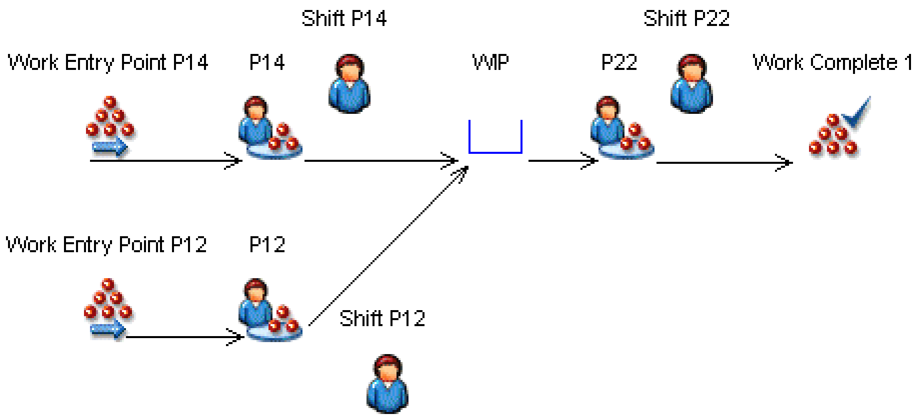

Figure 6.1. Current Model in Simul8

A work item in the simulation models will be represented as being a production order. Every order will receive a couple of attributes, in Simul8 called *labels*, as it enters the simulation model. In Simul8 every work item enters the model through a *work entry point*. In this model there are two work entry points, one for P12 (Work Entry Point P12) and one for P14 (Work Entry Point P14). As an order (*work item*) enters the simulation through Work Entry Point P14 it will receive a value for every label attached to it. The two labels, lbl Anilox and lbl Tool, are used in the model to control the setups that occur in P14. One setup in the model, setup 12-01, occurs every time a new order enters P14. However, the setups 12-02, 12-03, 12-04 and 12-05 are dependent on the materials input. To control these setups the labels, lbl Anilox and lbl Tool are used. The logic is that; if there is any change in the value of lbl Anilox or lbl Tool between the order currently being processed in P14 and the following order waiting to be processed then there will be a setup depending on which label (lbl Anilox or lbl Tool) that changes value. When an order enters P14 its label values are saved in two temporary global variables. As the next order enters P14 the temporary global variables, representing the values of the last order, are compared with the next orders label values. If there are any changes in label values then it will lead to a setup. If the value for lbl Anilox is different between two consecutive orders then this will lead to the setup 12-02. If the value for lbl Tool is different between two consecutive orders then the setup 12-03 will occur. Finally, if both values of the two labels lbl Anilox and lbl Tool are different between two consecutive orders the setup 12-04 will occur. The values for the labels that every order receives entering the simulation model will be taken from imported data of the materials input from Excel representing the actual materials input into P14 during the period of this study, August 2009.

The third label that every order receives as it enters through Work Entry Point P14 is lbl Size, representing the size of the order expressed in meters. The value this label receives follows a distribution and is an input into the model. Orders that enter Work Entry Point P12, receive only one label, lbl Size. Although there are different setups that occur in P12, depending on the attributes of the order, they have been modeled as leading to the same average setup time.

The work entry points are set to unlimited arrivals, this means that when P12 and P14 are working and available they will always have orders to take from.

There are three *work centers* in the model representing the three machines in the production line, P12, P14 and P22. Every machine has a resource attached to it that restricts the work center from working certain times during the week.

- P12 is restricted to working during the time Mon 06:00 – Fri 23:00, every week, which means that it is manned during 452h (27 120min) of the totally 672h (40 320min) that the simulation is run. This represents 56.5 shifts (1shift = 8h) during the four weeks that the simulation is run.

- P14 is restricted to working during the time Mon 06:00 – Fri 20:00, every week, which means that it is manned during 440h (26 400min) of the total result collection period. This represents a total of 55 shifts.
- P22 is restricted to working during the time from Wed 04:00, the first week, to the end of the simulation time. It is manned during totally 626h (37 560min) of the total result collection period. This represents a total of 78.25 shifts.

The amount of time that every order spends in the work centers P12, P14 and P22, the process time, is in this model calculated by dividing the order size with the machine speed. The machine speed follows a distribution and is an input into the model and the order size, as discussed earlier, is determined as an order enters the model (lbl Size).

Every work center has certain characteristics that define the work center; one of them being the efficiency of the work center. The efficiency depends on the stops or breakdowns that occur in the work center. In every work center the stops that happened during August 2009 are included to happen either planned or randomly. There are two inputs that define every stop, one is *Mean Down Time (MDT)* and the other one is *Mean Time Between Failure (MTBF)*. The input values and the followed distributions for the stops that occurred during the studied period for P12, P14 and P22 can be seen in Appendix 6. The MDT for the unplanned stops was analyzed according to the input analysis in chapter 5.4. The MTBF was assumed to be exponential distributed for all the unplanned stops except the short stops coded with event code 26 that were analyzed accordingly to chapter 5.4. This is due to that no data was available but for event code 26. The MTBF for the other unplanned stops were taken from the report *101 Feedback,* which is a report that is automatically generated by the information system used in the packaging company.

When an order has finished processing in P12 or P14 it arrives to a storage area, called WIP, representing the inventory between the printers and the laminator. P22 takes orders from the WIP as the inventory fills up. Before entering the P22 every order receive two labels attached to it, lbl Type and lbl Width, which control the setups that occur in P22. The values for these two labels will be set in the model by importing data of the materials input from Excel representing the actual materials input into P22 during the period of this study, August 2009. The logic behind the setups is the same as for P14. If the value of lbl Width is different between two consecutive orders then either setup 12-03 or 12-04 will occur depending on if there is a change in width from wide to narrow or from narrow to wide.

When the work item, in this model being an order, leaves the laminator it leaves the work center and arrives to the object Work Complete where it departs from the model.

In figure 6.2, a snapshot of the basic model developed for the production line is shown. The changes in this model is that P12 is removed, and also the resources that restrict P14 and P22 from working continuously 24 hours a day during the simulation period is removed. Except from that, the base model is the same as the current model. The different scenarios will be tested and evaluated by starting from this base model and modifying various parameters.

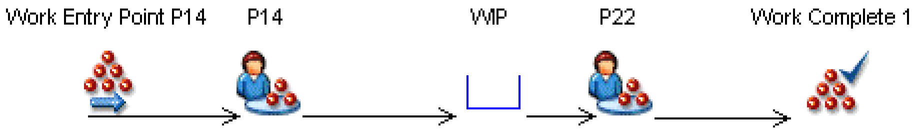

Figure 6.2. Balanced model, "1 to 1"

In table 6.2 all model properties have been summarized.

Table 6.2. Model properties

| **Model properties** | |
|---|---|
| **Clock Properties** = 7 days/week, 00:00 – 24:00 | **Result Collection** = 40320 minutes |
| **Simulation objects**<br>**Work Entry Point Objects**<br>Work Entry Point P12<br>Work Entry Point P14<br><br>**Work Center Objects**<br>P12<br>P14<br>P22<br><br>**Resources**<br>Shift P12<br>Shift P14<br>Shift P22<br><br>**Storage Area Objects**<br>WIP | **Work Complete Objects**<br>Work Complete 1<br><br>**Work Item type**<br>1 order<br><br>**Labels**<br>lbl Anilox<br>lbl Size<br>lbl Tool<br>lbl Type<br>lbl Width |

## 6.2. Scenarios

**Scenario 1**

The first scenario is the basic model, modeled as described earlier. Thus, the basic model represents a continuous production, meaning that both machines, P14 and P22, run continuously during the whole time the simulation is run and are manned 24 hours a day, 7 days a week for 4 weeks.

**Scenario 2**

The parameter changed in scenario 2 compared to scenario 1 is that the average run speed for the machine P14 is changed to a higher value. This value is 519.43 m/min and was chosen after a benchmark with the run speed in another facility with similar complexity as the facility studied in this thesis. It follows the same type of distribution. The old value and the new value for the average speed can be seen in table 6.3.

Table 6.3. Old and new Run speed values

| | Machine Run speed (m/min) | | |
|---|---|---|---|
| | **Distribution Type** | **Average** | **Standard deviation** |
| Old value | Normal | 463.74 | 75.10 |
| New value | Normal | 519.43 | 75.10 |

**Scenario 3**

The parameter changed in scenario 3 compared to scenario 1 is that the variation (standard deviation) and average for setup 12 – 01 and 12 – 03 in P14 have been reduced according to the analysis in chapter 5.5. The old values and the new values for the setups can be seen in table 6.4.

Table 6.4. Old and new values for setup 12-01 and setup 12-03

| | Setup (min) | | |
|---|---|---|---|
| | **Distribution Type** | **Average** | **Standard deviation** |
| **12-01** | | | |
| Old value | Lognormal | 10.77 | 4.19 |
| New value | Lognormal | 9.60 | 1 |
| **12-03** | | | |
| Old value | Lognormal | 23.96 | 11.13 |
| New value | Lognormal | 20.40 | 2 |

**Scenario 4**

The parameter changed in scenario 4 compared to scenario 1 is that the stops 23 Lack of Resources time, 25 Waiting for Approval time, 27 Cleaning time and 31 Force Majeure time are removed from the model for both work centers P14 and P22.

**Scenario 5**

Scenario 5 is a scenario containing all modifications made in scenario 2-4.

## 6.3. Results of simulation

The complete results of every simulation run can be seen in Appendix 7. In table 6.5 the output for the different simulation runs for every scenario are summarized. Every scenario has been tested by running a trial of 30 000 production runs, each run with new random numbers.

Table 6.5. Results of simulation runs

| Scenario | Average Output (m) |
|---|---|
| Current model | 12 148 883 |
| Scenario 1 | 9 779 155 |
| Scenario 2 | 10 548 469 |
| Scenario 3 | 10 015 165 |
| Scenario 4 | 10 119 275 |
| Scenario 5 | 11 219 763 |

The scenarios one through five are to be seen as possible areas of improvement and are not intended to be a final solution. The result of scenario five yields an output of 11 219 763 meters, which is approximately 900 000 meters less than the current model and thus the improvements suggested and simulated are not enough to compensate for the removal of one of the printers.

In these simulations there was no inventory control when the machines were run together - for example a feasible simulation could be to lower the speed in the laminator when there is a stop in the printer. This yielded a low inventory level but also a high time of waiting for materials in the laminator. Thus, the simulations could be improved by controlling the machines so that they are ran together, i.e. having a continuous production that does not generate a waiting time in the printer and has a stable level of buffer.

# 7. Discussion and conclusions of simulations

From the simulations it can be concluded that by improving different parameters the total output of the production line, consisting of the printer P14 and the laminator P22, can be increased. However, these improvements are not sufficient enough to compensate for the output loss resulting from removing the printer P12.

For some of the data there are few data points, thus the validity of the input analysis and ultimately the validity of the model could be increased by extending the analysis to cover a longer period and by that increasing the amount of data points for this data. Further, in this model the run speed for the machines when producing an order was modeled as a fixed value for the whole order. However, the run speed for the printer follows a normal distribution while the run speed in the laminator was taken as an average. By this, the variation of run speed in the model is an input to the model and not a result of for example ramping during the production.

For the laminator the setups 12-06, 12-07, 12-09 and 12-11 were not included in the models because there were few data points available and there were no clear connection between these setups and the attributes of an order.

**Current Model**

The simulation of the current model could be improved by making an input analysis on the printer P12. The data for the printer P12 was taken from the MTBF and MDT report that is automatically generated by the database used in the packaging company. The distributions for the down time of the setups, planned and unplanned stops were assumed to be average while the mean time between failure is assumed to be exponential distributed. The output though is fairly close to the real output in August 2009.

**Scenario 1**

The output for this model is approximately 9 800 km. For the printer P14 this is an increase of 2 700 km, and is achieved by increasing the availability for the machine. In this scenario the availability is 672 hours in both the printer and the laminator. This is equivalent to 84 shifts á 8 hours per shift. Note that a month has 720 hours, thus by increasing the availability to 720 hours one would cover a whole month of production.

**Scenario 2**
The TAK-calculation shows that the maximum output the printer can produce is 11 500 km. By increasing the speed the theoretical maximum output is increased to 12 200 km. The simulation done with an increase in speed, scenario 2, gives a total output of 10 500 km. The difference is due to the TAK-value is calculated with an maximum available time during a month, 720 hours, while the simulated scenario was carried out with an available time of 672 hours.

The run speed was benchmarked with a facility of the same complexity as the one covered in this study, thus reaching a run speed for 519 m/min should not be hard to achieve.

**Scenario 3**
By reducing the variation and mean time of setup 12-01 and 12-03 it was possible to increase the output from 9 800 km to 10 000 km. The reduction of variation was under the assumption of Six Sigma levels on the variation, a level which is considered to be tough to achieve. This scenario should be seen as a model of the idealized setup.

**Scenario 4**
By removing the stops 23, 25, 27 and 31 the output was increased to 10 100 km. It can be discussed whether or not these stops can be prevented. The scenario is to give an idea of what these stops mean in loss of production.

**Scenario 5**
Simulation scenarios one through five yields an output of 11 200 km. It can be discussed if scenarios one through five are achievable but the idea of this simulation is to show what can be achieved by making these changes and what is needed to do in order to increase the output of a production line consisting of one printer and one laminator.

## 7.1. Further possibilities

**Inventory control**
The simulations that were done were simulated without inventory control. In these simulations the buffer between the printer and the laminator was not controlled, no maximum or minimum level of the inventory was modeled. Without any inventory control there will be a large amount of waiting time in the laminator due to the reason that there is no material available in inventory, see figure 7.1.

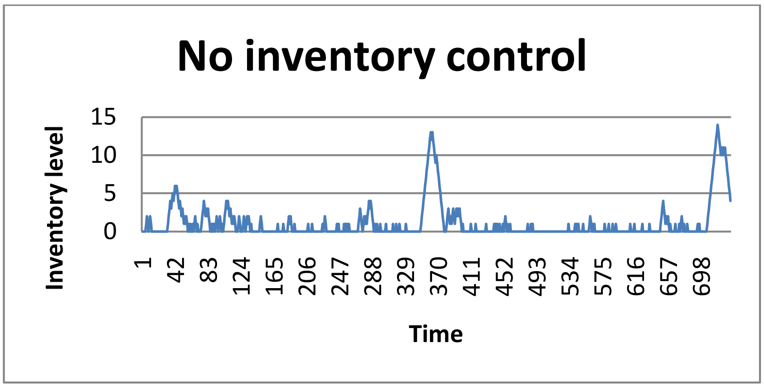

Figure 7.1. Inventory levels between the printer and laminator

In figure 17 it can be seen that the inventory will be at zero a considerable amount of time resulting in a high level of waiting for material in the laminator, for this run the waiting time was 22 % of the available time.

A possibility to reduce the waiting time in the laminator is by increasing the amount of material in the inventory so that there will always be material for the laminator. This was made by introducing an algorithm that controls the run speed of the laminator and the printer:

- The laminator starts when there is one order in the inventory
- When the inventory is below four orders the speed of the laminator is reduced to 250 m/min
- When the inventory level is above four orders the speed of the laminator is 483 m/min, accordingly to the input analysis made for August 2009
- When the inventory level is above 15 orders the speed of the printer is reduced to 250 m/min
- When the inventory level is below 15 orders the speed of the printer follows the input analysis made for August 2009

With this algorithm the amount of waiting time of the total available time was reduced in the printer to 4 %, see figure 7.2. But, the total output was reduced by about 300 000 meters.

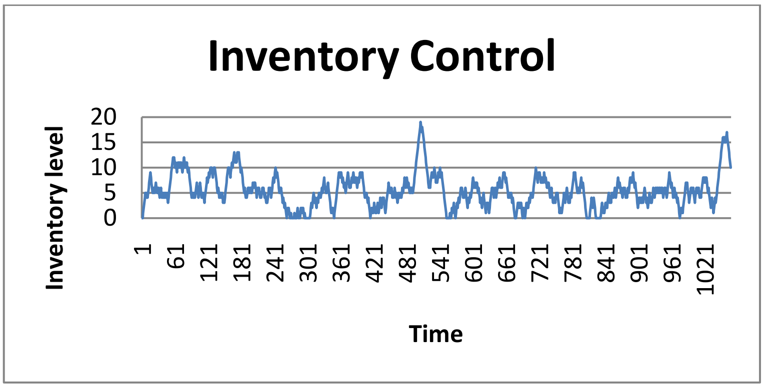

Figure 7.2. Inventory levels between the printer and laminator

Thus, by having an inventory control the waiting time in the laminator was reduced but the total output of the line was also reduced. By identifying another algorithm for inventory control it could be possible to reduce the waiting time in the laminator without reducing the total output produced by the printer and laminator, for example by reducing the speed in laminator in steps.

**Six Sigma**

The simulation of scenario 3 gave an increase in output of 200 000 meters by reducing the variation in two set ups. A possibility is to simulate the idealized production under the assumption that all the processes are following Six Sigma levels. This would most likely yield a higher output but also the possibility to reduce and better control the inventory.

**Materials Planning**

A simulation consisting of 30 000 runs and each with a new set of random numbers were made under the assumption that no orders under two rolls were produced. Here it was assumed that one roll has the length of 4000 m thus only orders above 8 000 m were produced. The result of the simulation yielded an increase in output from 9 800 km to 10 600 km.

Further possibilities in simulating materials planning are to simulate scenarios where product variety is lowered, as for example only producing packages of a certain width.

**Planned Stops**

In August 2009 the amount of planned stops was 18 hours per week.  A possibility is to simulate a production free of planned stops and see what impact these stops have on the whole production line.

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# Appendix 1

Critical KS values for a 95 % confidence and for a certain degree of freedom.

| Degrees of Freedom (n) | D0.05 | Degrees of Freedom (n) | D0.05 |
|---|---|---|---|
| 1 | 0.975 | 13 | 0.361 |
| 2 | 0.842 | 14 | 0.349 |
| 3 | 0.708 | 15 | 0.338 |
| 4 | 0.624 | 16 | 0.328 |
| 5 | 0.565 | 17 | 0.318 |
| 6 | 0.521 | 18 | 0.309 |
| 7 | 0.486 | 19 | 0.301 |
| 8 | 0.457 | 20 | 0.294 |
| 9 | 0.432 | 25 | 0.27 |
| 10 | 0.41 | 30 | 0.24 |
| 11 | 0.391 | 35 | 0.23 |
| 12 | 0.375 | Over 35 | $1.36/\sqrt{n}$ |

Source: Laguna et al., *Business Process Modeling, Simulation, and Design* (2005), pp.336

# Appendix 2

Table with the constants $c_4$, $d_2$, $D_1$, $D_2$, $D_3$ and $D_4$ for a given sample size n.

| **Sample size, n** | **C4** | **d2** | **D1** | **D2** | **D3** | **D4** |
|---|---|---|---|---|---|---|
| 2 | 0.798 | 1.128 | 0 | 3.686 | 0 | 3.267 |
| 3 | 0.886 | 1.693 | 0 | 4.358 | 0 | 2.575 |
| 4 | 0.921 | 2.059 | 0 | 4.698 | 0 | 2.282 |
| 5 | 0.940 | 2.326 | 0 | 4.918 | 0 | 2.115 |
| 6 | 0.952 | 2.534 | 0 | 5.078 | 0 | 2.004 |
| 7 | 0.959 | 2.704 | 0.205 | 5.203 | 0.076 | 1.924 |
| 8 | 0.965 | 2.847 | 0.387 | 5.307 | 0.136 | 1.864 |
| 9 | 0.969 | 2.970 | 0.546 | 5.394 | 0.184 | 1.816 |
| 10 | 0.973 | 3.078 | 0.687 | 5.469 | 0.223 | 1.777 |
| 11 | 0.975 | 3.173 | 0.812 | 5.534 | 0.256 | 1.744 |
| 12 | 0.978 | 3.258 | 0.924 | 5.592 | 0.284 | 1.716 |
| 13 | 0.979 | 3.336 | 1.026 | 5.646 | 0.308 | 1.692 |
| 14 | 0.981 | 3.407 | 1.121 | 5.693 | 0.329 | 1.671 |
| 15 | 0.982 | 3.472 | 1.207 | 5.737 | 0.348 | 1.652 |
| 16 | 0.984 | 3.532 | 1.285 | 5.779 | 0.364 | 1.636 |
| 17 | 0.985 | 3.588 | 1.359 | 5.817 | 0.379 | 1.621 |
| 18 | 0.985 | 3.640 | 1.426 | 5.854 | 0.392 | 1.608 |
| 19 | 0.986 | 3.689 | 1.490 | 5.888 | 0.404 | 1.596 |
| 20 | 0.987 | 3.735 | 1.548 | 5.922 | 0.414 | 1.586 |
| 21 | 0.988 | 3.778 | 1.606 | 5.950 | 0.425 | 1.575 |
| 22 | 0.988 | 3.819 | 1.659 | 5.979 | 0.434 | 1.566 |
| 23 | 0.989 | 3.858 | 1.710 | 6.006 | 0.443 | 1.557 |
| 24 | 0.989 | 3.895 | 1.759 | 6.031 | 0.452 | 1.548 |
| 25 | 0.989 | 3.931 | 1.804 | 6.058 | 0.459 | 1.541 |

Source: Bergman et al, *Quality – from Customer Needs to Customer Satisfaction* (2008), pp. 568

# Appendix 3

## 12-01

Sample groups taken from the production data for the setup 12-01. Each sample group consists of five values.

| Sample group | Average | Std | Range | Sample group | Average | Std | Range | Sample group | Average | Std | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.128 | 0.062 | 0.170 | 21 | 0.174 | 0.029 | 0.080 | 51 | 0.180 | 0.030 | 0.080 |
| 2 | 0.156 | 0.022 | 0.050 | 22 | 0.172 | 0.031 | 0.080 | 52 | 0.146 | 0.064 | 0.170 |
| 3 | 0.176 | 0.074 | 0.180 | 23 | 0.174 | 0.043 | 0.100 | 53 | 0.146 | 0.030 | 0.070 |
| 4 | 0.208 | 0.030 | 0.070 | 24 | 0.138 | 0.019 | 0.050 | | | | |
| 5 | 0.154 | 0.024 | 0.060 | 25 | 0.198 | 0.128 | 0.310 | | | | |
| 6 | 0.166 | 0.028 | 0.070 | 26 | 0.218 | 0.058 | 0.140 | | | | |
| 7 | 0.194 | 0.071 | 0.180 | 27 | 0.248 | 0.144 | 0.360 | | | | |
| 8 | 0.220 | 0.053 | 0.140 | 28 | 0.170 | 0.078 | 0.180 | | | | |
| 9 | 0.168 | 0.019 | 0.050 | 29 | 0.174 | 0.038 | 0.090 | | | | |
| 10 | 0.116 | 0.033 | 0.080 | 30 | 0.186 | 0.042 | 0.100 | | | | |
| 11 | 0.108 | 0.020 | 0.050 | 31 | 0.228 | 0.085 | 0.210 | | | | |
| 12 | 0.264 | 0.121 | 0.310 | 32 | 0.142 | 0.043 | 0.110 | | | | |
| 13 | 0.134 | 0.043 | 0.100 | 33 | 0.158 | 0.026 | 0.060 | | | | |
| 14 | 0.196 | 0.063 | 0.170 | 34 | 0.178 | 0.068 | 0.150 | | | | |
| 15 | 0.174 | 0.050 | 0.120 | 35 | 0.176 | 0.025 | 0.060 | | | | |
| 16 | 0.188 | 0.038 | 0.090 | 36 | 0.196 | 0.072 | 0.200 | | | | |
| 17 | 0.254 | 0.052 | 0.110 | 37 | 0.094 | 0.030 | 0.080 | | | | |
| 18 | 0.206 | 0.044 | 0.110 | 38 | 0.172 | 0.069 | 0.150 | | | | |
| 19 | 0.178 | 0.070 | 0.170 | 39 | 0.232 | 0.048 | 0.120 | | | | |
| 20 | 0.178 | 0.084 | 0.230 | 40 | 0.238 | 0.195 | 0.490 | | | | |

### 12-03

Sample groups taken from the production data for the setup 12-03. Each sample group consists of five values.

| **Sample group** | **Average** | **Std** | **Range** |
|---|---|---|---|
| 1 | 0.500 | 0.149 | 0.310 |
| 2 | 0.294 | 0.110 | 0.290 |
| 3 | 0.320 | 0.064 | 0.150 |
| 4 | 0.278 | 0.095 | 0.260 |
| 5 | 0.364 | 0.056 | 0.140 |
| 6 | 0.424 | 0.300 | 0.710 |
| 7 | 0.356 | 0.116 | 0.290 |
| 8 | 0.438 | 0.259 | 0.690 |
| 9 | 0.362 | 0.185 | 0.490 |
| 10 | 0.310 | 0.104 | 0.220 |
| 11 | 0.624 | 0.207 | 0.490 |
| 12 | 0.578 | 0.173 | 0.460 |

# Appendix 4

The distribution shown is the one chosen to describe the input data. The distributions used in this study are the normal, lognormal and exponential distribution functions. Thus, an improvement in the input analysis can be made by taking into consideration more distribution functions as for example the gamma distribution.

The column *# variables* state the amount of data that was available. For some input data the amount of variables was small and thus an improvement in the input analysis can be made by improving the amount of variables.

For the goodness-of-fit tests the distribution is accepted if one out of the three tests accepts the hypothesis that the chosen distribution function can be used to described the data. The KS-test was made manually in Excel while all three of the tests were done in Stat::fit.

**Order size (m)**

| | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| **P12** | | | | | | | | |
| Flexo Process Claycoat Duplex | Lognormal | 14813 | 12694 | 344 | Reject | Reject | Reject | No |
| **P14** | | | | | | | | |
| Flexo Process Claycoat Duplex | Lognormal | 16200 | 13231 | 218 | Reject | Accept | Accept | No |
| Flexo Claycoat Duplex | Lognormal | 17724 | 12515 | 37 | Accept | Accept | Accept | No |
| Flexo Duplex | Lognormal | 25320 | 19177 | 115 | Reject | Reject | Accept | No |

**Setup (min)**

| | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| **P12** | Average | 11.60 | - | - | - | - | - | - |

| **P14** | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| 12-01 Sleeve change | Lognormal | 10.77 | 4.19 | 266 | Accept* | Accept | Reject | No |
| 12-02 Sleeve & Anilox change | Exponential | 18.47 | 14.13 | 9 | Accept | Accept | -** | No |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12-03 Creasing tool change | Lognormal | 23.96 | 11.13 | 62 | Accept | Accept | Accept | No |
| 12-04 Anilox &Creasing tool change | Average | 40.60 | 14.30 | 8 | - | - | - | No |
| 12-06 Sleeve & Chamber change | - | 4.20 | - | 1 | - | - | - | - |
| 12-07 Start up | - | 16.20 | - | 2 | - | - | - | - |

* The KS-test made in Excel rejects the hypothesis while the KS-test made in Stat::Fit accepts it

** The amount of variables was not enough to make a Chi Squared test in Stat::Fit

| **P22** | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| 12-01 Heating | - | 3.90 | - | 2 | - | - | - | - |
| 12-03 Width change From Wide to Narrow | Lognormal | 27.44 | 33.42 | 20 | Accept | Accept | Accept | No |
| 12-04 Width change From Narrow to Wide | Exponential | 52.15 | 51.02 | 13 | Accept | Accept | -* | No |
| 12-05 Grammage Change | Lognormal | 8.86 | 5.54 | 17 | Accept | Accept | Accept | No |
| 12-06 Specification change Adhesive | - | 17.85 | 25.02 | 8 | - | - | - | |
| 12-07 Lam Material setup | - | 12.60 | - | 1 | - | - | - | |
| 12-09 PLH setup | - | 59.88 | 32.00 | 5 | - | - | - | |
| 12-11 Specification change 2nd Inside | - | 16.50 | - | 2 | - | - | - | |

* The amount of variables was not enough to make a Chi Squared test in Stat::Fit

**Planned- and Unplanned stops (min)**

| | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| **P12** | | | | | | | | |
| **21 Repair time** | | | | | | | | |
| Mean Down Time | Average | 87.72 | - | - | - | - | - | - |
| Mean Time Between Failure | Exponential | 3926.57 | - | - | - | - | - | - |
| **23 Lack of Resources time** | | | | | | | | |
| Mean Down Time | Average | 36.22 | - | - | - | - | - | - |
| Mean Time Between Failure | Exponential | 2804.70 | - | - | - | - | - | - |
| **25 Waiting for Approval time** | | | | | | | | |
| Mean Down Time | Average | 9.43 | - | - | - | - | - | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mean Time Between Failure | Exponential | 577.44 | - | - | - | - | - | - |
| **26 Short stop time** | | | | | | | | |
| Mean Down Time | Average | 15.72 | - | - | - | - | - | - |
| Mean Time Between Failure | Exponential | 154.59 | - | - | - | - | - | - |
| **27 Cleaning time** | | | | | | | | |
| Mean Down Time | Average | 39.00 | - | - | - | - | - | - |
| Mean Time Between Failure | Exponential | 19632.00 | - | - | - | - | - | - |
| **28 Maintenance time** | | | | | | | | |
| Mean Down Time | Average | 96.18 | - | - | - | - | - | - |
| Mean Time Between Failure | Exponential | 1618.90 | - | - | - | - | - | - |
| **31 Force Majeure time** | | | | | | | | |
| Mean Down Time | Average | 61.22 | - | - | - | - | - | - |
| Mean Time Between Failure | Exponential | 11332.50 | - | - | - | - | - | - |

The MDT and the MTBF for the P12 was taken from the report *MDT and MTBF*. The MDT was assumed to be average and the MTBF was assumed to follow an exponential distribution. Thus no analysis according to chapter 5.4 was made on this data.

| **P14** | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| **17 Non working time** | | | | | | | | |
| Mean Down Time | Average | 480.00 | - | 13 | - | - | - | - |
| Mean Time Between Failure | Average | 9600.00 | - | - | - | - | - | - |
| **21 Repair time** | | | | | | | | |
| Mean Down Time | Lognormal | 171.80 | 201.50 | 12 | Accept | Accept | -* | Yes |
| Mean Time Between Failure | Exponential | 1600.00 | - | - | - | - | - | - |
| **23 Lack of Resources time** | | | | | | | | |
| Mean Down Time | Lognormal | 36.92 | 28.15 | 15 | Accept | Accept | Accept | No |
| Mean Time Between Failure | Exponential | 1500.00 | | | | | | |
| **25 Waiting for Approval time** | | | | | | | | |
| Mean Down Time | Lognormal | 12.32 | 28.15 | 26 | Accept | Accept | Accept | No |
| Mean Time Between Failure | Exponential | 923.00 | - | - | - | - | - | - |
| **26 Short stop time** | | | | | | | | |
| Mean Down Time | Lognormal | 14.64 | 18.57 | 84 | Accept | Accept | Accept | No |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mean Time Between Failure | Lognormal | 261.60 | 350.74 | 98 | Accept | Accept | Accept | No |
| **28-1 Maintenance time** | | | | | | | | |
| Mean Down Time | Average | 60.00 | - | - | - | - | - | - |
| Mean Time Between Failure | Average | 1380.00 | - | - | - | - | - | - |
| **28-2 Maintenance time** | | | | | | | | |
| Mean Down Time | Fixed | 300.00 | - | - | - | - | - | - |
| Mean Time Between Failure | Fixed | 40173.00 | - | - | - | - | - | - |
| **31 For Majeure time** | | | | | | | | |
| Mean Down Time | Average | 147.00 | - | 31 | - | - | - | - |
| Mean Time Between Failure | Fixed | 40173.00 | - | - | - | - | - | - |

* The amount of variables was not enough to make a Chi Squared test in Stat::Fit

The MDT for the unplanned stop was analyzed according the chapter 5.4 and so was the MTBF for *26 Short stop time.* The MTBF for the rest of the unplanned stop were assumed to be exponential distributed. The MDT and MTBF for the planned stops follows schedule described in chapter 4.3. The analysis for the laminator was carried out in the same way.

| **P22** | Distribution | Average | St. Dev- | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| **17 Non working time** | | | | | | | | |
| Mean Down Time | - | 1008.80 | - | 6 | - | - | - | - |
| Mean Time Between Failure | - | - | - | - | - | - | - | - |
| **21 Repair time** | | | | | | | | |
| Mean Down Time | Average | 61.20 | 69.07 | 10 | - | - | - | - |
| Mean Time Between Failure | Exponential | 3016.20 | | | | | | |
| **23 Lack of Resources time** | | | | | | | | |
| Mean Down Time | Average | 315.60 | - | 2 | - | - | - | - |
| Mean Time Between Failure | Exponential | 16588.00 | - | | - | - | - | - |
| **25 Waiting for Approval time** | | | | | | | | |
| Mean Down Time | Average | 82.20 | - | 1 | - | - | - | - |
| Mean Time Between Failure | Exponential | 33176.00 | - | - | - | - | - | - |
| **26 Short stop time** | | | | | | | | |
| Mean Down Time | Lognormal | 27.70 | 40.35 | 111 | Accept | Accept | Accept | -* |
| Mean Time Between Failure | Exponential | 273.84 | 264.88 | 126 | Accept | Accept | Accept | No |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **27 Cleaning time** | | | | | | | | |
| Mean Down Time | Average | 28.80 | - | 1 | - | - | - | - |
| Mean Time Between Failure | Exponential | 33176.00 | - | - | - | - | - | - |
| **28 Maintenance time** | | | | | | | | |
| Mean Down Time | Average | 960.00 | - | 3 | - | - | - | - |
| Mean Time Between Failure | Fixed | 19200.00 | - | - | - | - | - | - |
| **29 Planned stop** | | | | | | | | |
| Mean Down Time | - | 3358.80 | - | 1 | - | - | - | - |
| Mean Time Between Failure | - | - | - | - | - | - | - | - |
| **31 For Majeure time** | | | | | | | | |
| Mean Down Time | Average | 68.00 | 45.71 | 4 | - | - | - | - |
| Mean Time Between Failure | Fixed | 8834.00 | - | - | - | - | - | - |

* The autocorrelation could not be calculated due to there were no data.

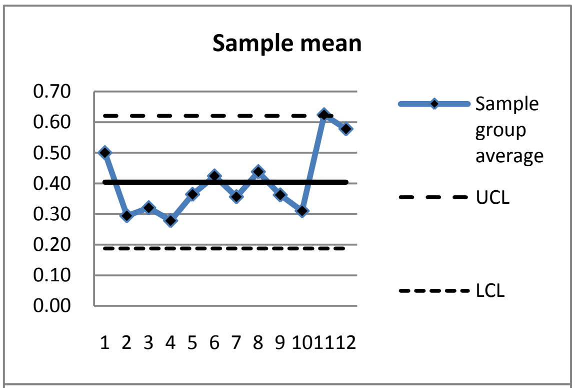
**Machine Run Speed (m/min)**

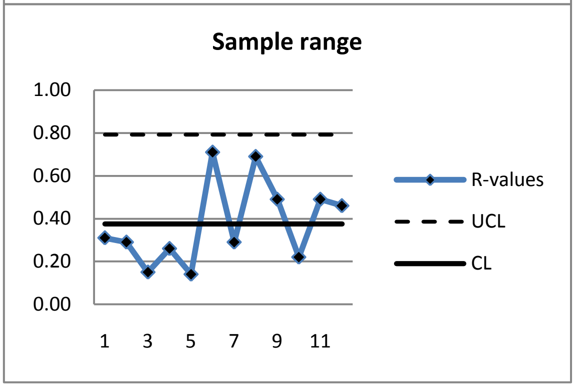
| | Distribution | Average | St. Dev. | # variables | KS-test | AD-test | Chi Squared test | Autocorrelation |
|---|---|---|---|---|---|---|---|---|
| **P12** | Normal | 317.67 | 99.48 | 100 | Accept | Accept | Accept | No |
| **P14** | Normal | 463.74 | 75.1 | 366 | Accept | Accept | Reject | No |
| **P22** | Average | 483.56 | 33.42 | 680 | - | - | - | - |

# Appendix 5

Values and control charts for the process setup 12-03 before any changes are made:

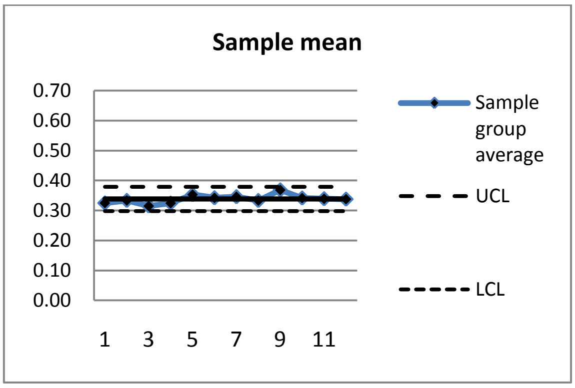
| | Mean Chart (h) | Range Chart (h) |
|---|---|---|
| UCL | 0.62 | 0.793 |
| CL | 0.404 | 0.38 |
| LCL | 0.188 | 0 |

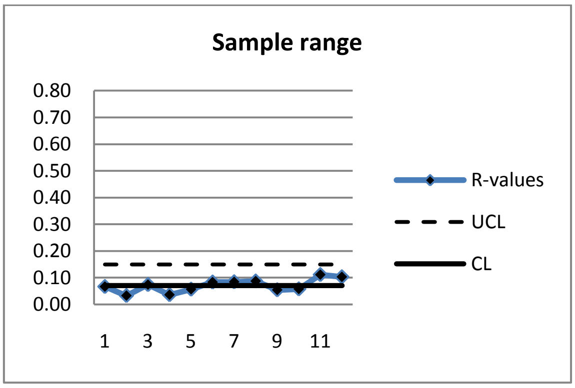




Values and control charts for a process setup 12-03 with Sig Sigma levels:

| | Mean Chart (h) | Range Chart (h) |
|---|---|---|
| UCL | 0.379 | 0.149 |
| CL | 0.338 | 0.07 |
| LCL | 0.298 | 0 |


Sample mean
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
3
5
7
9
11
Sample group average
UCL
LCL


Sample range
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
3
5
7
9
11
R-values
UCL
CL

# Appendix 6

| Order size (m) | | | |
|---|---|---|---|
| | **Distribution Type** | **Average** | **Standard Deviation** |
| **P12** | Log Normal | 14813 | 12693.6 |
| **P14** | | | |
| Flexo Process Claycoat Duplex | Log Normal | 16200 | 13231 |
| Flexo Claycoat Duplex | Log Normal | 17724 | 12515 |
| Flexo Duplex | Log Normal | 25320 | 19177 |

| Setup (min) | | | |
|---|---|---|---|
| | **Distribution Type** | **Average** | **Standard Deviation** |
| **P12** | Average | 11.6 | |
| **P14** | | | |
| 12 – 01 Sleeve change | Log Normal | 10.77 | 4.19 |
| 12 – 02 Sleeve and Anilox change | Exponential | 18.47 | |
| 12 – 03 Creasing tool change | Log Normal | 23.96 | 11.13 |
| 12 – 04 Anilox and Creasing tool change | Average | 40.6 | |
| **P22** | | | |
| 12 – 03 Width change – From Wide to Narrow | Log Normal | 27.44 | 33.42 |
| 12 – 04 Width change – From Narrow to Wide | Exponential | 52.15 | |
| 12 – 05 Grammage Change | Log Normal | 8.86 | 5.54 |

| Planned and Unplanned stops (min) | | | |
|---|---|---|---|
| | **Distribution Type** | **Average** | **Standard Deviation** |
| **P12** | | | |
| **21 Repair time** | | | |
| Mean Down Time | Average | 87.72 | |
| Mean Time Between Failure | Exponential | 3926.57 | |
| **23 Lack of Resources time** | | | |
| Mean Down Time | Average | 36.22 | |
| Mean Time Between Failure | Exponential | 2804.70 | |
| **25 Waiting for Approval time** | | | |
| Mean Down Time | Average | 9.43 | |
| Mean Time Between Failure | Exponential | 577.44 | |
| **26 Short stop time** | | | |
| Mean Down Time | Average | 15.72 | |
| Mean Time Between Failure | Exponential | 154.59 | |
| **27 Cleaning time** | | | |
| Mean Down Time | Average | 39 | |
| Mean Time Between Failure | Exponential | 19632 | |
| **28 Maintenance time** | | | |
| Mean Down Time | Average | 96.18 | |
| Mean Time Between Failure | Exponential | 1618.9 | |
| **31 Force Majeure time** | | | |
| Mean Down Time | Average | 61.22 | |
| Mean Time Between Failure | Exponential | 11332.5 | |
| **P14** | | | |
| **17 Non working time** | | | |
| Mean Down Time | Average | 480 | |
| Mean Time Between Failure | Average | 9600 | |

| | | | |
|---|---|---|---|
| **21 Repair time** | | | |
| Mean Down Time | Log Normal | 171.80 | 201.50 |
| Mean Time Between Failure | Exponential | 1600 | |
| **23 Lack of Resources time** | | | |
| Mean Down Time | Log Normal | 36.92 | 28.15 |
| Mean Time Between Failure | Exponential | 1500 | |
| **25 Waiting for Approval time** | | | |
| Mean Down Time | Log Normal | 12.32 | 10.85 |
| Mean Time Between Failure | Exponential | 923 | |
| **26 Short stop time** | | | |
| Mean Down Time | Log Normal | 14.64 | 18.57 |
| Mean Time Between Failure | Exponential | 261.60 | |
| **28-1 Maintenance time** | | | |
| Mean Down Time | Average | 60 | |
| Mean Time Between Failure | Average | 1380 | |
| **28-2 Maintenance time** | | | |
| Mean Down Time | Fixed | 300 | |
| Mean Time Between Failure | Fixed | 9780 | |
| **31 Force Majeure time** | | | |
| Mean Down Time | Average | 147 | |
| Mean Time Between Failure | Fixed | 40173 | |
| **P22** | | | |
| **21 Repair time** | | | |
| Mean Down Time | Average | 61.20 | |
| Mean Time Between Failure | Exponential | 3016.20 | |
| **23 Lack of Resources time** | | | |
| Mean Down Time | Average | 315.60 | |
| Mean Time Between Failure | Exponential | 16588 | |
| **25 Waiting for Approval time** | | | |
| Mean Down Time | Average | 82.20 | |
| Mean Time Between Failure | Exponential | 33176 | |
| **26 Short stop time** | | | |
| Mean Down Time | Log Normal | 27.70 | 40.35 |
| Mean Time Between Failure | Exponential | 273.84 | |
| **27 Cleaning time** | | | |
| Mean Down Time | Average | 28.80 | |
| Mean Time Between Failure | Exponential | 33176 | |
| **28 Maintenance time** | | | |
| Mean Down Time | Average | 960 | |
| Mean Time Between Failure | Fixed | 19200 | |
| **31 Force Majeure time** | | | |
| Mean Down Time | Average | 68 | |
| Mean Time Between Failure | Fixed | 8834 | |

| **Machine Run Speed (m/min)** | | | |
|---|---|---|---|
| | **Distribution Type** | **Average** | **Standard Deviation** |
| **P12** | Normal | 317.67 | 99.48 |
| **P14** | Normal | 463.74 | 75.10 |
| **P22** | Fixed | 483.56 | |

# Appendix 7

Number of runs in trial 30 000
Base Random Number Set 1

## Basic Model

| Simulation Object | Performance Measure | – 95 % | Average | 95 % |
|---|---|---|---|---|
| Work Complete 1 | Number Completed (meters) | 12 142 028 | 12 148 883 | 12 155 737 |
| P12 | Waiting % | 25.50 | 25.52 | 25.55 |
| | Working % | 45.63 | 45.66 | 45.69 |
| | Stopped % | 19.17 | 19.19 | 19.20 |
| | Change over % | 9.62 | 9.63 | 9.64 |
| P14 | Waiting % | 23.36 | 23.37 | 23.39 |
| | Working % | 37.55 | 37.57 | 37.59 |
| | Stopped % | 26.45 | 26.48 | 26.51 |
| | Change over % | 12.57 | 12.58 | 12.59 |
| WIP | Average queue size (meters) | 153 790 | 154 317 | 154 845 |
| | Maximum queue size (meters) | 657 870 | 659 627 | 661 385 |
| P22 | Waiting % | 18.15 | 18.18 | 18.22 |
| | Working % | 60.36 | 60.39 | 60.42 |
| | Stopped % | 17.34 | 17.36 | 17.38 |
| | Change over % | 4.06 | 4.06 | 4.07 |

## Scenario 1

| Simulation Object | Performance Measure | – 95 % | Average | 95 % |
|---|---|---|---|---|
| Work Complete 1 | Number Completed (meters) | 9 774 207 | 9 779 155 | 9 783 914 |
| P14 | Waiting % | 0.00 | 0.00 | 0.00 |
| | Working % | 55.27 | 55.30 | 55.32 |
| | Stopped % | 26.45 | 26.48 | 26.51 |
| | Change over % | 18.22 | 18.22 | 18.23 |
| WIP | Maximum queue size (meters) | 244 955 | 245 716 | 246 668 |
| | Average queue size (meters) | 16 178 | 16 368 | 16 368 |
| P22 | Waiting % | 28.78 | 28.81 | 28.84 |
| | Working % | 50.67 | 50.69 | 50.71 |
| | Stopped % | 17.34 | 17.36 | 17.38 |
| | Change over % | 3.13 | 3.13 | 3.14 |

## Scenario 2

| Simulation Object | Performance Measure | – 95 % | Average | 95 % |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Work Complete 1 | Number Completed (meters) | 10 543 521 | 10 548 469 | 10 553 418 |
| P14 | Waiting % | 0.00 | 0.00 | 0.00 |
| | Working % | 53.75 | 53.77 | 53.80 |
| | Stopped % | 26.45 | 26.48 | 26.51 |
| | Change over % | 19.74 | 19.75 | 19.76 |
| WIP | Maximum queue size (meters) | 291 395 | 292 537 | 293 489 |
| | Average queue size (meters) | 23 411 | 23 411 | 23 601 |
| P22 | Waiting % | 24.13 | 24.16 | 24.19 |
| | Working % | 55.20 | 55.22 | 55.24 |
| | Stopped % | 17.34 | 17.36 | 17.38 |
| | Change over % | 3.25 | 3.26 | 3.26 |

## Scenario 3

| **Simulation Object** | **Performance Measure** | **– 95 %** | **Average** | **95 %** |
|---|---|---|---|---|
| Work Complete 1 | Number Completed (meters) | 10 010 406 | 10 015 165 | 10 019 923 |
| P14 | Waiting % | 0.00 | 0.00 | 0.00 |
| | Working % | 56.80 | 56.82 | 56.85 |
| | Stopped % | 26.45 | 26.48 | 26.51 |
| | Change over % | 16.69 | 16.70 | 16.71 |
| WIP | Maximum queue size (meters) | 259 229 | 260 181 | 261 133 |
| | Average queue size (meters) | 18 272 | 18 272 | 18 462 |
| P22 | Waiting % | 27.37 | 27.40 | 27.43 |
| | Working % | 52.05 | 52.07 | 52.10 |
| | Stopped % | 17.34 | 17.36 | 17.38 |
| | Change over % | 3.16 | 3.17 | 3.17 |

## Scenario 4

| **Simulation Object** | **Performance Measure** | **– 95 %** | **Average** | **95 %** |
|---|---|---|---|---|
| Work Complete 1 | Number Completed (meters) | 10 114 517 | 10 119 275 | 10 124 033 |
| P14 | Waiting % | 0.00 | 0.00 | 0.00 |
| | Working % | 57.45 | 57.48 | 57.50 |
| | Stopped % | 23.63 | 23.66 | 23.69 |
| | Change over % | 18.86 | 18.86 | 18.87 |
| WIP | Maximum queue size (meters) | 249 903 | 250 855 | 251 616 |
| | Average queue size (meters) | 14 846 | 14 846 | 15 036 |
| P22 | Waiting % | 29.17 | 29.19 | 29.22 |
| | Working % | 52.67 | 52.70 | 52.72 |
| | Stopped % | 14.91 | 14.93 | 14.95 |
| | Change over % | 3.17 | 3.18 | 3.19 |

## Scenario 5

| Simulation Object | Performance Measure | – 95 % | Average | 95 % |
|---|---|---|---|---|
| Work Complete 1 | Number Completed (meters) | 11 214 434 | 11 219 763 | 11 225 092 |
| P14 | Waiting % | 0.00 | 0.00 | 0.00 |
| | Working % | 57.37 | 57.40 | 57.42 |
| | Stopped % | 23.63 | 23.66 | 23.69 |
| | Change over % | 18.93 | 18.94 | 18.95 |
| WIP | Maximum queue size (meters) | 309 857 | 310 809 | 311 761 |
| | Average queue size (meters) | 23 601 | 23 791 | 23 982 |
| P22 | Waiting % | 22.62 | 22.65 | 22.68 |
| | Working % | 58.94 | 58.96 | 58.99 |
| | Stopped % | 14.91 | 14.93 | 14.95 |
| | Change over % | 3.45 | 3.45 | 3.46 |