Master's degree thesis

LOG952 Engineering Logistics

Identifying bottlenecks in supply chains using visual analysis

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Acknowledgement

For the requirement of Master of Science in Engineering Logistic program at Molde University College, this master thesis present the study of different bottleneck identification techniques that has been studied with respect to production company.

We would like to express our sincere gratitude to Professor Johan Oppen, who gave us an opportunity to work under his valuable guidance. Prof. Johan Oppen’s was always available and responded swiftly through emails, whenever we ran into a trouble spot or had a question about our research. His inspiration, comments encouragement for the quality work and perfect sense of humor always helped us to stay motivated.

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Abstract

The performances of the company's production process are limited by the constraint usually termed as bottleneck. The performances of logistics or manufacturing system are measured by these constraints. All the production system throughputs are constrained by one or more bottlenecks. Since, the introduction of *Theory of Constraints* by Dr. Eliyahu M. Goldratt , all the researcher agrees about the importance of bottleneck identification and improvement as the iterative method towards the improvement of the overall system throughput. The identification of the bottleneck is often considered as the starting point of improvement initiative.

In this paper, we look forward to explore the common bottleneck detection method used by the production companies to visualize the constraints. The bottleneck identification is not the trivial task since the production companies' dynamicity leads the bottlenecks to shift between the machines. We focus on identifying the bottlenecks in the production facility with the available methods described in the literatures. For the real case scenario, the output data of Pipelife Norge AS from the year 2014 has been used. The conventional bottleneck identification and the practical bottleneck identification methods described in the literatures are used to evaluate these data sets.

The thesis uses four different approaches to measure the segregated performance parameter. The theoretical approach presents the influence of workload and material availability and the selection of particular operating point through newly developed assembly throughput curves. The mathematical and simulation approaches calculate the performance parameters, the average waiting time, queue length and utilization of the production system for the visualisation. Finally, the momentary shifting bottlenecks based on the active period method is visualised to monitor the shifting bottlenecks over the time. This method is easy to understand and quantifies the magnitude of tertiary bottlenecks in the production system.

Although, the thesis provides the framework for the holistic approach of bottleneck identification for the production companies, this also helps a decision maker to use right tools for the constraints visualization and aids the stakeholder for proper allocation and utilization of the resources.

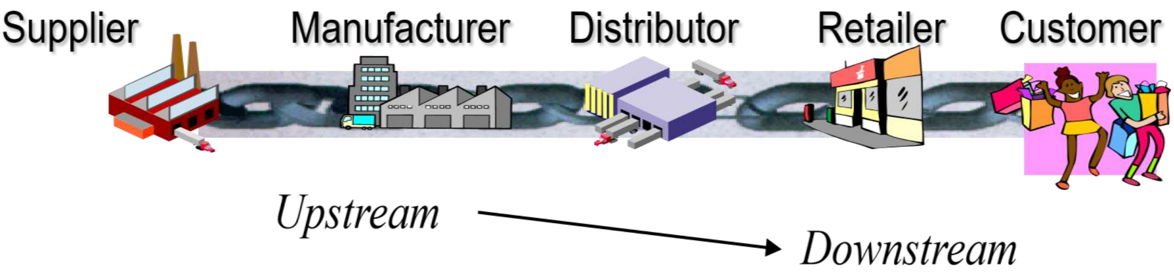
1.0 Introduction

This chapter highlights the introduction of the topic and its background. The overview of bottlenecks in one of the major components of the supply chain, the production system importance is defined. This chapter briefly explores the various bottlenecks identification methods from the literature. And finally culminates the importance of bottleneck identification which is followed by the brief layout of the thesis.

The supply chain is the networks of all the resources, organizations, individuals, activities and technology that supplies a particular product from raw materials to final customers (Hertz 2001). The common objective of the supply chain is efficiency and effectiveness. The efficiency in supply chains refers to get an adequate amount of output from the existing resources. The efficiency of the supply chain is achieved with the improvements in the productions as proven by numerous Just in Time productions. Whereas effectiveness is an innovative function. The effectiveness is obtained through related relationship functions like profits, volumes, market and product innovation functions (Möller and Törrönen 2003).

The production is one of the major modules of operational level in the supply chains. This is the module where all the raw materials are transformed or assembled into the deliverable products. The production system boosts the executive level decision since this involves real - time manipulation of production variable to deal with process disturbances and production rates (Muñoz et al. 2013). Most of the manufacturing process constitute of the transformation of the goods and the assembly operations. The inputs come from the upstream process (Figure 1-1), and its function is to provide the resources necessary for the downstream operations.

Figure 1-1 Supply chain components.



Source 1-1 Authors' own illustration based on literature

All the production systems are constrained by one or more bottlenecks (Goldratt and Fox 1986). They are in the production system for an instant or for the whole period. They could behave as a stage that stop the production or as a step for slowing down the production. This leads the manufacturing process to hold its production at the bottlenecks (Wang, Zhao, and Zheng 2005) . If the goal is to enhance the system performance, it is mandatory to identify these system constraining factor and then increase its throughput. The time lost on these constraints is the time loss in the whole production system, whereas time saved at bottleneck add extra time to time to whole production system. A time saved at non-bottleneck is mirage it only adds idle time to non- bottlenecks. (Kuo, Lim, and Meerkov 1996, Goldratt 1990).

Traditionally, the identification and the improvement of production bottlenecks were based on the five focusing steps elaborated by Dr. Eliyahu M. Goldratt as Theory of Constraints. (Lima, Chwif, and Barreto 2008). However, there are many deficiencies in TOC while dealing with multiple constraints in a complex environment (Ray, Sarkar, and Sanyal 2010, Wang et al. 2014). The product enhancement and the production process development leads to the powerful search of new control methods.

For the improvement of the performance, the bottlenecks should be improved and to improve the bottleneck it has to the identified. Therefore, to determine the bottleneck this thesis uses the conventional method such as average cycle time, utilization percentage, queues length for the short and long term static bottlenecks. One of the most critical resource constraining function is shifting bottlenecks, and this is studied separately under visual analytics. Both the conventional method and the bottleneck shifting are visualized and presented with their pros and cons.

The contents in this research start with the introduction, where the objective and the scope of the thesis are justified. In reference, with the firm case process structure and collected data, the distinctive theories and models are explored in the assessments and our findings are presented with associated limitation.

1.1 Background

The production process constitutes of the major two sets of resources, the transforming resources, and the transformed resources. The transforming resources are the machinery equipment's, computer systems and the human resources. The transformed resources include the raw materials and the final components that go through transforming process. Any production process, while transforming a range of inputs into outputs undergoes several steps. These stages during the transformation process add value to the products. The production lead time, flexibility in the manufacture, new product development time, quality, price, accuracy, types of materials, processes and the technologies, etc. are some factors that help manufacturing companies to define these values in their productions.

The poor visibility in identifying these value adding factors in the productions abruptly increases the inventories and back orders, and are most critical assets for the companies. The increase in backorders affect the loyalty with customer and increment in the inventories increases the carrying cost as well as the halted stock gets damaged over the time. However, there always exist the challenges to the manufacturer to find the right technique, hardware, software and middleware[1] solutions to help them perform business analytics (Marx 2012). Even the data are captured with advanced technology, and the manager needs the technique to link various stream of data to create the coherent picture of the particular problem for the better insight into the issue being analysed , as this will create more value for the company (Tan et al. 2015).

This thesis provides the insight to use those collected data to identify the bottlenecks. For this reference, the data has been used from pipe manufacturing company. The conventional method that follows to identify these constraints are put forward with their limitation. The active period method known to determine the momentary shifting bottleneck has been visualized.

This thesis helps to reduce the time for the analysis of the bottleneck identification in the production. On the other hand, this provides a better visibility of the potential areas for the improvements to the decision makers with real -time data.

[1] The software that bridge between database and application

1.2 Problem Overview

The production process in the today's turbulent environment is progressive with the innovative technology. The data capturing and monitoring tools helps the companies to captures every processes. This process if not monitored and controlled, leads to the problem with high variation in the downstream assembling process causing the Bullwhip effect (Hinckeldeyn et al. 2011).

The collection of information with an advance technology is no longer a big problem, but to extract the valuable knowledge from the collected or available information is a big problem. The main issue is how to represent these ubiquitous data to understand and obtain the knowledge. For an enhancement of this process, supply chain analytical tools help to make the better decision regarding the material and information flow in the supply chain (Souza 2014).

Exploration in the identifications of these resources constraining the production plants is necessary to optimize the production rates. In reviewing the literature, (Lima, Chwif, and Barreto 2008) define bottlenecks, also called constraints, as the root of the system's performance problem.

Therefore, in the coming chapters, we put forward to clarify the associated problems in identification of bottlenecks. The study will use the data collected from the case firm to evaluate the various method discussed in the literature. The thesis will be concise:

- Within the study of the company, production flow.
- Extraction of the data from the ERP system.
- Manipulations and analysis of the data's.
- Exploration of conventional bottleneck identification methods.
- Identification of the congestion points(bottlenecks) in the production.

Finally, these congestion points will be landscaped based on our finding, including the feedbacks, suggestions and further exploration for future research.

1.3 Objectives of the Study

We seek to focus our research on identifying the production related bottlenecks of the supply chains. The qualitative approaches defined in the literature along with the quantitative models will be followed for the exploitation of the topic. Thus, as explained in the problem overview, this thesis this is undertaken on the first steps from the core concepts of TOC[2] proposed by (Goldratt and Cox 1984), i.e. identification of the constraints. The overall objective of the thesis is summarized as:

1. Understanding the importance of bottlenecks identifications.
2. Segregation of the bottleneck bases on the static and dynamic and exploiting the available bottleneck identification tools.
3. Use of sophisticated problem-solving methodology, “Thinking Process” to answer,
   - What should to be changed?
   - To what to change?
   - How to cause (action) the change?
4. Presentation of an above studies framework on a visual approach to ease the communication as improvement measures.
5. Verification and validation of our finding.
6. Conclusion and recommendation for the future work.

[2] Theory of Constrain

1.4 *Justification of Study*

In product manufacture, production needs to be given significant importance, since the production related operations amount to 70% of the total product cost (Boothroyd, Dewhurst, and Knight 2010). In this view, the manufacturing business world is in competition to reduce costs and to increase productivity. The modifications of the productions firms from the manual system to the fully automated system helps to lower the cost. However, in the dynamic manufacturing process, every stage in the production lines have different capacities. These variations in the capacities cause the bottlenecks that are not static. The reduction in the productivity is because of the bottlenecks that arises in its station and shifts to another station easily if not identified and corrected (Hopp and Spearman 2008).

The non-uniformity in the product quality might occur because of the dynamicity in the manufacturing. The understanding of this dynamicity and how it affects the performances is of particular importance. The appropriate tools such as dynamic planning, integer programming, linear programming, simulations and queuing theory have been implemented to plan and monitor the production process (Khalafi and Raissi 2014). All these theories, planning and scheduling discussed are challenging to forecast and implement in the dynamic manufacturing system

The analytical tools with the dawn of ERP[3] system became more realistic and is still worth to be used for the emerging data application. A sharp dynamic adaption analytical instrument for the manufacturing companies involved in the production is visualization tools (Tan et al. 2015). The visualization tools help decision makers to grasp the concepts and correct relevant business decision as they see the analytics presented visually from the bundles of the vast volume of both internal and external data.

The production being the major module, its management is of vital importance than other elements[4] of networks (Cappello, Lösch, and Schmitz 2008). This thesis indicates and summarized the process for identification of the bottlenecks affecting the smooth manufacturing process. Each and every system has a bottleneck, even though it might be a minor one, to tackle these uncertainties and getting rid of the bottlenecks for the smooth

[3] Enterprise Resource Planning- A Business Management Software
[4] Service level managment. Order and demand mangement. Supply managment. Distribution management. Integrated SCM plannig and execution

production processes is challenging (Heinicke and Hickman 2000). Marx (2012) presented variability, velocity and visibility the 3v's to focus on the production facility. The lack of visibility negatively impacts the performances. The author abstracted, visibility as the main tools in the identification of unreliable, faulty manufacturing process and equipment's. The data collection, processing and analysing the available data from the existing system in order to provide the visibility in the identification of bottlenecks has been regarded as the primary objectives of the thesis.

1.5 Scope and Constrains of our Study

This study covers the analytical and simulation models that have been studied thoroughly. The research has been categories into theoretical, mathematical, simulation and shifting bottlenecks visualization.

The literature suggested approach “Throughput Curves” (Hinckeldeyn et al. 2011) for the observatory analysis is presented theoretically to define the bottlenecks, throughput, work in progress, constraints, stations and other parameters. This approach has been used based on the nine different cases of the production facility.

The mathematical model is computed based on the average calculation of the stations process with the predominantly used method “Average Cycle Time”.

“Average Utilization” and “Average Queue Length” method have been studied and calculated to build the baseline for the quantitative study. To understand and to provide details visibility for the shifting bottlenecks in the productions and assembly line simulation modelling is used (Kralova and Leporis 2004). The ARENA Simulation Software has been used for the simulation propose in our case.

Due to the limited resources, data and period, this study has covered only the six stations from the production facility. All the six stations are chosen as a sample frame since their data’s are coherent. Few data sheets were manipulated without manipulating the nature of data. The method and tools in this study are used based on our knowledge of understanding from the list of works of literatures and case studies.

1.6 Organization of Study

Following the introduction of problem, objectives and justification of the topic, rest of the chapters are structured in the following ways.

The Second Chapte,

This section includes the description of the company and their existing process flow of the production.

The Third Chapter

This section puts the literature review from the famous authors and researchers with generic definitions and contradictory definitions.

The Fourth Chapter

This section explains the methodologies that have to be followed in the thesis. Research, design, factory visit, data collection and all the approaches for the assessment in chapter 5 are explained in this section.

The Fifth Chapter

This chapter provides the insight of the core part of the thesis. The assessment of data from the methodologies discussed in the fourth chapter have been applied in this chapter.

The Sixth Chapter

This chapter conclude the thesis with our finding in the best possible way, the future research's on the topic is suggested.

.

2.0 Research Environment

This chapter provides the overview of the Pipelife Norge AS. We have studied the organisational structure, and their existing production flow. Their production environment and data flow diagram layout is presented in this chapter.

The case company in this thesis is Pipelife Surnadal. The Pipelife Norge AS with the joint venture of Solvay (Belgium) and Wienerberger (Austria) is Norway's largest producer and supplier of plastic pipe and accessories. The company is part of pipelife Group which is active in 26 countries and achieved a total of 872 million Euros of sales in 2014. The company extended its branches in other countries through the acquisitions and foundations of companies in Hungary, France, Germany, Greece, Turkey, Czech and the Slovak Republic

Pipelife's unique position of providing customers with excellent services and products is the result of constant improvement and innovation at the highest quality level. Outstanding competence, extraordinary team spirit, and visionary management are the key factors for being number 1 regarding customer satisfaction. The vision of Pipelife is to be NUMBER ONE value creator in the markets, and their mission is to improve the quality of pipe providing high -value solutions for the protection and flow of water and energy with their motto “pipes *for life*.” Pipelife Norway has two factories. The one is in Stathelle which produces large PE tubes and the other one is in Surnadal which produces smaller pipes in polyvinyl chloride and polypropylene used for water and wastewater, ventilation, cable protection, and electric installation. For the transportation of surface water and domestic wastewater, Pipelife offers several gravity pipe systems with both compact and structured wall pipes in PVC[5], PP[6] and PE[7] for the European market.

- **Production environment**

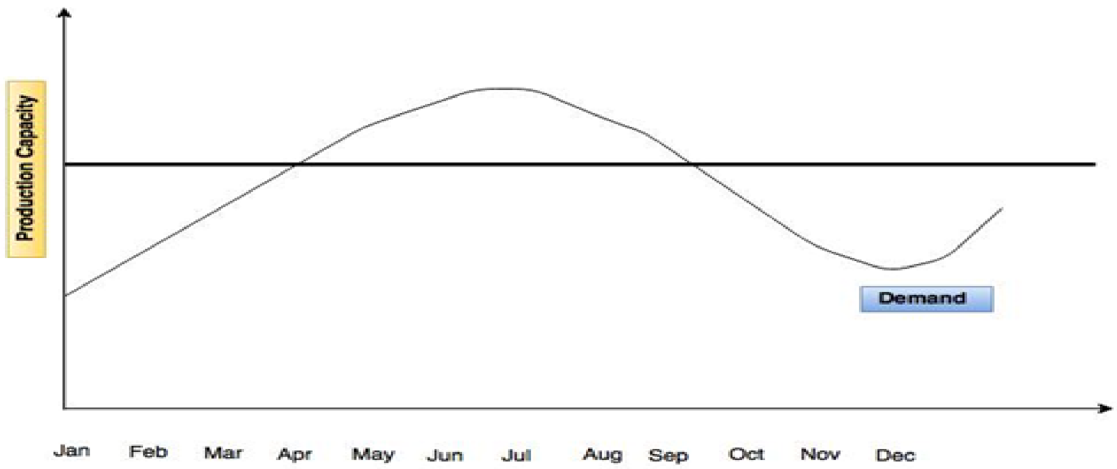
The production environment is MTS[8] (90%) and also has MTO[9]. By the use of make-to-stock strategy, the company enables to keep a delivery promise of that standard orders received before 11:00, are picked, packed and shipped within the next day. The practice of

[5] Polyvinyl chloride, highly used synthetic polymer.
[6] Also known as Polypropene, is a thermal polymer used in making plastic, carpeting, reusable etc products
[7] polyethylene
[8] Make to Stock
[9] Make to Order

accepting orders varies between standard orders and specific/customized orders. A standard order is received through EDI[10]. With the help of EDI, the various message in the order management cycle flows between vendors and customers electronically based on the defined and agreed specific criteria. When a customer orders a product, the EDI converts request information into the standardized format, and correspondingly this information flows into the vendor system. Thus, in Pipelife, a standard order precedes automatically into the ERP-system. The current ERP system is M3 that supports their sales and purchases related activities. The material planner in the ERP system is used to check the available stock and product that need to produce.

Starting from mid-May, the demand for the customer increases until the end of the August The peak of the sales happens in the months of May, June, July, August and September. The sales are directly proportional to production that means they can expect high production during this period Figure 2-1.

Figure 2-1 Case firm demand and capacity over the time horizon



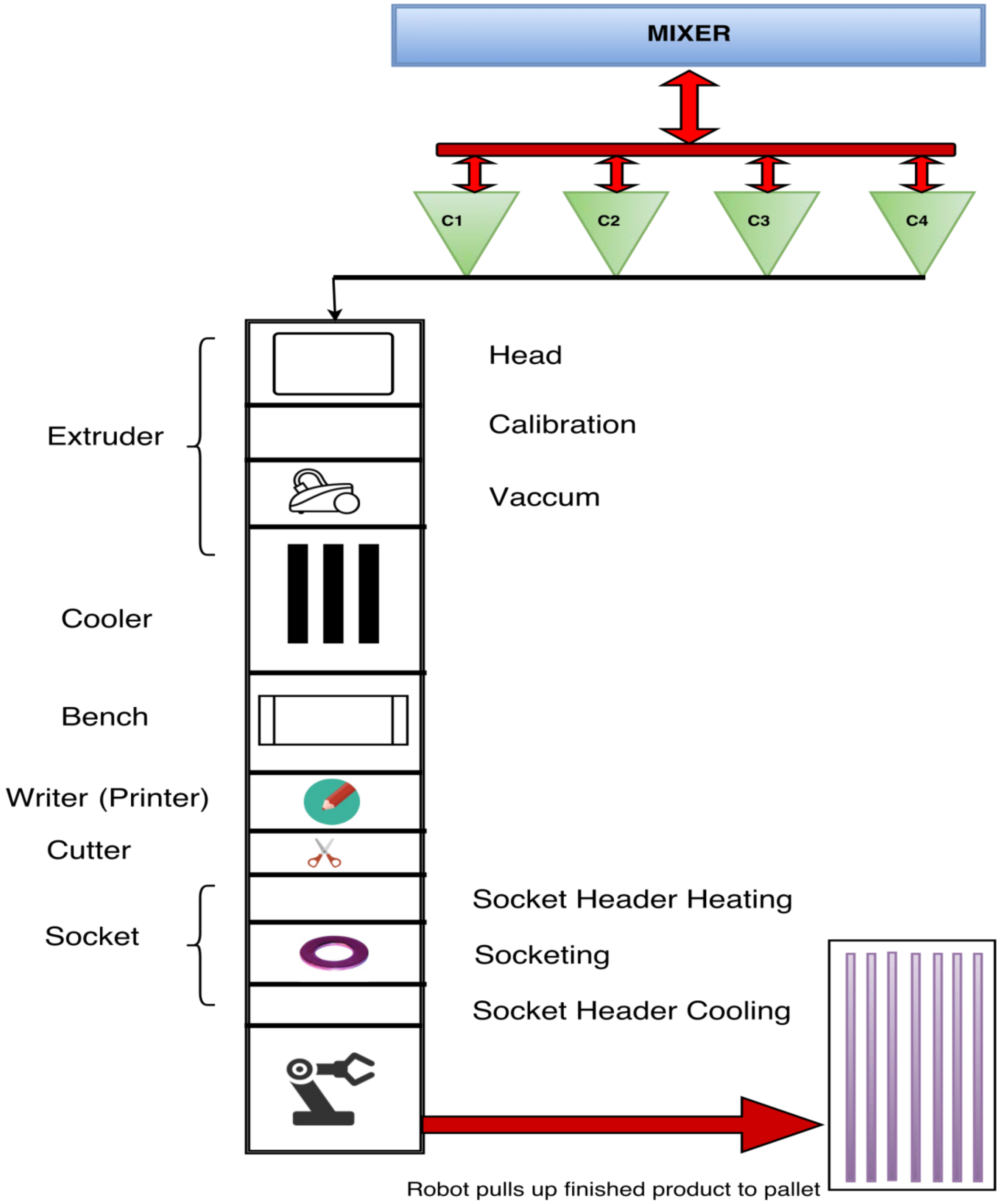
Source 2-1 Illustration based on the discussion

The production planning is based on three criteria's, product stock level, expected sales and efficient production (production productivity). The company has a strong focus on production efficiency and the utilization of production capacity, with the desired increase of 3,5% per year.

[10] Electronic Data Interchange

Figure 2-2 elaborate the process in the pipe manufacturing. The first process in the production starts with the mixing of the raw materials. The mixer has the capacity of mixing the raw material every day. The overall capacity of the mixture is 50,000 kg per day. After the mixture of four different raw components, the pipe manufacturing raw material are then transported into four different silos, each having capacity of 20,000 Kg. The total capacity of these silos is 80,000Kg. However, if the raw material inventory reduces to 20% the production process stopped. The silos are connected to the number of production stations where the production of pipes, parts in PVC and PP goes through numbers of procedures. These products are used in households piping, institution, and commercial organizations. There are numbers of manufacturing process performed inside the production stations. The process starts with extruding the raw materials, which then cooled, benched, segmented and socketed. The processes are not captured using the data capturing tools. Figure 2-2 shows the number of operations inside the production stations.

Figure 2-2 Production flow diagram of manufacturing process in Pipelife Norge AS



Source 2-2 Illustration based on explanations from production controller

The production controller uses 'Barco' as a PlantMaster, which is a leading MES[11] system for discrete manufacturing. It is a powerful and extensive yet flexible tool enabling managers to achieve operational excellence and rapidly respond to changing conditions. The system Barco shows a visualized the overview of the production plan. The controller creates a work

[11] Manufacturing Execution System

order in the ERP –M3 system and assign into machines. If the machines stop due to some error a fault message is send to Barco. This immediately change the status of the corresponding machines. The production operator should rectify the problems and the record the causes.

The company has a mix of automation and manual production. In reference with the specific orders and design, a manual workforce carries out the production. The company foresee to automate this specific production area in the future. The production of assembly pipes is fully automated with the use of robots. The operators need to be physically present at the production site since the robots cannot be controlled remotely. There are no 3D-printers in the production. The company mainly uses barcodes and QR-codes as the labelling system. The pipes are marked with production date/time and production line, pipe type.

In this thesis, we focused to identify the bottlenecks in the generic production stations using the data from Pipelife. Based on the nature of the available data, the related method and models have been studied. These methods are used for the computation for the identifications of bottlenecks and are visualized in the best possible way. We have minimized the stations of a similar product into six automated production stations.

3.0 Literature Review

This chapter includes the discussed literature relevant to the thesis. This section defines the fundamental and distinct concepts in the supply chain and productions. Our thesis mainly emphasized to identify the bottlenecks in the manufacture and visualized the identified bottlenecks. Therefore, the bottlenecks identification theories and model are presented for the theoretical, mathematical, simulation and visual approaches. From the discussed theories and models, some of the methodologies are abstracted for the identification of the bottlenecks and are computed in Chapter 5.0 "Assessment and Empirical Finding".

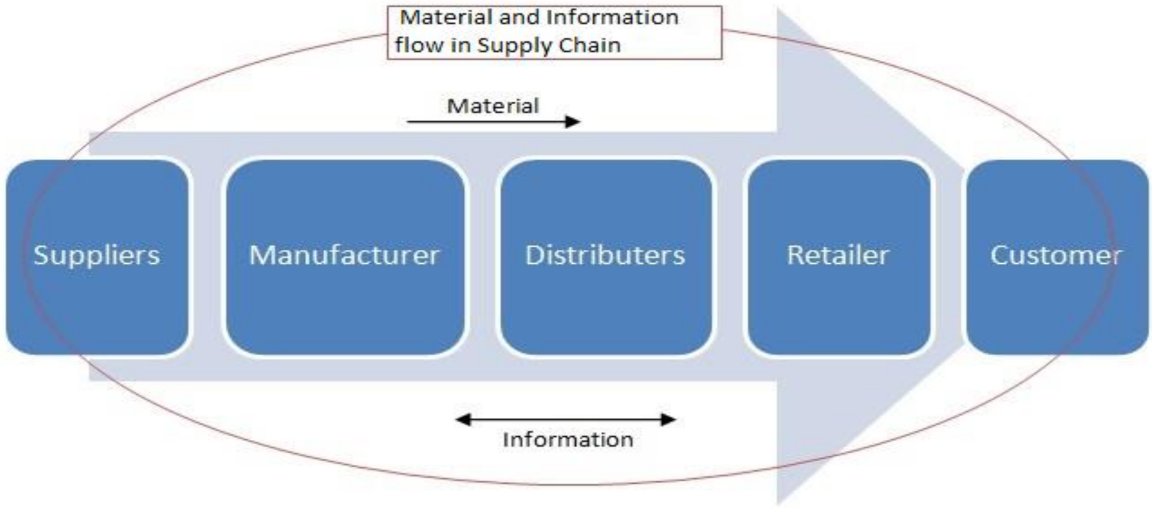
The bottlenecks concept for the production system is widely researched topic in the operations management and supply chains. Ever since the *" Theory of Constraints (TOC)"* put forth by Goldratt and Cox (1984) in their famous novel *" The Goal"* the popularity in this topics has drawn wide attention among academic researcher and practitioners (Beer 2015). TOC is the management philosophy which changes the analysing capabilities of the manager to focus and understand the own companies structures for the better performances (Şimşit, Günay, and Vayvay 2014). The examples set by Ford Motor Company, Motorola, Rockwell International and Boeing shows the positive changes in their performances after they have used the theory of constraints (Goldratt 2004). The TOC analogy is used for the supply chain, where the supply chain fails at the weakest link. The weakest link limits the efficiency and effectiveness of the entire supply chain (Min 2015).

3.1 Supply Chain

Supply chain covers the broad range of functional area within an organization. The functional activities include inbound-outbound transportation, inventory controlling, procurement, manufacturing, and sourcing. The supply chain is not only a chain of business with one to one, business to the business relationship but a network of numerous business and relationships (Pohja 2004) . From the literature review, seems that researchers have studied supply chain from various perspective. There has been much debate over the specific definition of the supply chains. Towill, Naim, and Wikner (1992) presented the definition of the supply chain on the basis of how information and materials flow in the supply chain,

" The supply chain is a system, the constituent parts of which include material suppliers, production facilities, distribution services, customers linked together via the feed forward flow of materials and the feedback flow information"

Figure 3-1Representation of Towill, Naim, and Wikner (1992) definition.



Source 3-1 Authors' illustration based on literature

The supply chain process is the repetitive and innovative process. A proper coordination and exchange of information among all the associated network are required. The efficient supply chain can only be envisioned if all the major elements in the supply chains are coordinated and integrated together. Furthermore, the scheduling, resources management, customer service handling, production planning, forecasting and finally the information systems to monitor all these activities embodies the supply chain (Zigiaris 2000).

There is an involvement of numerous suppliers, service providers, third parties and end consumers in the supply chain activities. The participation of multiple service providers, supplier and consumers make the supply chain an arena of the compound network. For everyone involved in the activities, the complexity in the supply chain causes more uncertainties, increases risks and vulnerabilities (Pfohl, Köhler, and Thomas 2010). Others factors including travel time, machines and vehicles breakdown, lean manufacturing, and outsourcing to another firm, and offshoring and manufacturers desire for flexibility are also a natural sources of uncertainties in supply chains. These risk and vulnerabilities lead to the situation of total absence of information and alertness of potential event occurrences (Ritchie and Brindley 2007).

To meet these challenges, the use of forecasting method and conventional thinking of demands as the only source of uncertainty is not enough. All the components involved in the supply chain network must work towards the unified system to identify these constraints (Arshinder, Kanda, and Deshmukh 2011). The coordination among the various component of the supply chain is needed to investigate. It is essential to identify the component in supply chain constraining the higher supply chain cost and imprecise information.

Although, these uncertainties is not possible to eliminate ,we can meet these challenges to minimize their effect in the high valued and vital components of the supply chain (Levi, Kaminsky, and Levi 2004).

3.2 Supply Chain Management

For the ceaseless integration within the network of supply chain, the researchers and industrial experts advise the manufactures for the judicious use of *"Supply Chain Management (SCM)".* The business size, the number of items produced, business volume, and the production makes the supply chain complex. The major objective of supply chain management is to link these components to cooperate jointly with the firms for maximum productivity and to create beneficial value for all the related parties (Finch 2006).

The premier organisation of supply chain researcher, practitioners and academicians, The Council of SCM Professionals (CSCMP), has recently defined supply chain management as,

"Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies. Supply Chain Management is an integrating function with primary responsibility for linking major business functions and business processes within and across companies into a cohesive and high-performing business model. It includes all of the logistics management activities noted above, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance and information technology." (Vitasek 2013)

The management of, the flow of goods, information's and financial flow are the mainstream objectives of supply chain management. The products in this stream refer to the goods from the upstream supply chain. The information flow includes the orders and delivery reports. Whereas, the financial flow deals with the credit, payment, and consignment. The implementation of supply chain management techniques helped several business entities to be more competitive by lower their cost of doing things and improved the customer services (Mentzer, Min, and Zacharia 2000). Mentzer et al. (2001) elaborate the supply chain management on the basis of its reason and objective, a strategic weapon to build up and enhance sustainable competitive advantage by cost reduction without compromising customer satisfaction. For an example, the efficient revolutionary supply chains strategy followed by US- based Dell Inc to manufacture each system based on the specific customer order and to deliver their products to the client directly has helped them to avoid the large inventory and prevent the need for large warehouses. Dells saved million dollars by reducing carrying the cost of the inventories and the indirect cost of holding obsolete technology (Gunasekaran and Ngai 2005).

Evolution of Supply Chain Management

In the early 1950s and 60s, manufacturers emphasized for the mass production to reduce the production cost with very less process flexibility. The innovative development of the products was very slow, and manufacturers were only depended on in-house technology. Only after the introduction of Manufacturing Resource Planning (MRP) in 1970s, managers realized the impact of Work in Progress (WIP) over the quality, cost, lead-time, and development of new products. On drilling the history over the supply chain, the literature explains the term supply chain management was introduced by Americans consultant in early 1980 (Lambert and Cooper 2000). Ever since the supply chain management concept has ramped with exponential growth in the manufacturing environment, the research of academics and practitioners on the topic has also been increased. The organizational interest to extend the best practices for the management of corporate resources with the involvements of strategic supplier and logistics functions further enhanced the efficiency and effectiveness of the supply chain. This sourcing of resources for the production assembly line and manufacturing plant also drastically ramped from intra-organisational to more inter-organisational (Burgess, Singh, and Koroglu 2006). Nowadays, the upstream supply chain elements, the manufacturers, exploit the supplier strength and technology and further downstream elements, the retailers, seamlessly integrate their physical distribution with transportation partner for efficient and effective supply chain process.

Figure 3-2 Era of the Supply Chain Management

S. No	Era	Era Description
1	Creation Era	The term supply chain management was first coined by an American industry consultant in the early 1980s. However the concept of supply chain in management, was of great importance long before in the early 20th century, especially by the creation of the assembly line.
2	Integration Era	This era of supply chain management studies was highlighted with the development of Electronic Data Interchange (EDI) systems in the 1960sand developed through the 1990s by the introduction of Enterprise Resource Planning (ERP) systems.
3	Globalization Era	This era is characterized by the globalization of supply chain management in organizations with the goal of increasing competitive advantage, creating more value-added, and reducing costs through global sourcing
4	Specialization Era Phase One-Outsourced Manufacturing& Distribution	In the 1990s industries began to focus on “core competencies” and adopted a specialization model. Companies abandoned vertical integration, sold off non-core operations, and outsourced those functions to other companies.
5	Specialization Era Phase Two - Supply Chain Management as A Service	Specialization within the supply chain began in the 1980s with the inception of transportation brokerages, warehouse management, and non asset based carriers and has matured beyond transportation and logistics into aspects of supply planning, collaboration, execution and performance management.
6	Supply Chain Management 2. 0 (SCM 2. 0)	Web 2. 0 is defined as a trend in the use of the World Wide Web that is meant to increase creativity, information sharing, and collaboration among users.

Source 3-2 (Jain et al. 2010).

Figure 3-2 summarized the literature on the evolution of supply chain management. The development of ERP system and the introduction of revolutionary word wide web for the creativity and information sharing that has been adding the value in its evolution. Six major movements have been visualised. The creation, integration, globalisation, specialization phase one and two and SCM 2.0 (Jain et al. 2010).

3.2.1 Components of Supply Chain Management

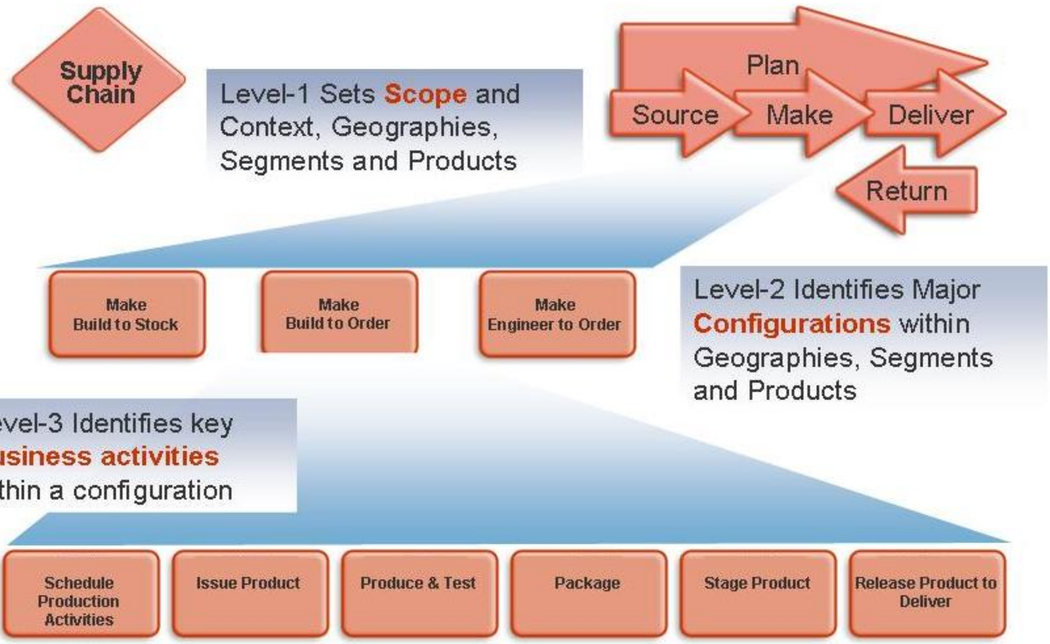
In the supply chain, from the hierarchical perspective level Figure 3-3, there exist three decision levels, strategic, tactical and operational (Ilyas, Banwet, and Shankar 2007). The strategic level defines the business scope over the long term. The strategic level establish the objectives, policies, operating footprint and service levels of the organisation. The medium-term tactical level deals with the production and targets to facilities and transportation. This level determines how the production planning, procurement, logistic plan, inventory targets and the deployment of resources to match the supply and demand. Finally, the operational level in a supply chain hierarchy is related to the short-term planning or scheduling. This level determines, on a daily or weekly basis, the assignment of tasks to units and sequencing of tasks in each unit (Muñoz et al. 2013).

Figure 3-3 Hierarchical level of supply chain management.

Source 3-3 (Ilyas, Banwet, and Shankar 2007)

The supply chain operations reference model (SCOR) developed by American Production and Inventory Control society (APICS) defines the five basic components in the supply chain management. The five focusing processes are, plan, source, make, deliver and return which repeats along the supply chain operations. (Persson 2011). Figure 3-4, shows the basic components are further categories into three level of process details. Level-1, defines the scope of the supply chain, whereas level-2 defines the type of supply chain and level-3 defines the performance attributes. The Supply Chain Council (2012) has also described each of the five components by their distinct management processes.

Figure 3-4 Basic components of supply chain management



Source 3-4 (Council 2012)

Plan: This level addresses the demand, supply planning and its management. The business rules to improve and measure the supply chain efficiency along with the balancing the resources among the entire supply chain is defined.

Source: This level defines the procurement activities like sourcing infrastructure and material acquisition. This level deals with the inventory, inspection, store handling and also discuss how to handle the financial transactions.

Make: Production, assembling, manufacturing constitutes this level. This level includes whether the manufacturing process would be MTS, MTO, ATO[12], CTO[13] or ETO[14]. This

[12] Assemble to Order
[13] Configure to Order
[14] Engineer to Order

level also includes the activities like packaging, staging, releasing and managing production network, equipment and facilities.

Deliver: Delivery consists the warehouse management, order management, and transportation. Furthermore, this manages the inventories, importing and exporting requirement.

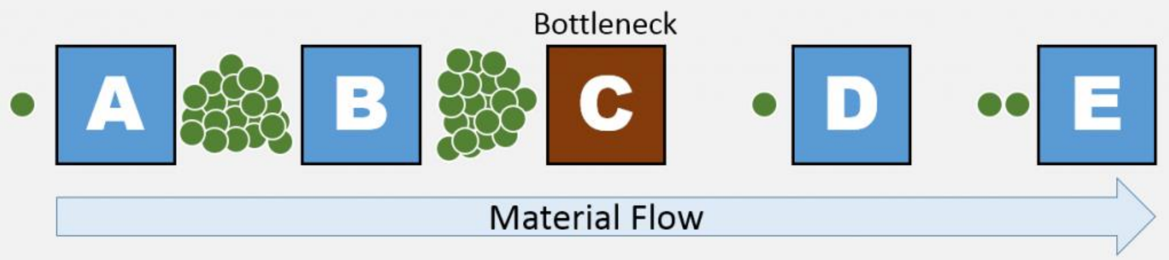
Return: The return involves handling of return flow of the materials. This handle the return of containers, packaging or defective items.

SCOR is recognized as a systematic approach to identify, evaluate and monitor the supply chain performances. SCOR is supposed to be the most promising management tools used to address, communicate and improve the supply chain management decision within the companies and with supplier and customers (Huan, Sheoran, and Wang 2004).

3.2.2 Constraints/ Bottlenecks

Every workplace in the supply chain is characterized by a certain capacity, different work rates, production capabilities and subjects to influences the random variations (Kasemset and Kachitvichyanukul 2007). Machine failure and temporary delays are also the factor to reduce the performance. The differences in their performances lead to the increase the WIP or production in the progress of an individual workplace. The long-term changes in the production system with the demand fluctuation, introduction of new product increases the variability. The variability of the machines causes the blockade or the starvation in the machines. The starvation or blockage could be on either upstream or the downstream of the workplace. Blocking occurs if the machine blocks the flow of products while starvation is the result of waiting. These two stages in a system have the largest effect on slowing down or stopping the entire system. The lowest performance is called the constraints or the bottlenecks, and these bottlenecks in the system have an impact on every logistical target parameters (Schultheiss and Kreutzfeldt 2009).

Figure 3-5 Replication of Bottlenecks with stations



Source 3-5 By Christoph Roser at AllAboutLean.com under the free CC-BY-SA 4.0 license.

Figure 3-5 replicates the bottleneck in the production process with five different stations. The green balls are the products for the further process. The number of green balls in the station C is more which leads to the blocking of products in the station B and starvation in station D and E. This point is the bottleneck and if there is a bottleneck, noting done elsewhere in the value stream can improve the throughput (Goldratt and Cox 1984).

Roser, Lorentzen, and Deuse (2015) definition measure the influence of the bottlenecks by defining:

"Bottlenecks are process that influence the throughput of the entire system. The larger the influence, the more significant the bottleneck".

However, American Production and Inventory Control Society (APICS) relates the bottleneck with the capacity constraints. They define a bottleneck as,

"A facility, function, department for resource whose capacity is smaller than or equal to the demand".

The effects of bottleneck cause the increase in the queues of the workstation. This increment makes the succeeding workstation to starve and impact results in the formation of idle time in the nearby machines. The workstation in the upstream will be full of the buffers while the downstream workstation will have empty buffers.

All the literature work, agrees to the fact that the bottleneck has a negative constraining impact on the system. Since, every cycle a bottleneck is running is a cycle wasted on every one of the waiters of the bottlenecks.

3.2.3 Types of Bottlenecks

All of the discrete events systems have the bottleneck, the biggest problem is they are not momentary, rather shift between the different parts of the system(Lawrence and Buss 1994)

This classification of shifting process is due to the randomness and variation of the production lines. Based on the stations utilization and probability of the specific station being the bottleneck, Lawrence and Buss (1994) have defined scalar measure of bottleneck shiftiness with β.

$$\beta = 1 - (Cv/\sqrt{n})$$

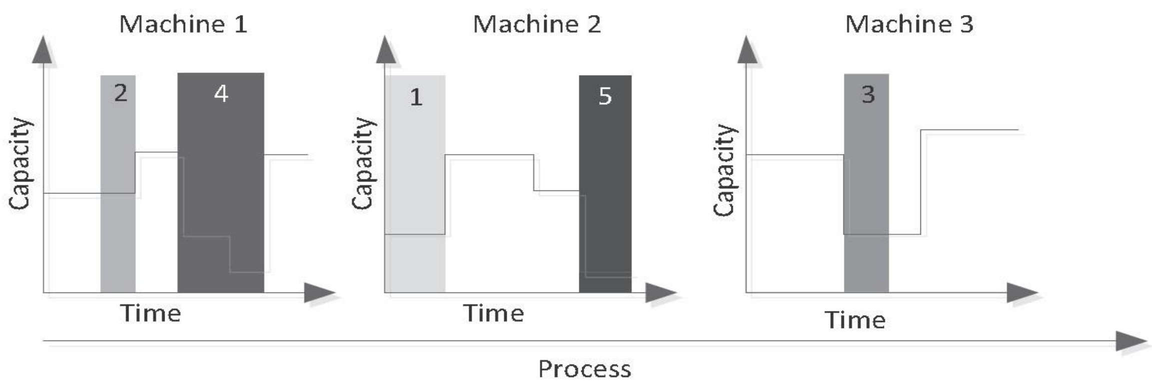
C_v = coefficient of variation of inclusive bottleneck probabilities of the n stations.

N = the total number of stations.

β=0 if production line has one constant bottleneck and β=1 if all the stations have an equal probability of being bottleneck.

However, they also agree on the static appearance of the bottlenecks but mentioned that they are temporary. These temporary bottlenecks are not from the resources, process, facility but could be influenced by the functions and operators.

Figure 3-6 Dynamic bottlenecks behaviour example



Source 3-6 (Lemessi et al. 2012)

Hopp and Spearman (2008) states the shifting bottlenecks shift to another station easily if not identified and corrected and drastically constraints the overall throughput. Figure 3-6 shows the dynamicity of shifting bottlenecks during the process with three different machines, processing in five stages. Initially, the bottleneck (colour rectangular boxes) on machine 2 is seen in the 1^{st} period of the cycle and gradually the bottleneck in machine 1 and machine 3 is considered in the 2^{nd} and 3^{rd} cycle period, which again yields the bottleneck in machine 1 in the 4^{th} cycle period.

Bottlenecks in the manufacturing companies could be internal or external. The internal constraints are those that can easily control or changed. This includes the capacity of machines, workstation, transportation and the ability of production team to schedule, allocate and manage the production process. The external constraints are those that are difficult to control immediately. External constraints include the availability of sufficient raw material, labour's distributions channel management, market demands.

Wang, Zhao, and Zheng (2005) defines the classification of the bottlenecks based on the real time performances of the system and the potential for the improvement, i.e. measurement of performance and the sensitivity. The performances based bottlenecks affect the average waiting time and the capacity workload (utilization), whereas sensitivity based bottlenecks affect the overall system throughput. One of the examples of sensitivity is the economic bottleneck since it limits the profitability (Lawrence and Buss 1995). Based on the literature, frequently explained bottlenecks in the production are summarized below.

- **Material Constraints:**

Insufficient inventories, inadequate forecast and financing system, unable to incorporate customer and supplier change request.

- **Labour Constraints:**

Amateur production workforce, union involvement, labour law, traditional work culture, lack of innovative technical training, hiring and firing policies, poor scheduling.

- **Equipment Constraints:**

Equipment breakdown, improper maintenance, lack of automated equipment, scale and capacity of the machine and work area.

- **Environmental Constraints:**

Government rules and regulation, state and regional laws, social responsibilities, advancement in eco-friendly technology.

- **Policies Constraints:**

Company policies e.g., bonus plans, overtime policy, union contracts, response to demand changing.

3.3 Theory of Constraints (TOC)

Tomas Bata, who founded the world –famous shoe company on the beginning of 20th century, regarded production planning as one of the most important parts of business management (Denisa 2012). He then followed by next famous person, Dr. Eliyahu M. Goldratt who started to deal with productivity improvement tool, developed as Theory of Constraints (TOC) (Sprague 2007). TOC is a management philosophy which focuses on the weakest ring in the chain to improve the performance of the system.

The aim of TOC is to identify and eliminate the constraints in any operation. The limitations in the chain or the process are the weakest link. They are the source of interference for any attempts of improving productivity and increasing throughput (Goldratt and Cox 1984). One of the basic ideas of this theory is the supply chain, any production company contains one or other restrictions, which affects the overall throughput of the real system.

It is, therefore necessary to determine the weakest link, since this is the reason for system degradation (i.e. bottlenecks). In production processes, TOC concentrates on the process that slows the speed of product throughput. For the increment in the system performance and the flow, it is necessary to increase the throughput. TOC emphasize to increase the throughput to a maximum by identifying and eliminating the constraints that reduce overall throughput which could be otherwise unachievable (Jevgeni, Eduard, and Roman 2015). Hence, by removing the bottleneck in an operation, significant improvements follow automatically. The way to overcome the constraints (bottlenecks) is formulated into five basic steps (Figure 3-7) , a company can use to improve the performance and objectives (Goldratt 1990).

- **Identify the system constraint**

To manage and handle the constraints it is necessary to determine them. Identification is a quite straightforward process. Like a technician, who assesses the nature of the problem in the system and comes up with the suggestions, it is necessary to determine an exact source where these constraints are originating before to address them. The constraints could be because of the large accumulation of WIP, variation in cycle time, irregularities in demand and more.

- **Decide how to better exploit the system's constraint**

The basic idea of this step is to make most out of identified bottlenecks. The idle time of the system hinders its output. The best way to exploit the constraints is to get rid of any non-value adding work, its removal or limiting interruptions. The removal of the impediments, providing high-quality tools and materials to making sure that the constraint resource work at a steady pace. Prioritization of the constraint's tasks is necessary and should make them work on the most important ones. The assignment of the work on the resources should be made sure so that no resources goes idle.

- **Subordinate everything to the constraint**

Only the exploitation of the constraints doesn't increase the performances in the weak link. The focus should also be driven to the non-constraints. The principal objective of this step is to fine-tune the rate of non-constraints resources in the process so that they can align with the constraints. DBR[15] is considered as of the technique to subordinate the process in manufacturing (Schrangenheim and Dettmer 2000). The subordination of the non-constraints in both upstream and downstream process could be done by:

- Synchronizing the work rate to avoid overload in the constraints.
- Securing the buffer of work for the constraint is always filled, but not overloaded.
- Ensuring the resources after constraints have some slack to deal with variations.
- Only high-quality work in progress handed to the constraint.

Figure 3-7 Theory of Constraints by Dr. Eliyahu M. Goldratt

Source 3-7 Illustration based on TOC literature (Goldratt and Cox 1984)

[15] Drum Buffer Rope

- **Elevate the constraint**

This is the first step the most of the companies will automatically adopt. It is important to note that elevate comes after the exploit and subordinate. In *the Goal* Goldratt and Cox (1984), scheduler were able to remove some of the load from the constraints by rerouting it across the other two machines. This makes sure if the output of the constraints is enough to supply the demand. The elevation could be done by increasing people, increasing machines, increasing training, increasing tools and its utilization and switching to modern technology.

To achieve elevation improvements, it is difficult, because it requires additional investment in capital. It also requires the significant amount of time to see the positive results. The outcome might even worsen until the improvements start to have positive effects. Hence, it suggested to elevate the only after the exploitation and subordinate.

- **Repeat the process**

Once, the constraint has been improved, it is recommended to identify new constraints if any in the system. This inertia should not allow to causing the system constraints. The validation in the elevation of constraints should be done and could be should be verified by defining,

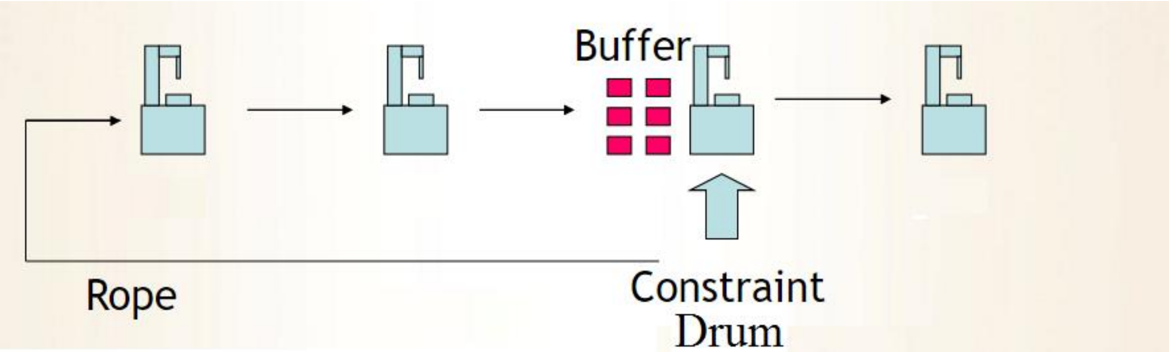
- Whether our goal is still valid?
- Whether our measurement of throughput is still correct?
- Where's the constraint?

3.4 Drum Buffer and Rope

The Drum-buffer-rope is a part of TOC philosophy that represent the synchronised production control approaches. This is bottleneck based order release system. This tool helps to resolve the capacitance problem of semi-finished products that are piled up in the constraints (Georgiadis and Politou 2013). The algorithm is based on the definition of the buffers and sets the pace of the manufacturing system (Watson, Blackstone, and Gardiner 2007).

The logic for DBR is to synchronized production entry work order with the production rhythm of constraints workstation i.e. drum.

Figure 3-8 Drum-Buffer-Rope



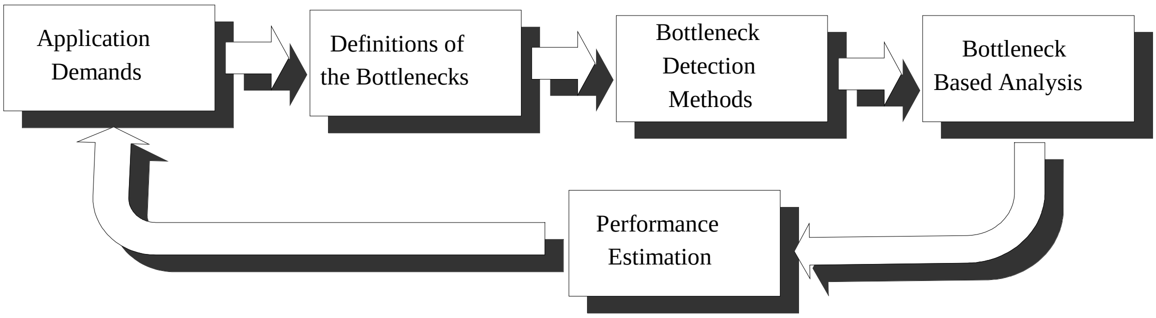
Source 3-8 Authors' illustration based on literature

Figure 3-8 shows the schematic layout of drum-buffer-rope theory. A drum itself is a constraint that sets drum beats (rhythm) for the other processes. It acts as a key factor for the synchronizations of all other resources. A buffer is also called equalization, and this serve to compensate the performances of all the workplaces. A buffer is termed as an analogous to a shock absorber in mechanical system. It protects the drum from starving, the time buffer and stock buffer are inserted to ensure that the material and work-in-process arrives at drum before the schedule. A rope is the information flow from the drum to the material release point, which chokes to match the flow. This makes sure that the raw material is not allowed into the production process with the rate faster than the drum beat.

Also, for the external constraints, Dr. Eliyahu M. Goldratt in his book *The Race* has introduced the simple DBR model (S-DBR), considering the market as the drum (Goldratt and Fox 1986).

The bottlenecks identification is the iterative process as there's always a constraint in the production process Figure 3-9. Soon after the improvements, we might have resolved our priority problem, but we should shift our focus to the second priority issues as the manufacturing process always encounter the bottlenecks and these bottlenecks changes in the process. Also, the TOC cycle repeats with the identification the bottlenecks (Goldratt 1990)

Figure 3-9 Bottlenecks improvements iteration



Source 3-9 (Wang, Zhao, and Zheng 2005)

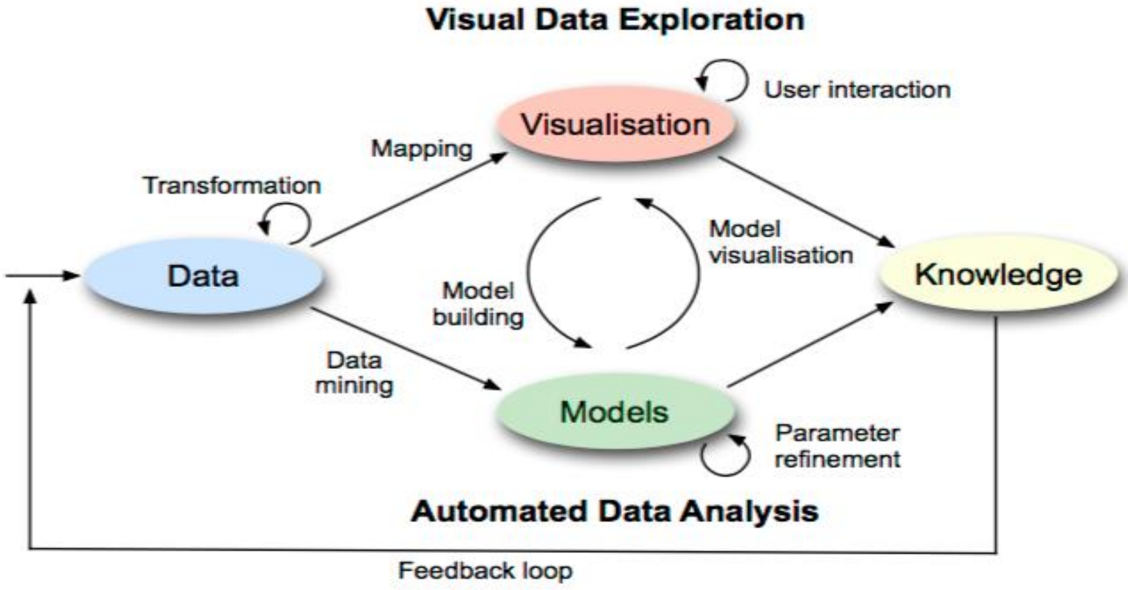
3.5 Data Visualization

A picture is worth a thousand words derives from the fact that the human brain processes pictures and models easier than text and numbers (Lindskog et al. 2016). This approach uses data visualization to build a pictorial or graphical format. It helps decision makers to identify trends; patterns visually, so that they can quickly grasp the difficult concepts. The visual analytic software contributes to provide the interactive visualization so that one can take a step further by drilling down into graphs and charts for more detailed information.

It is very easy for the human brain, to process information, using graphs or charts to visualize clusters amount of data rather than using traditional spreadsheets or reports. (Lindskog et al. 2013) The visualization is also used widely in different industries such as security, health, energy, economy, transportation and individual and personal use.

To gain the visibility of bottlenecks, we need to have an efficient design to identify where the bottleneck resides. The data, models, knowledge, and visualization, are interrelated to form the automated data analysis tool (Daniel Keim et al. 2010). Figure 3-10 shows, the relation of the data mining, model building, model visualization, parameter refinements, mapping and where the user interface with the visualization tool. The user only analysed the output shown in the display, however in the back end, all these processes are mapped. This tool helps to provide the maximum information from the collected data.

Figure 3-10 Visual Analytics process through interaction between data, visualisations, models and the knowledge



Source 3-10 (Daniel Keim et al. 2010)

The simple visualization means the plotting of the graphs for the various processes. However most of the organization have their IT service management and data capturing capabilities, the obtained data (information) from their workflow provides a lot more information for the problem identification, data analysis and evaluation (Sindiy et al. 2013). For instance, in a production line, the number of stations, start time, end time, capacity and utilization if plotted systematically, will ease in the identification of the bottlenecks. Using the business logics and analytical tools helps the manufacturing companies to visualize the system constraint. If more detailed information is collected, there is the high possibility of improving the process constraints identification (Daniel Keim et al. 2010) .

3.6 Identification of bottleneck

There always comes the situation to, which bottlenecks offers the greatest potential for the production planning and optimizations. Knowing the bottlenecks allows the increasing flow by just improving one process in the system rather than all its remaining parts (Kralova and Leporis 2004). Mostly for the potential optimization, the evaluation of these bottlenecks with the support of modern information technology is essential (Schultheiss and Kreutzfeldt 2009).

Identification of bottleneck is not a trivial task. There are numbers of conventional methods to find the bottleneck based on the queues length, average waiting, and utilization. The authors have also discussed the analytical and simulation methods for the identification of bottleneck. The analytical method is appropriate for long term prediction. The drawbacks of the analytical models is they are less accurate and is not suitable short- term bottleneck problems (Yu and Matta 2014). For the complex and dynamic production process, the simulation method helps in identification and the verification of the system performances (Kralova and Leporis 2004). Different researches have been focused for the identification of the bottleneck based on the performances parameter such as production rate (Kuo, Lim, and Meerkov 1996), longest queue length (Lawrence and Buss 1995), highest utilization (Law and Kelton 2000), longest active duration (Roser, Nakano, and Tanaka 2002b) and buffer size and sensitivity (Kuo, Lim, and Meerkov 1996). Mathematical models has the great impact for the scheduling and control of the production line bottleneck management (Aggarwal, Tikekar, and Hsu 1986). Ching, Meerkov, and Zhang (2008) have also developed the practical mathematical method to analyse the non-exponential machine throughput based on the occurrences of blockage and starvation.

Although critics mention, the simulation model takes long-developing time and is tedious to analyse the output. However, most of the literature considered the analytical and simulation method as a tool for the visualisation of the bottleneck detection. Some of the frequently discussed method and tools for the identification bottlenecks are briefed below with their pros and cons.

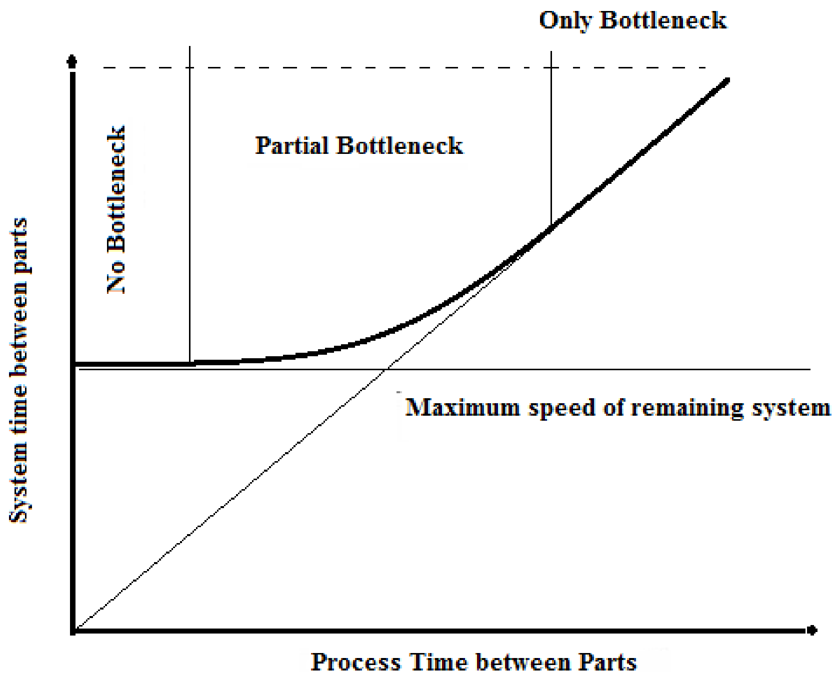
3.6.1 Average Cycle Time

The average amount of time taken to complete the single order is the cycle time. The cycle time is the sum of the processing time of all the steps required to complete a product plus all the waiting or queue time the products incurs in the process (Duwwayri and Mollaghasemi 2001).

$$Cycle\ Time(CT) = Processing\ Time\ per\ order$$

Cycle Time is an essential key dimension to measure the performance of the system as it deals with the waiting time for any process to complete (Muthiah and Huang 2007). The cycle time is the ratio of work in process and the throughput. The bottleneck is the station with slowest cycle time. This station determines the capacity of the entire manufacturing firms.

Figure 3-11 Influence of single process over the system performance



Source 3-11 (Roser, Lorentzen, and Deuse 2015)

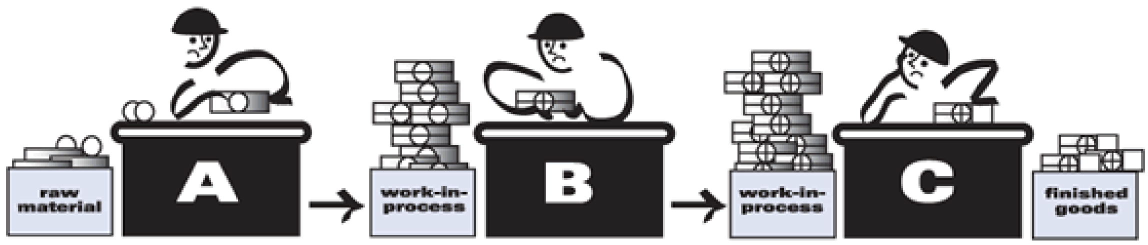
Figure 3-11 shows the influence of the a single process time on the overall system performance with the three condition of being, no bottleneck, partial bottleneck and only bottleneck. Initially, the increment in the process time between parts will be compensated by other slower processes in the same system. Over the period, the process becomes slower as the time between the parts increase, the overall system process degrades. Further increasing the process time between parts will have significant influence over the increase of time between the parts for the entire system.

To improve the Cycle time and throughput of the whole manufacturing process, the increment of the processing rate at the bottleneck is necessary. In the production with high production cost, the cycle time reduction is highly considerable.

3.6.2 The queue length method

In the production line operation, the items are produced and moved to next stations regardless of whether they are actually needed. This conditions leads the stations to wait for the process in a queue. The queue method is the measurement of number of queue in all the workstations. Lawrence and Buss (1994) proposed this method where the machines with the longest queue of the products is the bottleneck.

Figure 3-12 Formation of queue in production line



Source 3-12 Lean Enterprise Institute.

The blocking and starvation are considered as the main reasons for the variation of the queue length. The improvement of queue length is performed either by adding or improving the expensive parallel machine or changing the layout of the products or by correcting the process design. While the literature also suggests the methodologies like the use of buffer size in different production scenarios to reduce the queue length (Conway et al. 1988). The simulation model widely uses the queue length method to analyse the output for number replenishments. The workstations with highest queue is the bottleneck (Hopp and Spearman 2008).

3.6.3 The utilization method

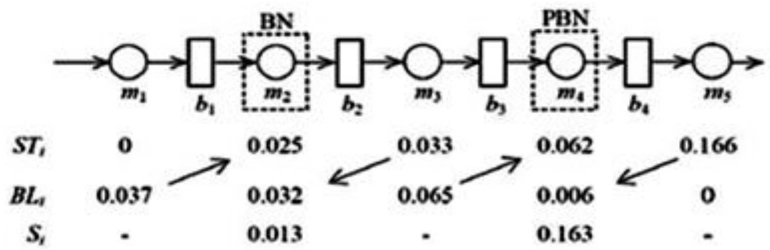
The method of utilization tells how well the resources are used. This method determines the percentage of the time, a machine is active, and then defines the machine with the highest active percentage as the bottleneck. The utilization method is the ratio of flow rate and capacity and always lies between 0-100%. This measure the utilization of the machine involve in the production process by including the performance loss. The bottlenecks shifting are often seen where the utilization rate of the station is same. Lawrence and Buss (1994) derived the formula for the production line utilization as:

$$pi = \frac{\lambda i}{\mu i}$$

Where, p_i is the utilization rate, μ_i the distribution service time with λ_i as the arriving rate. This method states that the machine with highest utilization is the bottleneck (Law and Kelton 2000).

3.6.4 The Arrow based Method.

The arrow based method is dependent on the frequency of the processes being starved or blocked. This approach was developed by Kuo, Lim, and Meerkov (1996) as a system-theoretic model that utilizes the probabilities of starvation and blockage to identify the location of bottleneck (Yu and Matta 2014). The illustration of the arrow based method in the production line is shown below, with machine five different machine(m_i) and buffer(b_i).



The arrows in this method shows the direction of the bottlenecks. The rules for placing the arrows is defined in two steps. If the frequency of blockage of machine m_1 is greater than the frequency of starvation of machine m_2 the arrow is directed to m_2 and if the frequency of starvation of m_2 is larger than the frequency of blockage of m1, the arrow is directed from m_2 to m_1. However, for the multiple bottlenecks the bottlenecks with highest severity is the bottleneck as defined by,

$$S_1 = ST_2 - BL_1$$

$$S_i = ST_{i+1} - BL_i + ST - BL_{i-1};\ \ i = 2,\ldots, M-1$$

$$S_M = ST_M - BL_{M-1}$$

Where, ST_i is the probabilities of starvations and BT_i is the probabilities of blockages.

3.6.5 The bottleneck walk

The method *"The Bottleneck Walk"* proposed by Roser, Lorentzen, and Deuse (2014) is developed at Robert Bosch GmbH and is still in use. This method helps to find the bottlenecks in the manufacturing system through the observation. Two parameter, process and inventory observations are used since, all the equipment's in the production system are not equipped with the data monitoring system. The major use of this method is to identify the direction of the obstruction and to identify that resources as a bottleneck.

For this method, the few observations over the processes and numbers of stations are needed to be observed. The further insight could be taken from the production historical data.

<u>Observation of Process</u>

- Stations waiting for the material, the bottleneck is towards the stations where the parts come from. (Upstream because of Starvation)
- Station waiting to transport the semi-finished products, the bottleneck is towards the stations where the parts go. (Downstream because of Blockade).

<u>Observation of the Inventories</u>

- Station having low level of inventory, the bottleneck is towards the stations where the parts come from (Upstream because of low inventories).
- Station having high level of inventory, the bottleneck is towards the station where the parts go (Downstream because of high inventories).

Figure 3-13 The bottleneck walk method

Source 3-13 Illustration based on the literature

This method is simple and need not much of mathematics and calculations. However, this method could only be unitized to a limited extent, where the production processes aren't too complex.

3.6.6 Critically Indicators based Method

Kralova and Leporis (2004) proposed the criticality indicator approach for the detection of the critical workplaces to identify the bottlenecks. This critical indicator not only identifies the critical workplace but also evaluates the need for either capacity expansion or allowing better utilization. The criticality indicator KR_i for the i^{th} workplace is calculated considering the differences of the individual rates at the i^{th} workplace with respect to the whole system average rate.

$$KRi = \left|\frac{\sum_{i=1}^{n} Bi}{n} - Bi\right| + \left|Ii - \frac{\sum_{i=1}^{n} Ii}{n}\right| + \left|Bli - \frac{\sum_{i=1}^{n} Bli}{n}\right| + \left|Li - \frac{\sum_{i=1}^{n} Li}{n}\right|$$

The individual rates include the utilization (B_i), starvation (I_i), blocking (B_{li}), and waiting (L_i). The i^{th} workplace with minimum criticality factor is the bottleneck and the maximum is the capacity reserve.

3.6.7 Turning point method

Li et al. (2007) developed this data driven model based on the blockage and starvation . A turning point is defined where the difference between blocking and starvation alter from positive to negative. Along with the sum of turning point machine blockage and starvation is lower than two adjacent machines. Thus, the “turning point” machine has the highest percentage of the sum of operating time and downtime compared to other machines in the segment (Kralova and Leporis 2004) .

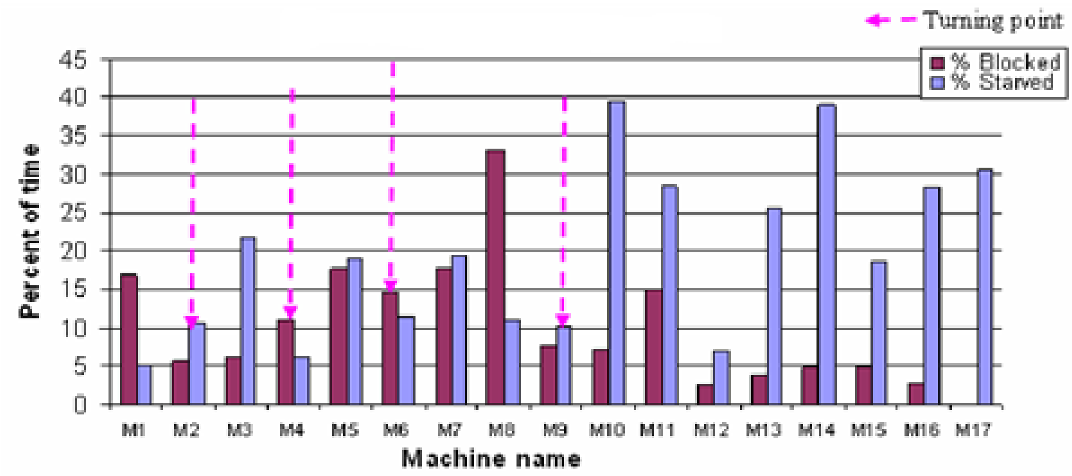
The machine i^{th} is the turning point in a n machine stations, if

$$TB_i - TS_i < 0 \text{ also,}$$

$$TB_i + TS_i < TB_{i-1} + TS_{i-1} \text{ and}$$

$$TB_i + TS_i < TB_{i+1} + TS_{i+1}.$$

Figure 3-14 Graphical representation of Turning Point Method.

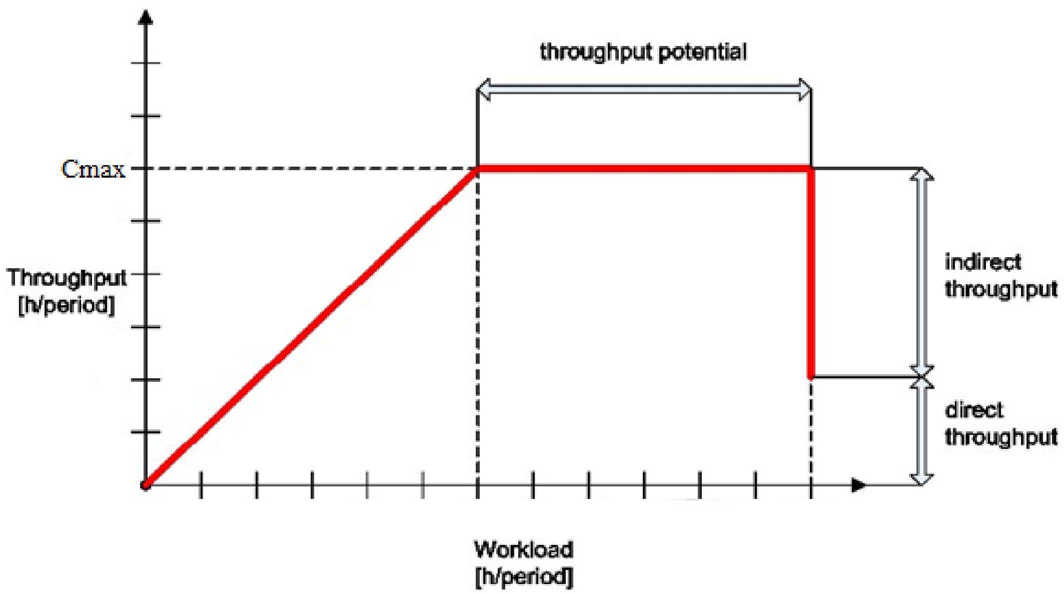


Source 3-14 (Li et al. 2007)

3.6.8 **Throughput curves**

Previously, the funnel model was used to describe the logistical system graphically, where the workload is depicting by the fill level, and the neck of the funnel define the capacity (Nyhuis and Wiendahl 2009). The bottleneck management instrument with throughput curve is developed by (Kubera et al. 2010) for the identification and evaluation of the bottlenecks.

Figure 3-15 Throughput Curves



Source 3-15 (Kubera et al. 2010)

The throughput curves provide the visual approach to the relationship of various inputs variables in relation with the output variables. The inputs variables include work load, capacity and work plan whereas, the output variable includes the inventory levels, performances, and capacity. The Figure 3-15 represents the throughput curve analysis based on the capacity constraint. This represent the single order stream where the capacity constraints of the bottleneck restrict the throughput of the production. The bottleneck of the workstation determines the order stream in the production and this control the performances in the system (Goldratt 1990). The x-axis represents the workload hour per period and the y-axis represents the throughput. In the initial stage, the increase in the workload also enhances the throughput of the production, however when its capacity limits the bottleneck workstation, the further increase in the workload doesn't have any significant improvement in the throughput. This ceiling the overall performance potential to be saturated at the level represented by angle bisector of the line.

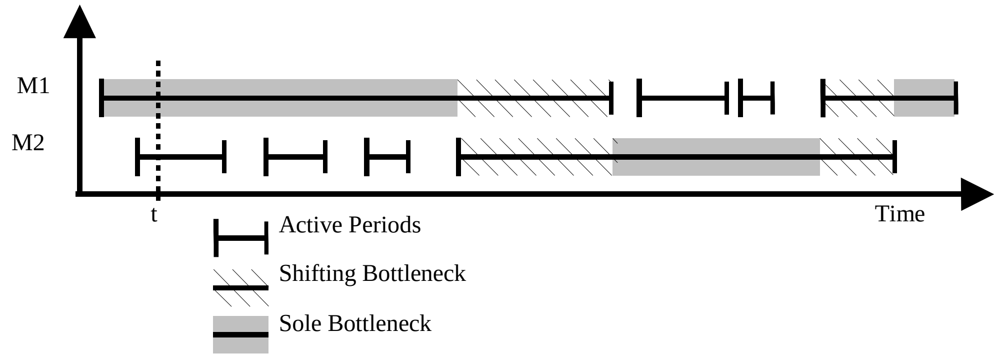
The vertical line at the end shows the work processed before or after the bottlenecks workstations. This line is called the indirect throughput whose starting point, and the area between the bottom of diagram is the direct throughput. The direct throughput represents the amount of work process in the bottleneck workstation. The bigger the ratio of indirect and direct throughput the higher will be the effect over the productivity optimization of whole production system.

3.6.9 Momentary Shifting Method

The conventional methods described above have lots of drawbacks and errors. These methods provide rare information of the production system in today's turbulent environment of production (Wedel et al. 2015). The momentary shifting bottleneck detection method is based on the analysis whether the processing machine is active with the longest uninterrupted period. This model underline the concept of active duration method developed by (Roser, Nakano, and Tanaka 2002b) . The period of the analysis is compulsory in this method to identify the momentary bottleneck.

In a production system bottlenecks frequently shift because of the frequencies of the machine being starved or block. The longer the machine runs without interpretation, the more likely the machine will have a negative impact on production. This will ultimately lead to the loss of the performance in the production; as a result, it is the bottleneck (Roser, Lorentzen, and Deuse 2015).

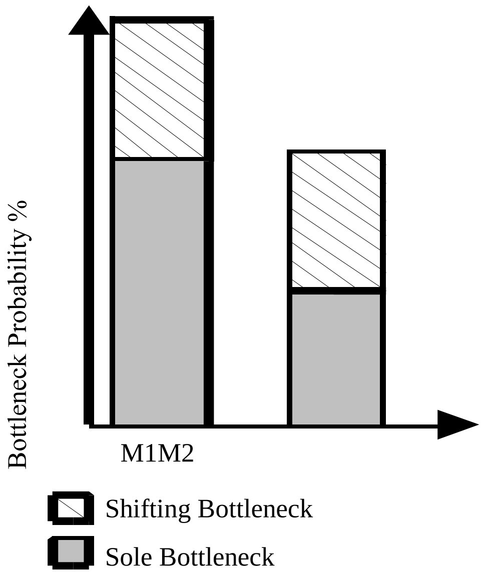
Figure 3-16 The momentary shifting bottleneck visualization



Source 3-16(Roser, Nakano, and Tanaka 2002a)

The Figure 3-16 visualize the momentary shifting bottleneck, where two different machines are active and inactive during the period. At the initial momentary period t, the machine M1 is active for the longer period than machine M2 which is active and inactive on that period. This shows machine M1 as the sole bottleneck. However, in the mid time period the bottleneck shift from M1 to M2 as M2 has longer active period than M1. Again at the end of the time period, M1 is active for the longer period than M2 which again make M1 as a subsequent bottleneck. This shifting details in the bottleneck identification is used to evaluate the probability of machine being the bottleneck and is helpful for the sensitivity analysis.

Figure 3-17 Graphical percentage representation of sole and shifting bottleneck



Source 3-17 From Figure 3-16

This method defines the roles of bottlenecks and quantifies their occurrences. This provide strength to investigate the momentary bottlenecks over the selected period. This ultimately lead to investigate the percentage of time machine being sole bottleneck and same machine roles for being shifting bottleneck. Figure 3-17 shows the machine M1 and M2 from Figure 3-16 being the sole bottleneck and the shifting bottlenecks with their respective percentage. From the Figure 3-17, we can conclude M1 is the primary bottleneck and M2 is the secondary bottleneck. The improvement in the machine M1 will have larger effect in the performance improvement of the overall system throughput.

Table 3-1 Summarized bottleneck identification method used in the thesis.

Method	**Characteristic**	**Measurement**
Queue Size before the machine	The bottleneck is the machine which has the longest queue before the machine, waiting to be processed.	Quantity of products
Utilization Factor	The percentage of time that the machine is working with regards to the system"s overall time is measured. The machine with highest utilization is the bottleneck.	Percentage
Cycle Time	The cycle time is the sum of processing time of all the steps required to complete a product	Processing Time
Waiting Time before the machine	It is measured on how long a product will wait in queue to be processed.	Time
Active State Method	Sum of the overall duration that a machine is in active state (working state). The machine with the highest continuous active period is the bottleneck. This method is applied for dynamic bottleneck detection methods.	Percentage of time or Time unit
Shifting Bottleneck Method	Duration of the active state without interruption in a period of time for a production station. Even though instantly some machines can be the bottleneck, the one with the highest value is the bottleneck.	Percentage of time or Time unit

Source 3-18 Illustration based on the literatures

4.0 Research Methodology

This chapter provides the methodologically relevant procedure adopted for the thesis. Since the study is focus for the identification of bottleneck, this section provides the best possible approaches for the solution. The first part gives the overview of the research design. Secondly, it presents the data collection techniques and types of data collected. Finally, the analysis tools and technique adopted for the assessments in Chapter 5.0 are explained.

This thesis studies both the descriptive and exploratory method. It aims to describe, organize and present the information's for identifying the bottleneck in the productions. Greene and David (1984) also refers, the research design can either be descriptive or exploratory focusing on the nature of research. The research begins with qualitative method and to further enhance the finding, a quantitative measure in formulating outcomes is followed.

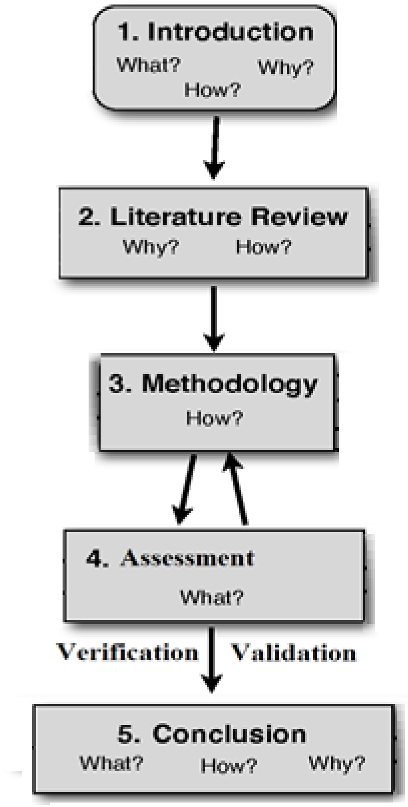
4.1 Research Design

The framework of this thesis has followed the steps found in Denscombe (2013) underlying logic of research activity and is summarized in Figure 4-1. The research objectives and the scopes are justified in the introduction. In reference with the case firm process structure and collected data, the distinctive theories and models are explored in the assessments and our findings are presented with associated limitation.

The study adopted the mixed method of research design, the combination of quantitative and qualitative methods. As defined by Fetters, Curry, and Creswell (2013) mixed method research is an approach to " *inquiry involving collecting both quantitative and qualitative data, integrating the two forms of data, and using distinct designs that may involve philosophical assumptions and theoretical frameworks and provides a more complete understanding of research than either approach alone*."

The thesis is intended to represent the ubiquitous data of Piplelife Norge AS production section, whereby a visual approach of bottleneck detection method could be applied. The aim of the thesis is, identifying the bottlenecks in the production by representing the collected data with best visual approaches. For this, the case environment had been explored to understand the process flow. To design the theoretical and to simulate the process flow, authors had visited the case firm production site along with their supply chain manager and the production in charge in Surnadal.

Figure 4-1 Logic of Research Design



Source 4-1 Illustration based on literature from (Denscombe 2013)

4.2 Data Collection

The data collection and case firm visit were done together while conceptualizing the methods to identify the bottlenecks. Most of the data in this thesis are from Merit Consultancy AS on behalf of Pipelife Norge AS's. Since the ERP system is handled and managed by Merit Consultancy AS.

Qualitative approaches were adopted in the preliminary phase where we had conducted rounds of meeting with Merit consultancy AS. The discussion and meeting were structured around the Pipelife existing production structure and their ERP system. These meeting provided us the opportunities to understand the business process orientation and information system that are installed in the Pipelife. This also helped us to understand nature of the data being recorded in the Pipelife and how these data could be gathered for the research. The information collected from those discussions provided the key information to test the associated correlation between the dependent and independent variables for the quantitative approach.

In order to scientifically address the research problem both the primary and secondary data were used. Hox and Boeije (2005) states, this ensure that the study is coherent and the information collected indeed helps to resolve the problems. The primary sources include the details production structure of the case firms, structured and relational questionnaires and the case firm visit. The secondary sources, use of the statistical records, internet archives, performance reports and ERP databases to analyse the current product manufacturing details. In additional with several e-mail correspondences, numbers of meeting and discussion were conducted with Merit Consultancy AS and a single meeting with Piplelife Norge AS.

Few data related to the types of machines and its working mechanism were from Pipelife Norge AS. These data were collected during our case firm visit. The very few data variables like amount of raw material, tools changed, waste, time period for the repair, maintenance were not feasible to collect. For the easiness in the calculations, the definition of the stations, selecting the number of stations for the evaluation are manipulated without manipulating the data.

4.2.1 Sample Frame and Sample

Brown and Churchill (2014) defines the sample frame as list of the elements from which the sample is drawn. Literatures have different perspective regarding the sample size as it depends on the discipline, level of confidence and expected output (Collis and Hussey 2014). In our case, the sample frame is only the production lines E1 to E6. These production lines are sorted as stations for the year 2014.

All the data are extracted from SQL server which than exported to Microsoft Excel 2016. The VBScript and Macros in Microsoft Excel 2016 are used for the calculation and to sort the data according to our requirement. The data contained the statistics for all the production line, along with different products type and different unit of measurements. The data contained the partial statistics from 2013 and 2015, however, there were more data and details for the year 2014. The start time, day, month and year with their respective finish time are sorted for the period of 2014. Product type and the measurement of unit are also sorted for the uniform result in every stations

All the participant’s involved in this thesis considered the data collected from the sources and existing ERP system of Pipelife to be highly confidential, hence a *Standard Agreement* and separate *Confidentiality Agreement* between authors, Pipelife Norge AS and Molde University College had been agreed on 18 Day of March 2016.

4.3 Research Approaches

Hult, Ketchen, and Slater (2004) mentioned the exploitation of the information to improve the outcomes is the focus of most of the supply chain activities. Application of TOC to exploit the available information is assumed to be the most successful method for the fixed bottleneck, that prevent the management to reach its goals (Okutmuş, Kahveci, and Kartašova 2015). However, this method limits its implementations in the production processes where the bottleneck changes depending on the portfolio of the product prepared.

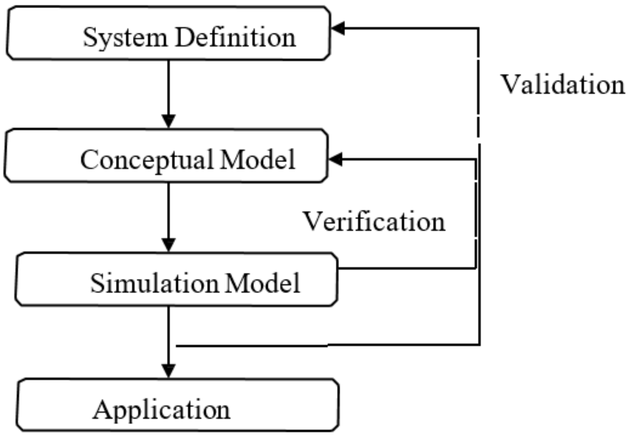
The authors archived the four detection solution approaches theoretical, mathematical, simulation and momentary shifting bottleneck visualization to be implemented for the identification of bottlenecks. The approaches presented, enhances the effectiveness and efficiency of the production. The addition of business analytics tool visualization, contribution could be vividly framed in the business operation. The following section provides the insights of all the four approaches adopted in the thesis. These approaches explain how the assessment and empirical finding of this thesis is conducted.

The observation approach uses the two major parameters, the observation of the available materials and the observation of the process (3.6.5 The bottleneck walk). The material availability itself is not the bottleneck; however, its availability level provides the directional information to identify the bottlenecks. Similarly, the observation of the process provides the direction of the process being slow. These parameters are observed to identify whether the bottleneck flow is upstream or downstream. For this method, the few observations over the processes and numbers of stations were observed. The further insight was given by the production controller from their historical data.

The mathematical approach uses the calculation of the cycle times. The average cycle time is calculated for each stations, and their comparison is made based on the average length of the cycle time in each stations (3.6.1 Average Cycle Time).

The simulation approach simulates the conceptual model developed to evaluate all the stations averages over the numbers of replications. Simulation provides the superior insight into complex theoretical relationships, especially when challenging empirical data limitations exist. The average queue length (3.6.2 The queue length method) average utilization (3.6.3 The utilization method) have been analysed in this approach. The simulation model framework has been adopted from Law and Kelton (2000). The developed simulation model has been verified and validated.

Figure 4-2 Simulation model framework



Source 4-2(Law and Kelton 2000)

Finally, in the Momentary Shifting Method approach based on the active period method developed by (Roser, Nakano, and Tanaka 2002b, a) has been analysed. The stations during the observed interval time have been classified into either being in an active state or inactive state. Processing all available data using this method shows at the particular time which machine is the bottleneck or non-bottleneck and when does the bottleneck shift(3.6.9 Momentary Shifting Method). Therefore, this provides the clear picture for the possibility to detect and monitor the bottlenecks and quantifies the bottlenecks at all the time.

5.0 Assessment and Empirical Finding

This chapter present the evaluation of the method discussed in the literature review. The methods used in this chapters are based on the nature of the collected data. This brings together the discussion, and the research approaches raised up in the previous chapters. Furthermore, the chapters calculate the key finding and discuss the pros and cons of the respective method to fulfil the objective of the thesis.

5.1 Observation Approach

As mentioned in research approach, this method is based on the experiences of the production controller to identify the primary constraints. The analysis is carried over the discussion based on the occurrences of various circumstances in the production.

The company ideal demand pattern over the horizon is shown in Figure 2-1. Starting from mid-May, the demand from the customer increases until the end of the August. The production company environment is MTS. The production is planned based on the three major criteria, the product stock level, expected sales and the production efficiency. The major components in the production system have already been discussed in 2.0 Research Environment. The replication of production flow is shown in Figure 2-2.

The first process in the production starts with the mixing of the raw materials. The mixer has the capacity of mixing the raw material every day. The overall capacity of the mixture is 50,000 kg per day. After the mixture of four different raw components, the pipe manufacturing raw material are then transported into four separate silos, each having capacity of 20,000 Kg. The total capacity of these silos is 80,000Kg. However, if the raw material inventory is reduced to 20% the production process is stopped. The production run 24 hours a day, and the production productivity is only limited on either of the three condition, production system failure, shortage of mixed raw material or warehouse space constraints.

In this approach, we focused on looking into the case firm production superficially. During the peak period, we have observed the production is constrained by the resources presented outside the observed system (production). The space constraints in the warehouse and the mixing capacity of the mixer are the two major limitations. The space constraints of the warehouse could be managed with the various space management technique, like vertical cube utilization, tunnel rack, and improved inventory management system but, the capacity constraint of mixer that leads into the shortage of material availability is very critical for the company overall performances and should be addressed with highest priority.

Working in the MTS environment, there is always a significant impact from the market demand and the workload (Aslan, Stevenson, and Hendry 2015). The availability of the material has the important role in the workload and the production capacity. The relation of workload W (derived from the work plans, planned demand and planned cycle time) and capacity (Ca) of the production will have either of three conditions;

Ca = W (Sufficient capacity and is not critical since capacity matches market demand (workload)

Ca > W (Excess capacity and is not critical)

Ca < W (Insufficient capacity, this leads to the capacity bottlenecks)

The material availability is another parameter for the production process, this could be derived from the respective bill of material. The material demand and the material supply should be sufficient for the necessary stations of the production. Material availability is the index to measure demand and supply ratio and could be either of three conditions.

$$Material\ Availability(MA) = \frac{Production\ Material\ \ Supply(MS)}{Produciton\ Material\ Demand\ (MD)}$$

MA = 1 (Sufficient material available and is not critical)

MA > 1 (Excess material available and is not critical)

MA < 1 (Insufficient material, this leads to the production stop)

Hinckeldeyn et al. (2011) visualize the 9 different cases in the production of MTS environment with enhanced throughput curves (Figure 5-1) . On observing the case firm, we focused to use this evaluation for the bottleneck, as this helps to prioritize the system optimization potential and ensure sustainable bottleneck management.

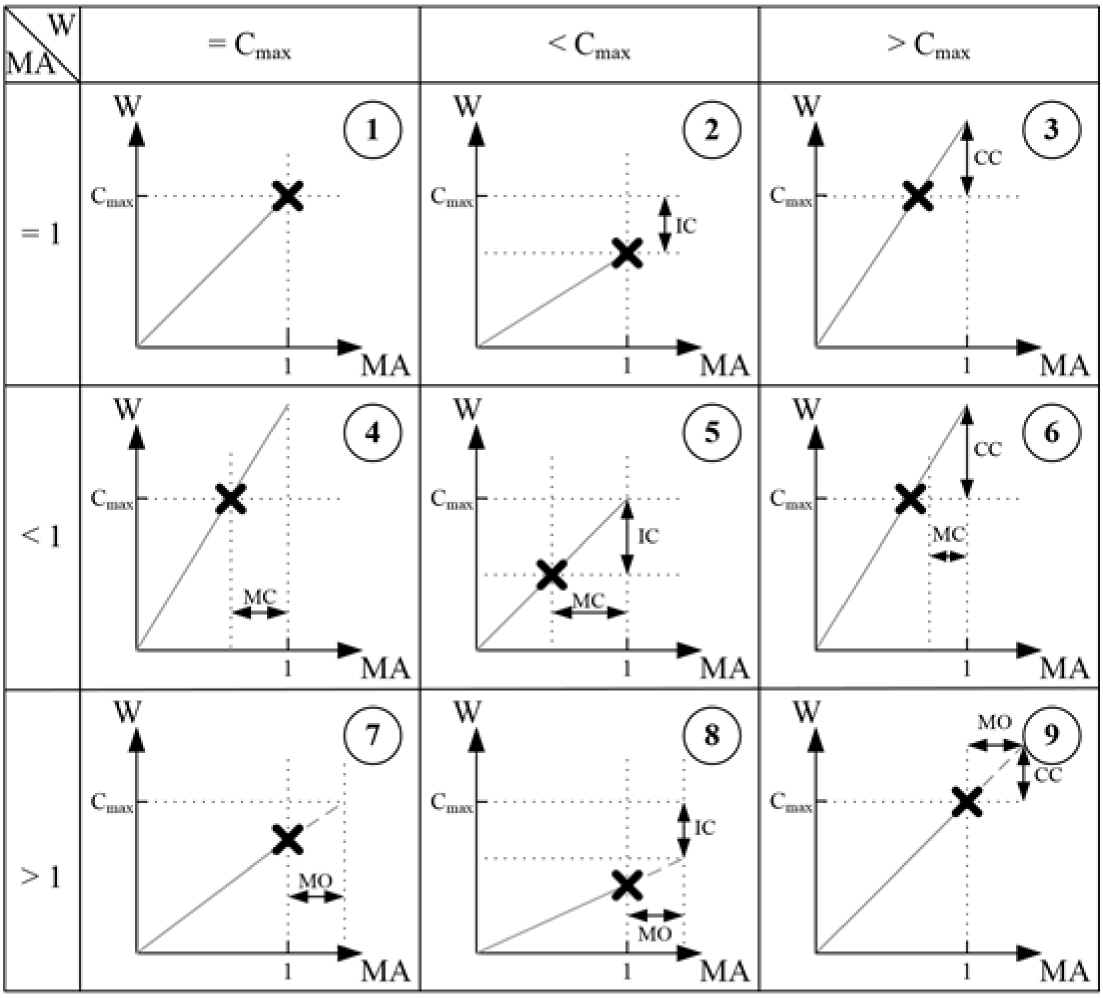
MA = 1

Case 1: This is the optimal planning; no any action is required. The material sufficient and there is no any bottleneck.

Case 2: This is case of IC[16], although this is not the bottleneck, the workload is satisfied, the capacity could be minimized to streamline the workload.

Case 3: This is the case of capacity constraints, the two options to deal with is either to the reduce the MA or increase in the capacity.

Figure 5-1 Possible condition in production with workload, capacity and material availability.



Legend

—— : Operating Curve
✕ : Estimating operating point under consideration of System contraints
MO : Material Over Supply
MC : Material Constraint
IC : Idle Capacity
CC : Capacity Constraints

Source 5-1 (Hinckeldeyn et al. 2011)

[16] Idle Capacity

MA < 1 (Restriction, because of Material Constraints)

Case 4: In this case, the increase in the material availability will not improve the system performance until the capacity is improved. This is because the capacity is fully loaded and couldn't yield more throughput. Hence, the synchronization of capacity with material availability is needed.

Case 5: Since, the workload is less than the capacity, the increase in material availability could be compensated by the idle capacity or else the capacity could be minimized for the optimal productivity.

Case 6: This is the most critical bottleneck situation in the production, the occurrence of material constraints and the capacity constraints at the same time. The case firm comes across the same position during the peak time. The operating point should be corrected twice in this instance since the operating point is dependent on both material constraint and capacity constraints. The dominating constraint has to be investigated, and countermeasure should be taken. However, to cover the demand throughout the year, the case firm could also produce more during the low season and build up their stock levels.

MA > 1 (High material availability)

Case 7: This is not likely to be the bottleneck, since the material is sufficiently large and the capacity is enough.

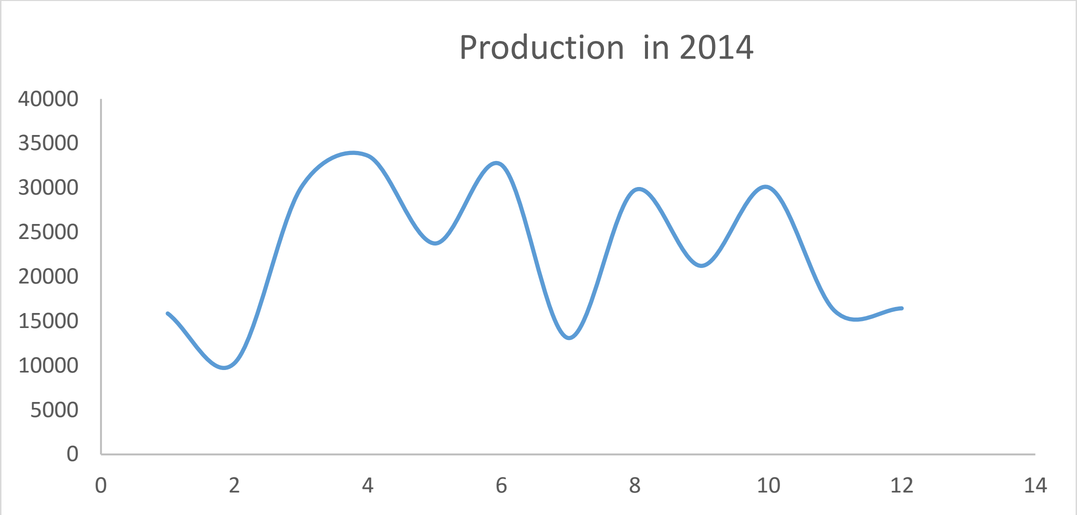
Case 8: This is also not the bottleneck; the workload is less than the capacity. The idle capacity emerges in this scenario which could be streamlined with proper planning

Case 9: The workload in this case is higher than the capacity, although the availability of material is sufficient. The bottleneck might be seen due to the capacity constraints. However, the increase in the capacity mitigate this scenario.

5.2 Mathematical Approach

The production curve for the 2014 from the six different station for item 001 is summed up in the Figure 5-2. Starting from the March the production has started increasing till April 2014. In the month of July, the production reduces abruptly to nearly 40% and for rest of the month the production was fluctuating. During this year, the company has production of around two hundred and seventy-two thousand piece of the units with an average of twenty-two thousand pieces.

Figure 5-2Production from E1-E6 in the months of 2014 for product type 001



Source 5-2 From the collected data

The measurement of the cycle times for the product type 001 in all the six stations have been calculated based on the processing time per order. Defined in 3.6.1 ,to find the bottleneck in these production lines we have calculated the average cycle times for all the stations in the year 2014. The different cycle times for all the dates have been recorded. Correspondingly, we have also calculated the average cycle time in the same year for two different periods i.e. from January to June and from July to December.

The average cycle time period of each station have been compared. The bottleneck has been identified as a station having longest cycle time since the bottleneck definition states that the bottleneck is supposed to be the machine whose cycle time reduction leads to the improvement in the system output (Yu and Matta 2014).

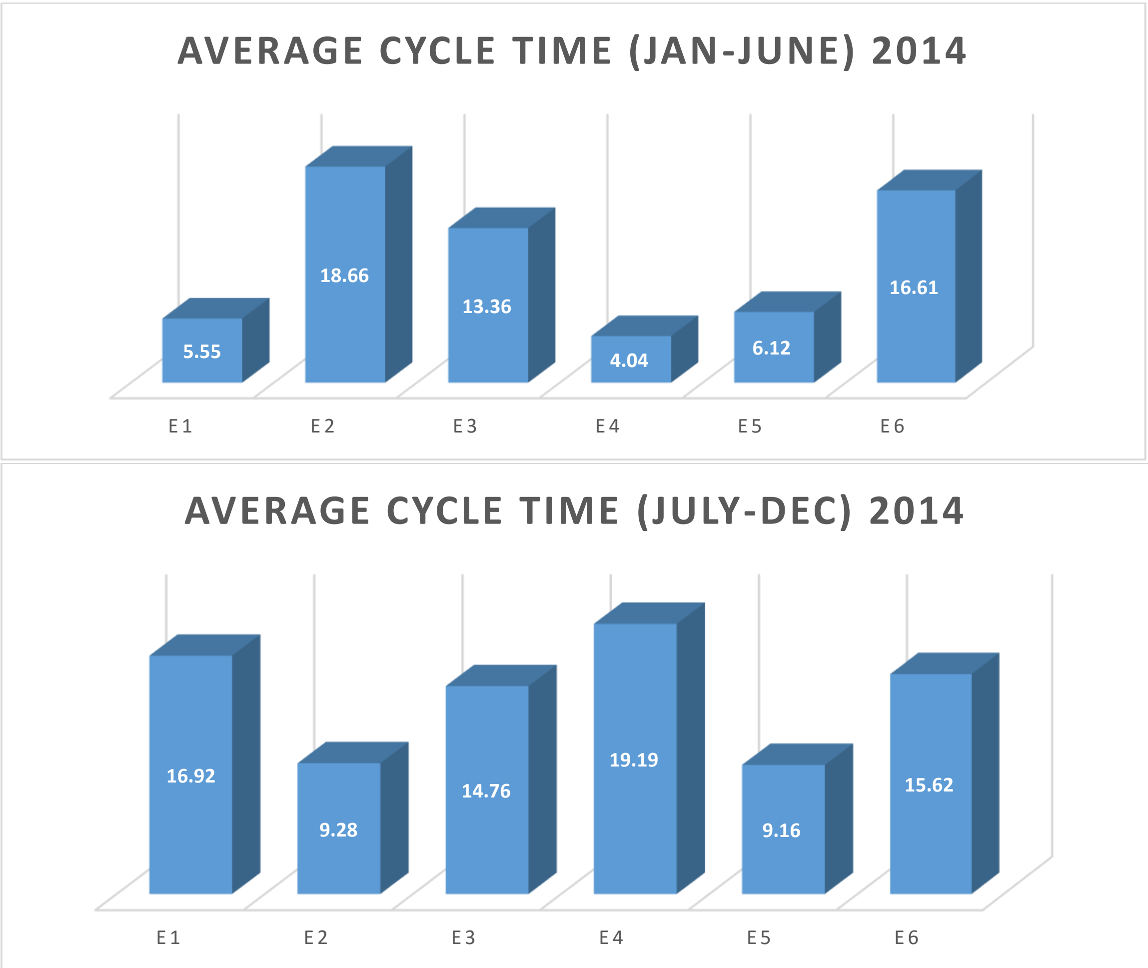
During our analysis, we have analysed the average cycle period method in two half of the year. The average cycle time of the station E1-E6 respectively from January to June and from July to December for the product type 001 in 2014. The respective data for both the half is shown in Table 5-1 and is graphically represented in Figure 5-3.

Table 5-1 Average cycle time of the station E1-E6 for product type 001 in 2014.

January to June	
Production Line	Average Cycle Time (m)
E1	5.55
E2	18.66
E3	13.36
E4	4.04
E5	6.12
E6	16.61

July to December	
Production Line	Average Cycle Time (m)
E1	16.92
E2	9.28
E3	14.76
E4	19.19
E5	9.16
E6	15.62

Figure 5-3 Graphical representation of Table 5-1



In Figure 5-3 the first figure starting from January to June, the bottleneck is identified as station E2 since, it has largest cycle time of 18.66m. Stations E6 and E3 are considered as the secondary bottlenecks with the average cycle time of 16.61m and 13.36m. The station

E4 has the cycle time of 4.04m which is less than all the other stations in that period. The station E4 has never been the bottleneck during this period.

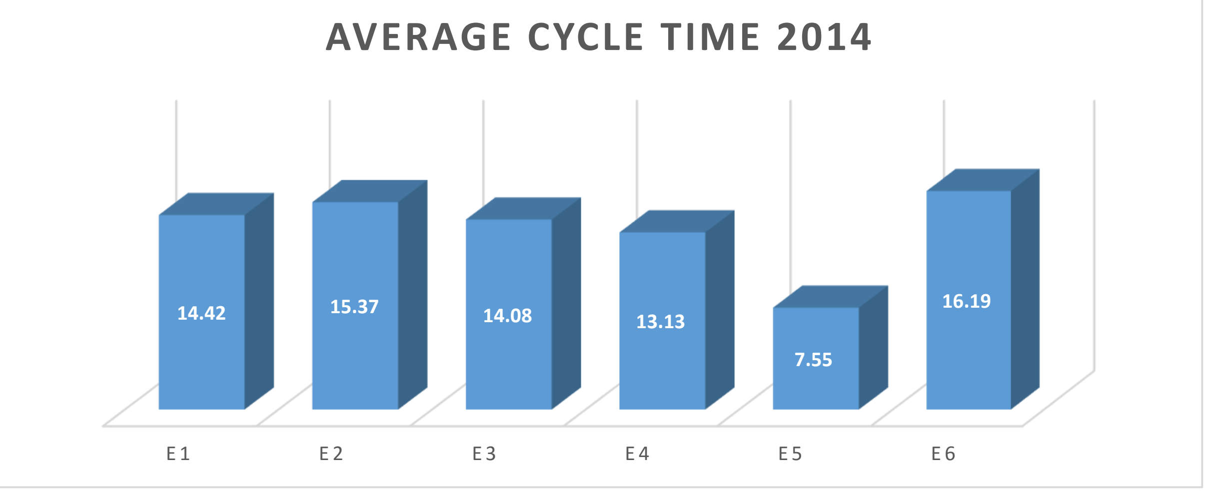
However, during the 2nd half of the period. E4 has been considered as the bottleneck with the longest cycle time of 19.19 m and E1 and E6 as the secondary bottleneck with the respective cycle time of 16.92 m and 15.62 m.

We now analysed the average cycle time of all the station throughout the year, and the bottlenecks identified during the halves are changed.

Table 5-2Average cycle time of the station E1-E6 for the product type 001 in 2014

Production Line	Average Cycle Time (m)
E1	14.42
E2	15.37
E3	14.08
E4	13.13
E5	7.55
E6	16.19

Figure 5-4 Graphical representation of Table 5-2



From the Figure 5-4, we have found the station E6 has largest average cycle time than all of the other stations in the production line. The average cycle time of station E6 is 16.19 m, which mean it takes 16.19 minutes for each product to manufacture. Additionally, E2 and E1 have the respective role in delaying the production line with their average cycle times of 15.37 m and 14.42 m. This method states that longest cycle time of station E6 is a bottleneck and the improvement in the processing time of station E6 will have accountable impact over the performance of the production.

This is the simple and fast method to identify the static bottleneck. However, this approach has disadvantages as it does not include any loss and only consider the capacity under ideal conditions. The bottleneck detection with averaging the cycle time fails to find the momentary and shifting bottlenecks. This method identifies the major bottlenecks but doesn't explains the influence of the other secondary bottlenecks in the production.

From the calculation, we conclude that the average cycle time method does not precisely specify the bottlenecks. This method identifies the bottlenecks that has never been a bottleneck. There will be huge variation in the analysis if this method to identify the bottlenecks is used.

5.3 Simulation Approach

The variation in the processing time for the different stations creates the variation in their utilization. This further leads the stations to have the queue in the processing of the raw material. The materials have to wait for the process to complete which degrade the production efficiency. The data driven modelling and simulation provides the user for simulating their existing production model to analyse above mentioned performance measurement factors. This simulation model provides the user to analyse their production system with the existing collected data collected in the spreadsheet, forms or template and do not require much of programming with limited simulation knowledge (Wang et al. 2011)

The object of this approach is to use the discrete event simulation to identify the bottlenecks in the existing production system based on the data collected for the year 2014. The simulation model calculates the quantitative data for average utilization, queue and waiting time for the each of the station and based on the result, the qualitative comparison between the stations is done. The model is developed using ARENA Simulation Software, developed by Rockwell Automation, USA.

5.3.1 Simulation Model Generation

The production line consists of the six different stations processing same product type 001 over the period of 2014. The production line data for all the six stations are summarized in **Error! Reference source not found.** .All the stations E1-E6 process the same raw materials a nd the production system operates 24 hrs. a day.

5.3.2 Data Preparation

The data collected from the ERP system is converted into the spreadsheet. The correlated data are stored in the spreadsheet database table (**Error! Reference source not found.**). T his datasheet is utilized for the simulation model. Importantly, in the data sheet four parameters have been sorted for the further analysis.

- The Time between the arrivals.
- Processing time (cycle time)
- Order frequencies.

5.3.3 Input requirement

The time interval between the arrivals of the data in each station is calculated based on the start time between two arrivals. The arrival time of the order is subtracted from the arrival time of the next order in the same stations.

The time between arrivals = Arrival time of 2nd Order - Arrival time of 1st order.

The processing time or the cycle for each station have been extracted into the spreadsheet. Each order quantity specific cycle time is calculated based on the time taken to process all the order. The total time taken to process the number of order is divided by the total order during that time. The processing time for each order is extracted in the spreadsheet.

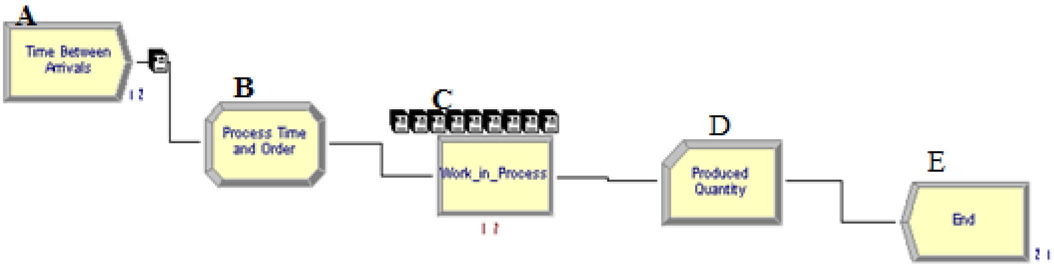
Processing Time (Cycle Time) = (Finish Time-Start time)/Number of order.

The order frequencies are extracted from the provided data, and has been sorted in the spreadsheet. The different order quantity over the different time period is sorted.

5.3.4 Logic requirement

A generic simulation model to reflect the production dynamic status has been visualized based on the process of the case firm and provided data. The model consists of the five block, the between arrivals (A), process time and order (B), WIP(C), produced quantity(D) and the end (E) to count the orders. The simulation model used to identify the bottlenecks is shown in Figure 5-5.

Figure 5-5 Conceptual simulation of the production line using ARENA simulation



All the inputs for these blocks are extracted from the data provided to us, which then are expressed into the expression generated from the Input Analyser of ARENA Software.

All the stations have different time between arrivals. These time intervals are sorted into the spreadsheets. The data from the spreadsheet is than analysed using Input Analyser of ARENA software. All the data point in the spreadsheet are used and the best fitting distribution with its expression and least square error has been used. The time between arrivals in the model above generates the order after certain interval, Table 5-3 shows all the expression generated from the Input Analyser for all the stations extracted from the datasheet.

Table 5-3 Time between arrivals generated from Input Analyser

Production Line	Time between arrivals (minutes)
E1	-0.001 + WEIB(1.06e+004, 0.921)
E2	-0.001 + 52500 * BETA(0.382, 0.884)
E3	-0.001 + GAMM(1.59e+004, 0.64)
E4	-0.001 + EXPO(4.35e+004)
E5	-0.001 + EXPO(2.14e+004)
E6	-0.001 + GAMM(3.73e+004, 0.534)

The processing time for each order has been calculated as presented in 5.2 Mathematical Approach. The process time for all the order during the time intervals are analysed using input analyser and are expressed in the equation. For this all the data point in the spreadsheet are used and the best fitting distribution with least square error expression has been used as shown in Table 5-4. The processing time for each station vary with the number of order during that time.

Table 5-4 Processing tme per order(minutes) generated from Input Analyser

Production Line	Processing Time per order (minutes)
E1	1 + WEIB(7.48, 0.607)
E2	3 + LOGN(12.3, 25.2)
E3	2 + LOGN(9.49, 20.8)
E4	1 + 38 * BETA(0.348, 0.534)
E5	25 * BETA(0.604, 1.4)
E6	NORM(16.2, 5.22)

The ordering frequencies of all the stations are again analysed in the input analyser. The expressions (Table 5-5) based on the ordering frequencies of the different time period is extracted. All the data point in the spreadsheet are used and the best fitting distribution with its expression and least square error has been used. These expressions generate the ordering frequencies for the simulation model.

Table 5-5 Ordering Frequencies(pcs) generated from Input Analyser

Production Line	Ordering Frequencies
E1	375 + 1.66e+004 * BETA(0.614, 3.29)
E2	140 + 1.54e+003 * BETA(0.781, 1.43)
E3	TRIA(100, 830, 4e+003)
E4	TRIA(50, 175, 300)
E5	TRIA(114, 580, 2.28e+003)
E6	TRIA(126, 178, 648)

All the distribution summary and the input analyser outputs are shown in Appendix B. The summary of the input analyser attached in the appendix consist of

- Type of Distribution (Beta, Weibull, Gamma, Triangular etc.)
- The expression for the input.
- Square Error of the distribution.
- Type of statistical hypothesis based on the goodness of fit (Chi Square test, Kolmogorov-Smirnov Test (Hu and Hong 2015)
- Data Summary (number of data, mean, standard deviations)
- Histogram summary

5.3.5 Output requirement

The main output requirement of the simulation is to identify the bottleneck with the available reports from the simulated data. Therefore, the number of the performance parameter for different stations are recorded for the analysis. The stations utilization, average waiting time, queue length and average number of order are the output requirement.

5.3.6 Model verification and validation (V&V)

Simulation model verification and validation in the simulation are done to increase the confidence in the model rather than demonstrating the absolute accuracy (Robinson 1997, Sargent 2007). The verification is the process of ensuring the conceptual model has been transformed into a simulated model. Whereas, the validation is the process of ensuring the model is valid to demonstrate the potential of simulation (Robinson 1997).

To ensure the correctness of the simulation model, the simulation analysis is performed for all the data sorted in the spreadsheet. The verification of the simulation verification is performed for all the expressions generated by ARENA Input Analyser. The model is then verified visually in reference with the process flow of the case firm. As referred by Robinson (1997), running the model and watching how each element behaves , both the logic and behaviour against the real word can be checked. The model progress was traced to verify the output. The programmed code, macros, and VBA script were verified manually. The simulation model code and the process flow were debugged by running it step by step for all the stations module.

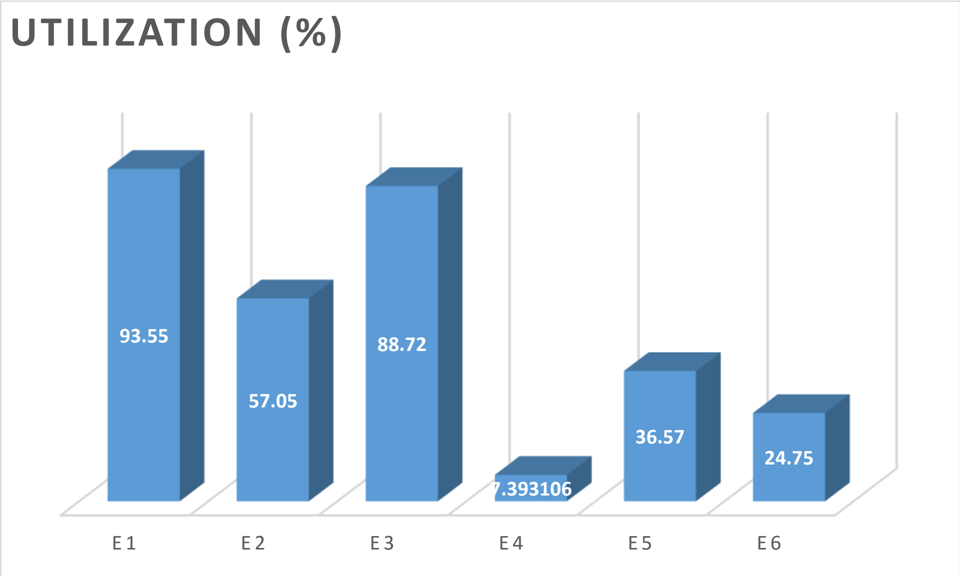
5.3.7 Bottleneck Identification

The constructed bottleneck identification simulation model was run in ARENA Free Trial Version 14.70 in Microsoft Windows 10 with RAM capacity of 6 GB, Intel i5 processor, 2.40 GHz. The model was run with 95% confidence interval with 30 replications. The warm up period was 240 minutes. The replication length was 365 days with 24 hours per day. The base time units of the measurement were set in minutes. The utilization and queue length of all the stations is recorded (Table 5-6) and the bar chart for the available data is visualized (Figure 5-6, Figure 5-7).

Table 5-6 Performance parameter of E1-E6 stations from the Simulation

Stations	**Utilization in percentage**	**Queue Length**
E1	93.55	11.5627
E2	57.05	1.4376
E3	88.72	7.0104
E4	7.393106	0.0046
E5	36.57	0.2000
E6	24.75	0.1143

Figure 5-6 Graphical representation of Simulation output from Table 5-6



The average utilization of the station E1 is higher than all the other stations in the production line, Figure 5-6 . From the output result, station E1 has the highest utilization of 93.55% percentage and is hugely used during this time period. Second most used station is E3 with 88. 72 % usage. With the conventional theory it seems, E1 is the primary bottleneck, however, the difference between E1 and E3 is too small, therefore, in the real world situation it is difficult to detect the primary bottlenecks by simply measuring the utilization.

According to this method station E1 is the primary bottlenecks, hence if enhancing the processing time of E1, the production rate should improve. In order to verify this, we reduce the processing time of E1 station by 30%. The new processing time expression per order for all the consecutive orders have been derived from the input analyser. For our reference, we also calculated the same for secondary bottleneck station E3. The new expression is shown in Table 5-7.

Table 5-7 Improved processing time per order(minutes) for E1only

Production Line	Processing Time per order (minutes)
E1	1 + WEIB(4.39, 0.559)
E3	1 + LOGN(6.74, 11.4)

With the new processing time, we simulated the model with 95% confidence interval over 30 replications. The warm up period was set 240 minutes. The replication length was 365 days with 24 hours per day. The base time units of the measurements were set in minutes.

Since the station E1, process time has been improved by 30%. The report generated with this changes in simulation run shows very few improvements have been achieved. The station own utilization and queue length is shown in Table 5-8.

Table 5-8 Improved performance parameter of E1 from the Simulation

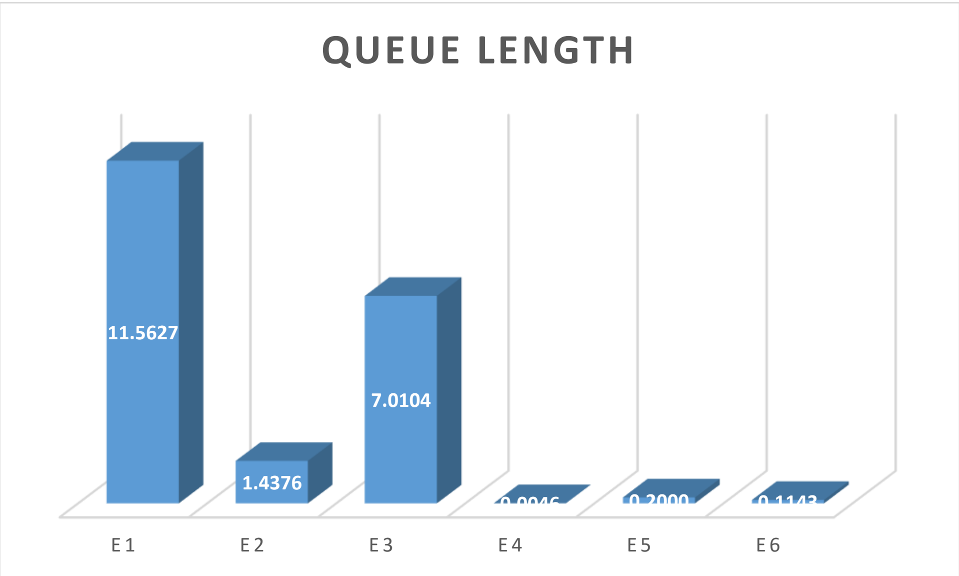
Stations	Utilization in percentage		Queue Length	
	Original	Improved	Original	Improved
E1	93.55	89.31	11.56	8.9
E3	88.72	78.81	7.0104	3.8

However, for the station E3 the changes have abruptly increases the performances in the system but for the station E1 the progress in utilization and queue length is not significant. With the significant reduction in process time, the improvement in the primary bottleneck has less impact than the improvement in the secondary bottleneck.

This gives the way that average utilization method does not provide the best way to identify and elevate the constraints in the productions system. If something is not really a bottleneck, creating more capacity will not speed up the whole system. This method contains the flaws while detecting the shifting bottlenecks in the dynamic systems as it does not provide any insight for secondary or non-bottlenecks. The significant influence of another bottleneck is completely ignored. This method does not return the quantitative measure of the bottleneck constraints.

Queue Length

Figure 5-7 Graphical representation of Simulation output from Figure 5-6



In Figure 5-7 the output report has been analysed based on the queue length. The average queue length of all the stations has been visualized by bar graph. From the graph station E1 has highest queue length of more than eleven orders and hence is the bottleneck. This method is difficult to implement in the real process. The requirement of long ideally infinite queue length capacity at every workstation is not realistic. The others factors like batch and lot sizes fluctuate the queue length which might increase the probability of identifying non-bottlenecks as a bottleneck.

5.3.1 Validation of Model

The simulation model is validated so that it should be reliable to simulate the real system behaviour. This provides the generated result are close enough and model is an approximation to the case firm. The validation of the model is validated in reference with the generated queue length. The station E1 queue length has been selected for the validation of the model. The above- developed model is run for 30 replications and for each replication the average queue length of model is sorted. The simulation run result is shown in Table 5-9.

Table 5-9 Simulation output of queue length for 30 replication

10.47	13.84	3.96	9.05	18.64
26.8	16.09	7.17	7.42	17.32
7.08	7.5	17.47	6.18	16.43
9.88	12.17	22.22	16.95	2.88
14.54	1.87	5.98	1.97	11.5
2.69	19.34	14.5	4.52	20.36

The calculated average and standard deviation from the table are respectively, 11. 55 and 6.67. One sample t test is done for the hypothesis testing over the variance of the queue mean length from the data (125.06) and the average mean of the simulation. The null hypothesis and alternative hypothesis at 95% confidence interval is,

$H_{0:}$ μ = 125.06

$H_{1:}$ μ ≠ 125.06

The calculated degree of freedom, df =n-1, =30-1 =29. The test statistic is calculated by the expression

$$t = \frac{x - \mu}{\frac{s}{\sqrt{n}}}$$

Where, x is the sample mean, μ is the population mean, s is the sample standard deviation and n is the number of observation. At the 95% confidence interval with df =29, the t distribution critical value is set from -2.045 to +2.045. The calculated t value is -93.1977 The hypothesis testing is summarized in Appendix C. This conclude the null hypothesis is rejected with p value less than 0.05 and the simulation model is significant to the result.

5.4 Momentary Shifting Bottleneck Approach

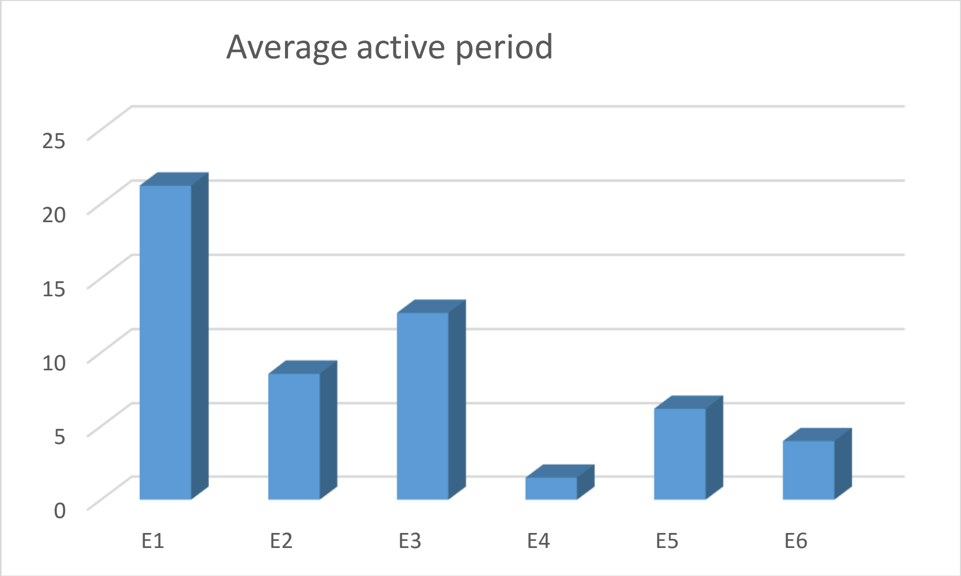
The momentary shifting approach is similar to utilization method adopted in the simulation approach (5.3.7 Bottleneck Identification). The same data could be used for the both the methods. Both the methods identify whether the machine is active or inactive. However, the only underlying difference is the utilization method determines the percentage of the machine being active and the momentary shifting approach measure duration of the machine being active without interruption. This process is archived from the average active period method where the specific duration is the point of analysis. The major advantage of this approach is the identification of the shifting momentary bottlenecks at any instant of time.

The active period method for all the station has been calculated. The active period is the difference between the finish time and the start time of all the production processes during the year 2014. The inactive period in this calculation is assumed to be either the stations being starved, blocked or the stations that are waiting for the raw materials. The difference is measured in the days. For all the station the measured value is plotted in the bar graph Appendix D.

Table 5-10 Average active Period for all the stations in Days

Stations	**Active Period(Days)**
E1	21
E2	9
E3	13
E4	2
E5	6
E6	4

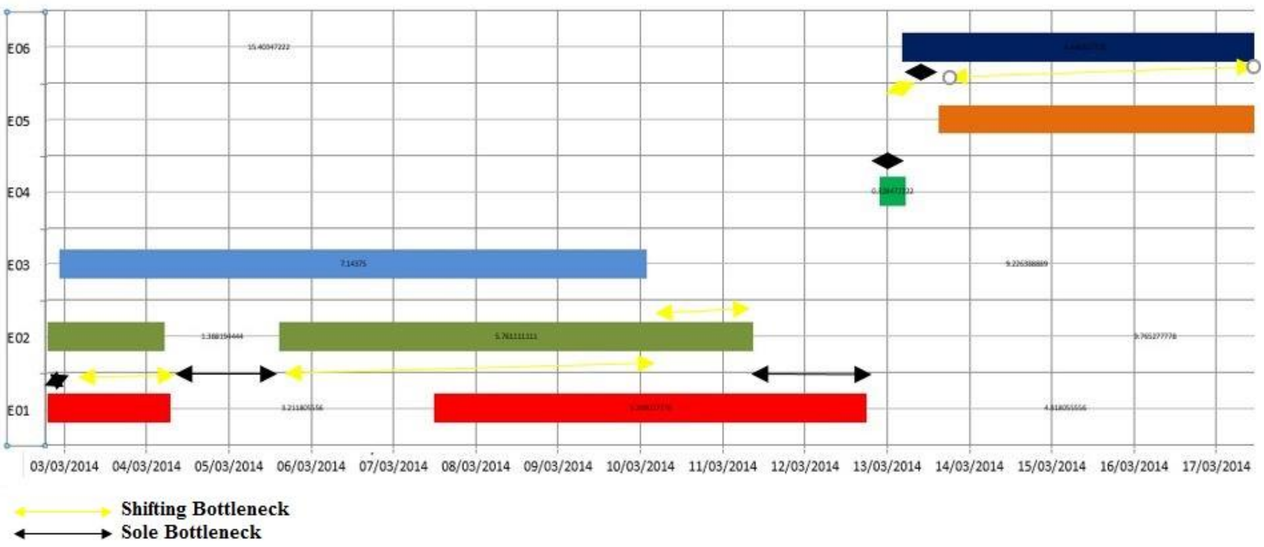
Figure 5-8 Graphical representation of Table 5-10



This approach compares the active duration of all the stations. From, Figure 5-8 we can see that in an average station E1 is running more than all other stations for this specific year which is followed by other two stations E3 and E2. The longer the machine runs without interruption higher the impact over other machines. Since, this method identifies the bottleneck with the longest average active period, as stated by Roser, Nakano, and Tanaka (2001) *" the machine with the longest average active period is considered to be the bottleneck, as this machine is least likely to be interrupted by other machines, and in turn is most likely to dictate the overall system throughput".* From this we can conclude during the year, 2014 station E1 has the highest probability of constraining the other stations for the production.

However, in order to visualise the momentary bottleneck in the production, the active period method over the selected period is used. This method provides the distinct sole and shifting bottlenecks based on the computation of historical data. The active and inactive period of the all the station during the month period of March from the available data has been plotted in the timeline chart.

Figure 5-9 Momentary Shifting Bottleneck from March 3- March 17, 2014



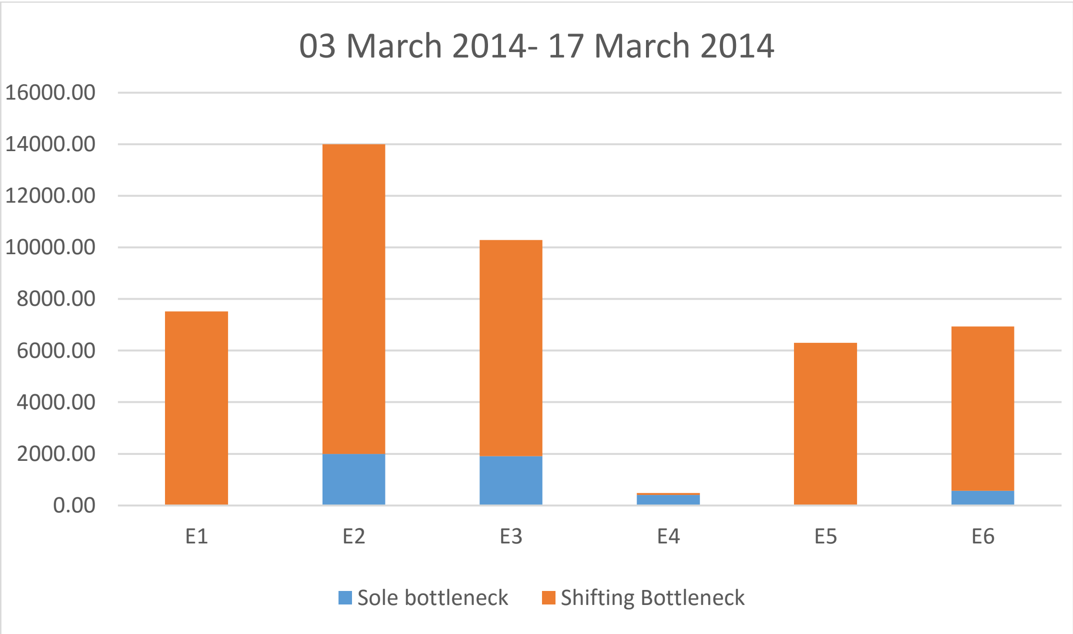
In Figure 5-9 the momentary shifting bottleneck has been visualised. During this period, five sole bottleneck and five shifting bottlenecks are obtained. At the beginning, E1 has longest active period hence is a sole bottleneck. This bottleneck is then shifted to E3 as it is more active than all the others stations, however both the stations share the same shifting bottlenecks. In the next period, the station E3 is again sole bottleneck which is then shifted to station E2 and again from E2 the bottleneck is shifted to E1. Similarly, during mid of March, the active and inactive period of all the station has been plotted. Station E4 and E6 are respectively the sole and shifting bottleneck. The sole and shifting bottlenecks are shown with two different coloured arrows.

This provides the reference for the calculation of the percentage of sole and shifting bottlenecks in the production. The machine being the sole or shifting bottleneck is measured and evaluated. With this, we can track and identify the moving bottleneck in any production system. The larger the time period, the larger is its effect in slowing down the production system.

Table 5-11 The Sole and Shifting bottlnecks (in Minutes)

03 March 2014- 17 March 2014		
	Sole bottleneck	Shifting Bottleneck
E1		7521
E2	1990	12020
E3	1912	8375
E4	407	66
E5		6303
E6	565	6369

Figure 5-10 Graphical representation of Table 5-11



In Figure 5-10, the sole bottleneck of E2 and E3 is almost same. However, the shifting bottleneck of E2 is higher than all the other bottlenecks. This means E2 is involved more in numbers for the shifting operations. From this analysis, we could say that station E2 is the primary bottleneck. The improvement in the performances of E2 would be beneficial for the improvement of the system performance. However, the improvement of secondary bottleneck E3 could also be considered, but should be based on the trade-off relation between the cost of improvement and the benefit of the improved system. E4 is unlikely to improve the system performance, therefore the enhancement of the resources at this station is not recommend.

Overall, this method provides the reliability and deeper understanding for detecting the bottlenecks in discrete production facilities, since the magnitude of related constraints is identified this helps to add value to the manufacturing facilities.

6.0 Conclusion and Future Research

This chapter culminates the discussion presented in the previous chapters. This chapter brings together all the methodologies, models and theories together to gives a brief outline of our finding. This chapter is containing the summary of the presented thesis and is followed by the suggestion for the future work.

6.1 Summary of the thesis

This thesis studies the bottleneck identification techniques from the literature and visualize them for the qualitative and quantitative analysis. The thesis is mainly focused to the production system analysis, for which the historical data sets are used from the Pipelife Norge AS, Surnadal. The production system of the case firm consist of numbers of stations. Based on the provided data and extracted information, six different stations are sampled in our study. The four different approaches, Theoretical, Mathematical, Simulation and Momentary Shifting Bottlenecks are discussed to evaluate the bottleneck identification techniques.

The theoretical analysis was based on the problems identified by bottleneck walk method. The performances evaluation curves, throughput curves were used to evaluate the identification of bottlenecks. The throughput curves provide the visually presented, easily understood approach that illustrates graphically the interaction between the workload, capacity and material availability. From the nine possible cases, the case firm exhibit the worst scenario during the peak period where, the material availability through the mixture is less and the work load is higher than the capacity of production. In this situation the case firm should reorder the operating point or they could produce more during the low demand period for the stock.

The mathematical analysis has been conducted from the available data, where the average cycle time of all the processes in all the stations is collected. We have calculated the average cycle time for all the stations. However, when evaluating the two different halves in the year, the average method did not provide the reliable data. This method identified the non-bottleneck as a bottleneck.

The simulation approach has been conceptualized based on the case firm production layout. The expression for the order quantities, ordering frequencies and the process time of the order were generated from input analyser. The average utilization method was unable to find the realistic bottlenecks in the production. This method could not find the tertiary bottlenecks and shifting bottlenecks. On the other hand, the queue length method found the bottleneck without any quantitative measure for the constraints. The limitation for the existence of separate queue size for every stations with infinite capacity is unrealistic. This yields difficulties in identifying the bottlenecks for the complex manufacturing system where the queue length size fluctuates frequently.

Finally, the bottlenecks are identified using the momentary shifting bottleneck detection method based on the active period. This method was complex to implement than other methods, but is superior than the conventional methods. This method not only detected the bottlenecks, but also determined the magnitude of the primary and secondary bottlenecks.

Recommendation

The turbulent manufacturing environment requirements are equipped with the automated and semi-automated system for the scheduling, real time machine monitoring and reporting. However, the main challenge is to utilize the data collected from these tools. The BARCO software for the production planning, monitoring and reporting is being used in Pipelife Norge AS for this purpose. This software is synchronized with their existing ERP system and often being used for the demand forecasting. As a recommendation, the use of BARCO with the help of momentary shifting bottleneck detection method would be beneficiary for the case firm.

It is also recommended to capture the information of every stage in their ERP system so that the same information could be used for forecasting with predictive analytics software and real-time information sharing throughout the organization using visualization tools.

The thesis concludes, the analysis from the conventional methods of bottleneck identification no longer provides the accuracy in the identifying the bottlenecks. Further, the use of momentary shifting bottleneck identification approach for the reliable and in - depth study of secondary and shifting bottlenecks in the production is advantageous.

Future work

The introduced literature establishes the link between the production system and the approach that could be used to identify the bottlenecks. Future research work should consider the development of additional methods and coverage of the production lines with high product variety. A much deeper understanding of the production system can be done by statistically analysing the interactions in the production firm. The coverage of whole logistic processes and could be the another possibility of the research field.

There are several others directions for the future work in this thesis. First of all, the machine failure time, breakdown time, maintenance time should be analysed for in-depth analysis of the production facility. Secondly, the advanced and complex simulation models have to be verified and tested with additional variables. And finally, the analysis of the bottleneck with respect to the mathematical modelling is recommended.

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Appendix A

Provided Data from Merit Consultancy.

Line	START_DATE	FINISH_DATE	STARTTIME	FINISH_TIME	O_QTY	REV_QTY
E01	02/01/2014	08/01/2014	06:49:00	11:42:00	2000	2250
E01	15/01/2014	21/01/2014	02:20:00	04:06:00	2500	3450
E01	21/01/2014	30/01/2014	12:10:00	00:00:00	4000	4000
E01	24/01/2014	27/03/2014	21:55:00	12:54:00	4500	4400
E01	27/01/2014	30/01/2014	01:04:00	16:10:00	1000	1050
E01	11/02/2014	25/02/2014	09:03:00	20:42:00	4000	4200
E01	25/02/2014	04/03/2014	18:24:00	06:49:00	4000	4110
E01	07/03/2014	12/03/2014	11:54:00	18:07:00	2000	2528
E01	17/03/2014	23/03/2014	13:45:00	10:29:00	3000	3000
E01	22/03/2014	26/03/2014	08:40:00	23:46:00	1000	1000
E01	23/03/2014	23/04/2014	10:50:00	08:09:00	3000	2150
E01	30/03/2014	28/04/2014	01:29:00	17:21:00	2258	4650
E01	08/04/2014	28/04/2014	13:34:00	04:14:00	375	5700
E01	09/04/2014	13/05/2014	11:26:00	13:12:00	2500	5050
E01	28/04/2014	29/04/2014	21:43:00	16:21:00	6000	500
E01	30/04/2014	05/05/2014	20:06:00	17:25:00	3000	3050
E01	05/05/2014	11/05/2014	19:00:00	17:01:00	3033	3250
E01	25/05/2014	17/07/2014	15:04:00	11:48:00	3000	1214
E01	27/05/2014	12/06/2014	14:00:00	20:10:00	8750	8850
E01	11/06/2014	14/06/2014	01:24:00	12:03:00	1500	1600
E01	14/06/2014	17/06/2014	05:46:00	16:08:00	1500	1750
E01	17/06/2014	24/06/2014	12:50:00	03:48:00	4500	5015
E01	24/06/2014	17/07/2014	07:20:00	07:00:00	1225	300
E01	28/06/2014	08/07/2014	11:28:00	03:03:00	1012	3750
E01	02/07/2014	10/07/2014	23:16:00	20:00:00	3000	3050
E01	06/07/2014	25/08/2014	09:42:00	07:01:00	3000	5479
E01	10/07/2014	25/08/2014	01:46:00	16:53:00	1200	1200
E01	08/08/2014	17/08/2014	17:45:00	14:29:00	3000	3000
E01	09/08/2014	13/08/2014	03:54:00	19:00:00	1000	2400
E01	23/08/2014	27/08/2014	15:48:00	21:37:00	2000	2450
E01	02/09/2014	04/09/2014	14:24:00	05:30:00	1000	1200
E01	04/09/2014	16/09/2014	05:03:00	05:54:00	8000	8000
E01	16/09/2014	24/09/2014	08:40:00	05:24:00	3000	2150

E01	25/09/2014	22/10/2014	07:32:00	07:20:00	17000	17100
E01	26/09/2014	30/09/2014	21:06:00	09:31:00	4000	2500
E01	25/10/2014	27/10/2014	06:07:00	17:19:00	900	1200
E01	31/10/2014	06/11/2014	00:00:00	06:15:00	2000	850
E01	04/11/2014	07/11/2014	09:06:00	15:19:00	2000	2250
E01	13/11/2014	21/11/2014	20:03:00	01:52:00	2000	50
E01	27/11/2014	02/12/2014	08:32:00	14:21:00	2000	2000
E01	28/11/2014	30/11/2014	13:36:00	00:00:00	900	1150
E01	30/11/2014	29/12/2014	23:59:00	20:43:00	3000	2050
E01	05/12/2014	08/12/2014	19:49:00	02:02:00	2000	2100
E01	08/12/2014	12/12/2014	04:28:00	10:17:00	2000	1085
E01	09/12/2014	12/12/2014	03:45:00	09:58:00	2000	2200
E02	05/07/2014	07/07/2014	00:00:00	18:43:00	504	532
E02	07/07/2014	15/07/2014	20:52:00	00:00:00	588	742
E02	08/08/2014	11/08/2014	22:20:00	15:59:00	210	256
E02	09/08/2014	11/08/2014	18:48:00	18:08:00	280	308
E02	10/08/2014	13/08/2014	02:44:00	14:36:00	140	145
E02	15/08/2014	18/08/2014	18:46:00	13:40:00	800	528
E02	18/08/2014	21/08/2014	15:08:00	07:08:00	512	504
E02	24/08/2014	29/08/2014	14:59:00	16:22:00	1120	1246
E02	29/08/2014	01/09/2014	07:22:00	12:57:00	840	862
E02	02/09/2014	03/09/2014	02:48:00	20:36:00	210	196
E02	03/09/2014	05/09/2014	14:47:00	04:00:00	980	490
E02	05/09/2014	08/09/2014	16:23:00	00:00:00	670	714
E02	08/09/2014	10/09/2014	01:01:00	11:06:00	392	420
E02	28/09/2014	30/09/2014	20:42:00	10:02:00	448	448
E02	29/09/2014	30/09/2014	18:48:00	06:40:00	140	140
E02	30/09/2014	06/10/2014	21:23:00	06:32:00	1134	1134
E02	08/10/2014	17/10/2014	05:41:00	19:41:00	688	760
E02	12/10/2014	17/10/2014	15:38:00	07:38:00	352	355
E02	07/11/2014	12/11/2014	22:11:00	02:50:00	1400	1400
E02	12/11/2014	15/11/2014	12:20:00	01:33:00	980	994
E02	15/11/2014	16/11/2014	02:36:00	22:46:00	238	238
E02	16/11/2014	17/11/2014	06:30:00	00:00:00	210	210
E02	17/11/2014	20/11/2014	12:12:00	16:40:00	910	910
E02	04/12/2014	09/12/2014	17:04:00	23:01:00	1092	938
E02	18/12/2014	19/12/2014	15:15:00	03:11:00	140	224

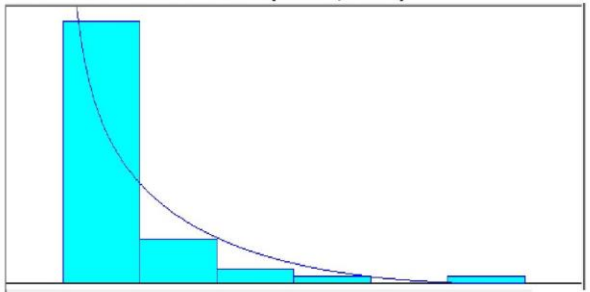
E03	04/01/2014	10/01/2014	06:39:00	12:08:00	1000	1220
E03	16/01/2014	20/01/2014	08:35:00	16:48:00	1500	1500
E03	11/02/2014	16/02/2014	17:31:00	15:02:00	1300	1300
E03	16/02/2014	17/02/2014	06:39:00	12:08:00	1000	200
E03	02/03/2014	07/03/2014	22:31:00	09:28:00	2000	2020
E03	07/03/2014	10/03/2014	02:48:00	01:58:00	1200	1200
E03	19/03/2014	23/03/2014	07:24:00	12:52:00	1000	1100
E03	21/03/2014	02/04/2014	00:00:00	19:23:00	2600	2600
E03	21/03/2014	31/03/2014	22:49:00	04:18:00	1000	1060
E03	22/03/2014	01/04/2014	21:29:00	10:19:00	240	260
E03	23/03/2014	27/03/2014	18:18:00	15:49:00	1300	1520
E03	31/03/2014	01/04/2014	17:14:00	23:39:00	120	140
E03	02/04/2014	16/04/2014	15:07:00	19:53:00	3100	2620
E03	02/04/2014	12/04/2014	17:32:00	15:11:00	2200	2300
E03	07/04/2014	09/04/2014	10:54:00	04:51:00	2000	20
E03	07/04/2014	10/04/2014	12:51:00	21:04:00	1500	1500
E03	10/04/2014	15/04/2014	05:59:00	02:40:00	2500	2540
E03	23/04/2014	28/04/2014	05:37:00	16:34:00	2000	1980
E03	28/04/2014	02/05/2014	08:09:00	13:38:00	1000	1000
E03	02/05/2014	13/05/2014	11:28:00	09:22:00	4000	4080
E03	13/05/2014	29/05/2014	06:15:00	11:43:00	1000	1000
E03	06/06/2014	11/06/2014	11:14:00	22:11:00	2000	2060
E03	11/06/2014	19/06/2014	13:56:00	06:22:00	3000	3240
E03	25/06/2014	29/06/2014	16:08:00	00:00:00	1500	1520
E03	29/06/2014	11/08/2014	22:42:00	20:36:00	4000	3980
E03	08/07/2014	14/07/2014	22:09:00	14:34:00	3000	3000
E03	14/07/2014	11/08/2014	03:53:00	14:50:00	2000	1920
E03	04/08/2014	07/08/2014	22:05:00	09:02:00	2000	800
E03	06/08/2014	11/08/2014	08:48:00	22:22:00	1600	1640
E03	11/08/2014	12/08/2014	00:00:00	00:00:00	280	280
E03	12/08/2014	13/08/2014	10:24:00	00:00:00	260	300
E03	12/08/2014	15/08/2014	23:19:00	04:47:00	1000	1000
E03	15/08/2014	18/08/2014	22:45:00	06:58:00	1500	1500
E03	27/08/2014	16/09/2014	03:19:00	11:32:00	1500	860
E03	23/09/2014	02/10/2014	21:42:00	13:52:00	1200	1220
E03	10/10/2014	13/10/2014	23:38:00	05:06:00	1000	840
E03	13/10/2014	21/10/2014	00:00:00	13:55:00	2500	1540

E03	14/10/2014	17/10/2014	15:25:00	20:46:00	100	100
E03	15/10/2014	17/10/2014	06:15:00	11:08:00	540	540
E03	20/10/2014	27/10/2014	09:28:00	12:35:00	3200	3200
E03	28/10/2014	11/11/2014	19:39:00	13:16:00	1545	140
E03	29/10/2014	08/11/2014	09:39:00	07:18:00	2200	1900
E03	06/11/2014	08/11/2014	13:17:00	17:56:00	2200	540
E03	09/11/2014	10/11/2014	11:13:00	13:57:00	500	160
E03	23/11/2014	28/11/2014	04:54:00	10:23:00	1000	1600
E03	06/12/2014	09/12/2014	08:31:00	00:00:00	1200	1220
E03	09/12/2014	09/12/2014	03:33:00	14:30:00	2000	120
E03	09/12/2014	17/12/2014	12:05:00	08:46:00	2500	3540
E04	29/01/2014	30/01/2014	16:57:00	04:46:00	300	300
E04	30/01/2014	30/01/2014	09:14:00	13:07:00	100	100
E04	12/03/2014	13/03/2014	21:38:00	05:31:00	200	250
E04	04/06/2014	05/06/2014	07:39:00	15:32:00	200	200
E04	09/07/2014	10/07/2014	21:24:00	10:34:00	250	300
E04	10/07/2014	15/07/2014	08:22:00	16:15:00	200	200
E04	25/08/2014	26/08/2014	00:00:00	07:56:00	100	50
E04	27/10/2014	28/10/2014	08:16:00	10:12:00	50	50
E04	27/10/2014	28/10/2014	18:06:00	05:55:00	300	300
E04	27/11/2014	27/11/2014	10:48:00	16:37:00	150	150
E05	13/03/2014	19/03/2014	14:56:00	11:27:00	2090	2166
E05	18/03/2014	21/03/2014	23:32:00	00:00:00	760	565
E05	19/03/2014	31/03/2014	18:29:00	08:31:00	1160	1180
E05	30/04/2014	03/05/2014	06:37:00	21:14:00	1178	1140
E05	03/05/2014	08/05/2014	15:32:00	17:22:00	1520	1596
E05	21/05/2014	23/05/2014	01:19:00	16:16:00	456	456
E05	31/05/2014	07/06/2014	18:37:00	21:22:00	2280	2318
E05	07/06/2014	09/06/2014	21:31:00	17:27:00	608	684
E05	24/06/2014	26/06/2014	02:30:00	21:11:00	570	646
E05	17/09/2014	19/09/2014	15:57:00	15:37:00	722	684
E05	22/09/2014	26/09/2014	18:24:00	14:00:00	1330	1330
E05	14/10/2014	23/10/2014	13:58:00	00:00:00	760	494
E05	22/10/2014	29/10/2014	06:10:00	00:00:00	380	494
E05	13/11/2014	16/11/2014	03:40:00	18:17:00	1178	1178
E05	23/11/2014	23/11/2014	02:04:00	05:48:00	114	114
E05	23/11/2014	26/11/2014	11:19:00	20:02:00	266	342

E05	23/11/2014	23/11/2014	13:09:00	18:44:00	1479	1453
E06	10/01/2014	12/01/2014	05:03:00	18:46:00	132	132
E06	23/01/2014	30/01/2014	23:29:00	10:12:00	420	427
E06	27/01/2014	03/02/2014	11:55:00	06:11:00	576	544
E06	03/02/2014	06/02/2014	06:21:00	11:31:00	270	270
E06	20/02/2014	23/02/2014	22:14:00	06:58:00	180	189
E06	23/02/2014	25/02/2014	02:27:00	18:44:00	141	144
E06	13/03/2014	17/03/2014	04:25:00	15:08:00	420	433
E06	18/03/2014	21/03/2014	20:36:00	15:15:00	336	357
E06	25/04/2014	29/04/2014	19:03:00	05:46:00	420	446
E06	30/04/2014	07/05/2014	05:30:00	14:03:00	648	710
E06	13/05/2014	14/05/2014	17:40:00	05:40:00	126	131
E06	14/05/2014	18/05/2014	12:32:00	07:05:00	234	236
E06	14/06/2014	16/06/2014	01:41:00	00:00:00	330	342
E06	17/06/2014	23/06/2014	17:49:00	20:25:00	618	619
E06	07/08/2014	09/08/2014	10:03:00	17:57:00	162	176
E06	12/08/2014	15/08/2014	17:18:00	07:01:00	216	219
E06	15/08/2014	19/08/2014	19:49:00	20:54:00	270	297
E06	11/09/2014	13/09/2014	16:59:00	22:09:00	270	270
E06	14/09/2014	19/09/2014	01:19:00	19:35:00	576	494
E06	23/10/2014	28/10/2014	09:56:00	00:00:00	504	504
E06	28/10/2014	30/10/2014	11:51:00	07:34:00	222	240
E06	10/11/2014	13/11/2014	16:40:00	10:40:00	231	231
E06	06/12/2014	08/12/2014	05:21:00	16:26:00	300	240

Appendix B

Output from the ARENA Input Analyser

<table>
<tr><th>ST</th><th>Order</th><th>Process Per order</th><th>Time between the order</th></tr>
<tr><td>E1</td><td>375 + 1.66e+004 * BETA(0.614, 3.29)

Distribution Summary

Distribution: Beta
Expression: 375 + 1.66e+004 * BETA(0.614, 3.29)
Square Error: 0.014175

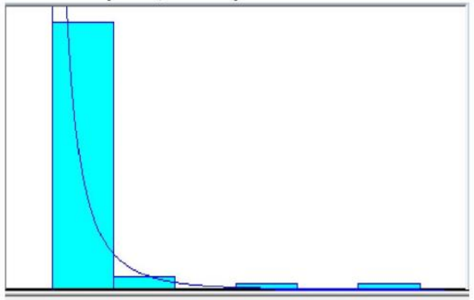
Chi Square Test
Number of intervals = 3
Degrees of freedom = 0
Test Statistic = 4
Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
Test Statistic = 0.25
Corresponding p-value < 0.01

Data Summary

Number of Data Points = 45
Min Data Value = 375
Max Data Value = 1.7e+004
Sample Mean = 2.99e+003
Sample Std Dev = 2.74e+003

Histogram Summary

Histogram Range = 375 to 1.7e+004
Number of Intervals = 6</td><td>1 + WEIB(7.48, 0.607)

Distribution Summary

Distribution: Weibull
Expression: 1 + WEIB(7.48, 0.607)
Square Error: 0.001262

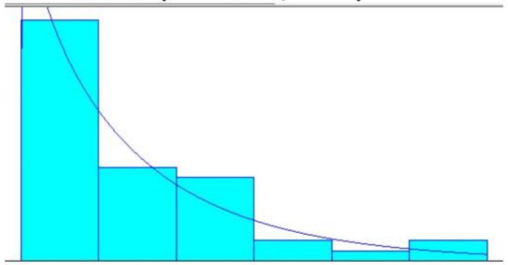
Chi Square Test
Number of intervals = 1
Degrees of freedom = -2
Test Statistic = 0.00471
Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
Test Statistic = 0.207
Corresponding p-value = 0.0382

Data Summary

Number of Data Points = 45
Min Data Value = 1.55
Max Data Value = 209
Sample Mean = 14.4
Sample Std Dev = 35.5

Histogram Summary

Histogram Range = 1 to 209
Number of Intervals = 6</td><td>-0.001 + WEIB(1.06e+004, 0.921)

Distribution Summary

Distribution: Weibull
Expression: -0.001 + WEIB(1.06e+004, 0.921)
Square Error: 0.005559

Chi Square Test
Number of intervals = 4
Degrees of freedom = 1
Test Statistic = 1.46
Corresponding p-value = 0.235

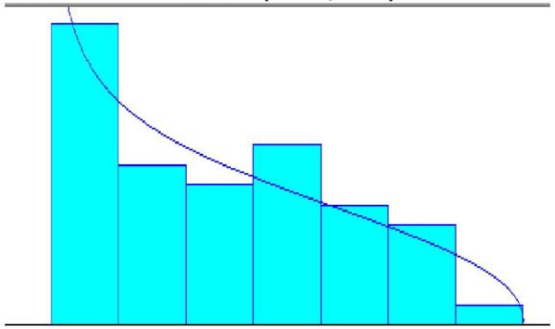
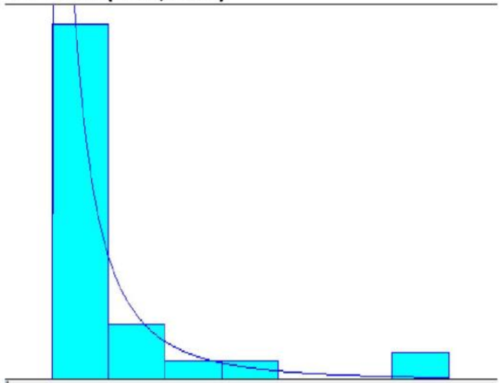
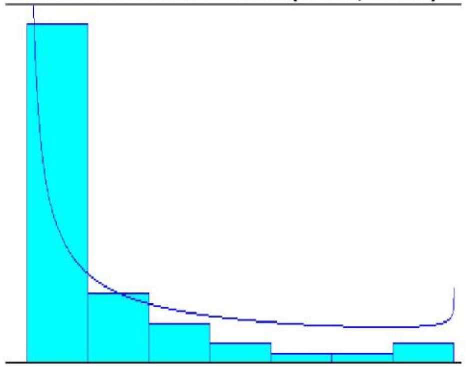
Kolmogorov-Smirnov Test
Test Statistic = 0.0915
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 45
Min Data Value = 0
Max Data Value = 4.27e+004
Sample Mean = 1.09e+004
Sample Std Dev = 1.01e+004

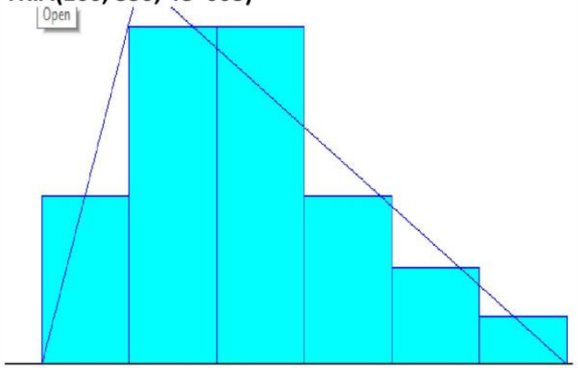
Histogram Summary

Histogram Range = -0.001 to 4.27e+004
Number of Intervals = 6</td></tr>
</table>

E2	140 + 1.54e+003 * BETA(0.781, 1.43)	3 + LOGN(12.3, 25.2)	-0.001 + 5.25e+004 * BETA(0.382, 0.884)
			
	Distribution Summary Distribution: Beta Expression: 140 + 1.54e+003 * BETA(0.781, 1.43) Square Error: 0.004892 Chi Square Test Number of intervals = 6 Degrees of freedom = 3 Test Statistic = 1.37 Corresponding p-value = 0.715 Kolmogorov-Smirnov Test Test Statistic = 0.0675 Corresponding p-value > 0.15 **Data Summary** Number of Data Points = 51 Min Data Value = 140 Max Data Value = 1.68e+003 Sample Mean = 685 Sample Std Dev = 411 **Histogram Summary** Histogram Range = 140 to 1.68e+003 Number of Intervals = 7	**Distribution Summary** Distribution: Lognormal Expression: 3 + LOGN(12.3, 25.2) Square Error: 0.004467 Chi Square Test Number of intervals = 3 Degrees of freedom = 0 Test Statistic = 0.978 Corresponding p-value < 0.005 Kolmogorov-Smirnov Test Test Statistic = 0.0837 Corresponding p-value > 0.15 **Data Summary** Number of Data Points = 51 Min Data Value = 3.2 Max Data Value = 85.5 Sample Mean = 15.4 Sample Std Dev = 19.3 **Histogram Summary** Histogram Range = 3 to 86 Number of Intervals = 7	**Distribution Summary** Distribution: Beta Expression: -0.001 + 5.25e+004 * BETA(0.382, 0.884) Square Error: 0.013775 Chi Square Test Number of intervals = 5 Degrees of freedom = 2 Test Statistic = 6.87 Corresponding p-value = 0.0342 Kolmogorov-Smirnov Test Test Statistic = 0.278 Corresponding p-value < 0.01 **Data Summary** Number of Data Points = 51 Min Data Value = 0 Max Data Value = 5.25e+004 Sample Mean = 9.79e+003 Sample Std Dev = 1.18e+004 **Histogram Summary** Histogram Range = -0.001 to 5.25e+004 Number of Intervals = 7

E3

TRIA(100, 830, 4e+003)



Distribution Summary

Distribution: Triangular
Expression: TRIA(100, 830, 4e+003)
Square Error: 0.003980

Chi Square Test
Number of intervals = 5
Degrees of freedom = 3
Test Statistic = 0.805
Corresponding p-value > 0.75

Kolmogorov-Smirnov Test
Test Statistic = 0.126
Corresponding p-value > 0.15

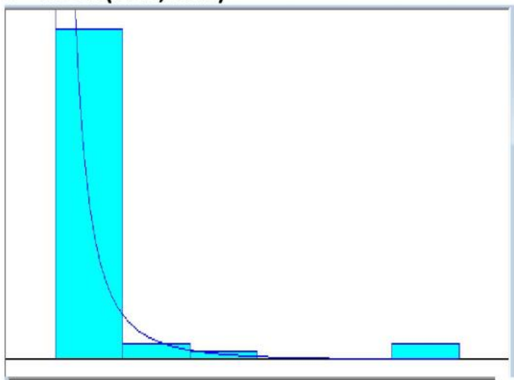
Data Summary

Number of Data Points = 48
Min Data Value = 100
Max Data Value = 4e+003
Sample Mean = 1.64e+003
Sample Std Dev = 944

Histogram Summary

Histogram Range = 100 to 4e+003
Number of Intervals = 6

2 + LOGN(9.49, 20.8)



Distribution Summary

Distribution: Lognormal
Expression: 2 + LOGN(9.49, 20.8)
Square Error: 0.002456

Chi Square Test
Number of intervals = 1
Degrees of freedom = -2
Test Statistic = 0.108
Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
Test Statistic = 0.106
Corresponding p-value > 0.15

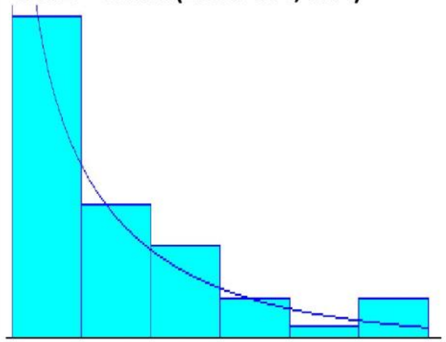
Data Summary

Number of Data Points = 48
Min Data Value = 2.25
Max Data Value = 141
Sample Mean = 14.1
Sample Std Dev = 27.3

Histogram Summary

Histogram Range = 2 to 142
Number of Intervals = 6

-0.001 + GAMM(1.59e+004, 0.64)



Distribution Summary

Distribution: Gamma
Expression: -0.001 + GAMM(1.59e+004, 0.64)
Square Error: 0.003745

Chi Square Test
Number of intervals = 4
Degrees of freedom = 1
Test Statistic = 1.08
Corresponding p-value = 0.319

Kolmogorov-Smirnov Test
Test Statistic = 0.165
Corresponding p-value = 0.134

Data Summary

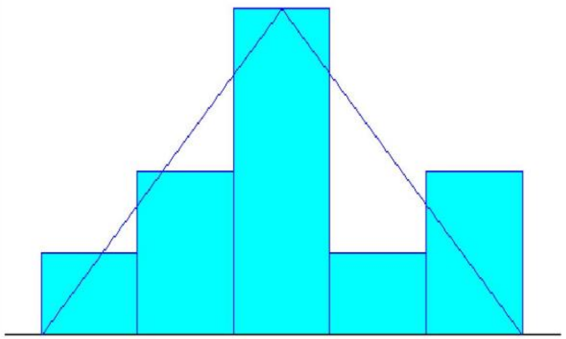
Number of Data Points = 48
Min Data Value = 0
Max Data Value = 4e+004
Sample Mean = 1.02e+004
Sample Std Dev = 1.04e+004

Histogram Summary

Histogram Range = -0.001 to 4e+004
Number of Intervals = 6

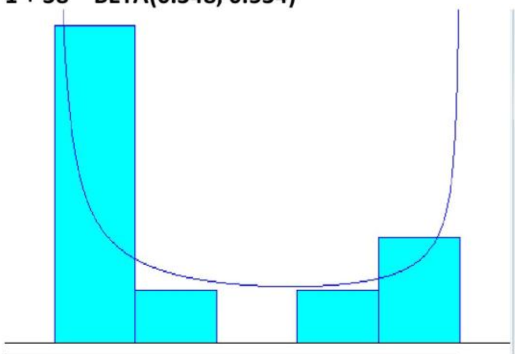
E4	TRIA(50, 175, 300)	1 + 38 * BETA(0.348, 0.534)	-0.001 + EXPO(4.35e+004)

TRIA(50, 175, 300)



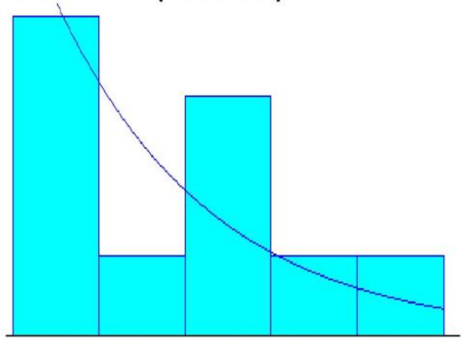
```
        Distribution Summary

Distribution:   Triangular
Expression:     TRIA(50, 175, 300)
Square Error:   0.037600


Kolmogorov-Smirnov Test
  Test Statistic          = 0.28
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points     = 10
Min Data Value            = 50
Max Data Value            = 300
Sample Mean               = 185
Sample Std Dev            = 85.1

        Histogram Summary

Histogram Range           = 50 to 300
Number of Intervals       = 5
```

1 + 38 * BETA(0.348, 0.534)



```
        Distribution Summary

Distribution:   Beta
Expression:     1 + 38 * BETA(0.348, 0.534)
Square Error:   0.018555


Kolmogorov-Smirnov Test
  Test Statistic          = 0.342
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points     = 10
Min Data Value            = 1.89
Max Data Value            = 38.4
Sample Mean               = 13.1
Sample Std Dev            = 16

        Histogram Summary

Histogram Range           = 1 to 39
Number of Intervals       = 5
```

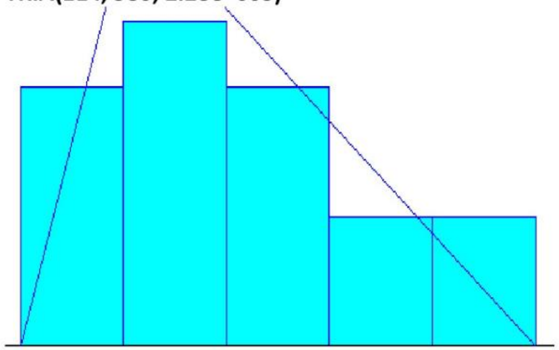
-0.001 + EXPO(4.35e+004)



```
        Distribution Summary

Distribution:   Exponential
Expression:     -0.001 + EXPO(4.35e+004)
Square Error:   0.050091


Kolmogorov-Smirnov Test
  Test Statistic          = 0.378
  Corresponding p-value = 0.0892

        Data Summary

Number of Data Points     = 10
Min Data Value            = 0
Max Data Value            = 1.2e+005
Sample Mean               = 4.35e+004
Sample Std Dev            = 4.26e+004

        Histogram Summary

Histogram Range           = -0.001 to 1.2e+005
Number of Intervals       = 5
```

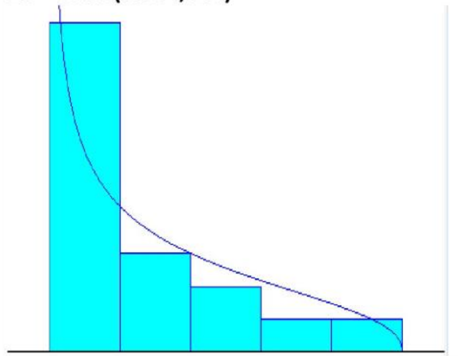
E5

TRIA(114, 580, 2.28e+003)



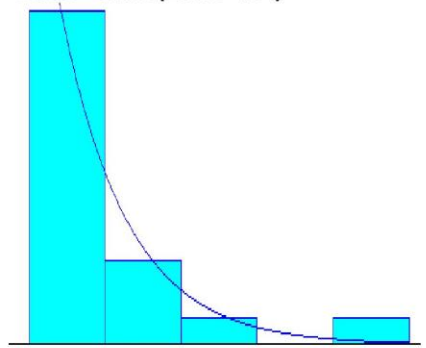
```
        Distribution Summary

Distribution:   Triangular
Expression:     TRIA(114, 580, 2.28e+003)
Square Error:   0.012244

Kolmogorov-Smirnov Test
  Test Statistic         = 0.13
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points    = 17
Min Data Value           = 114
Max Data Value           = 2.28e+003
Sample Mean              = 991
Sample Std Dev           = 615

        Histogram Summary

Histogram Range          = 114 to 2.28e+003
Number of Intervals      = 5
```

25 * BETA(0.604, 1.4)



```
        Distribution Summary

Distribution:   Beta
Expression:     25 * BETA(0.604, 1.4)
Square Error:   0.010988

Kolmogorov-Smirnov Test
  Test Statistic         = 0.274
  Corresponding p-value = 0.13

        Data Summary

Number of Data Points    = 17
Min Data Value           = 0.231
Max Data Value           = 24.5
Sample Mean              = 7.55
Sample Std Dev           = 6.63

        Histogram Summary

Histogram Range          = 0 to 25
Number of Intervals      = 5
```

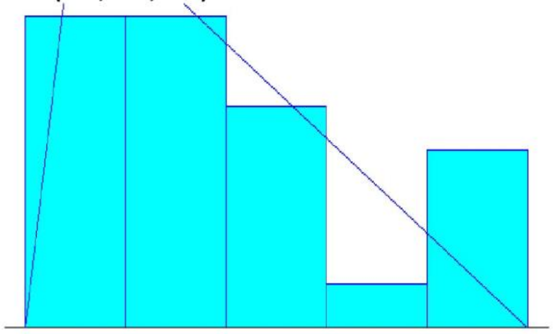
-0.001 + EXPO(2.14e+004)



```
        Distribution Summary

Distribution:   Exponential
Expression:     -0.001 + EXPO(2.14e+004)
Square Error:   0.005392

Kolmogorov-Smirnov Test
  Test Statistic         = 0.184
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points    = 17
Min Data Value           = 0
Max Data Value           = 1.23e+005
Sample Mean              = 2.14e+004
Sample Std Dev           = 3.04e+004

        Histogram Summary

Histogram Range          = -0.001 to 1.23e+005
Number of Intervals      = 5
```

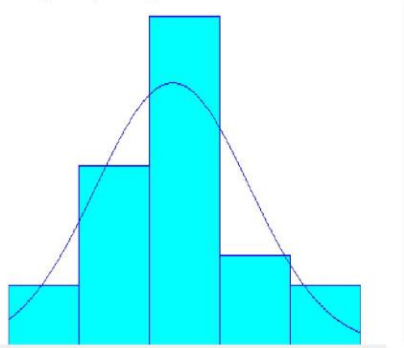
E6

TRIA(126, 178, 648)



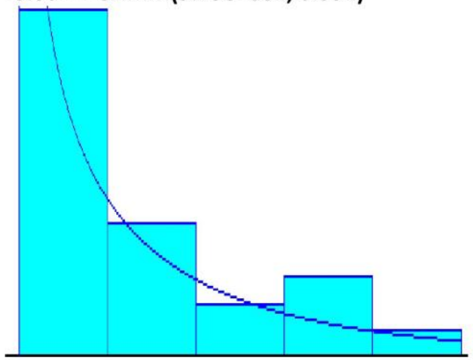
```
        Distribution Summary

Distribution:   Triangular
Expression:     TRIA(126, 178, 648)
Square Error:   0.023920

Chi Square Test
  Number of intervals   = 3
  Degrees of freedom    = 1
  Test Statistic        = 0.0673
  Corresponding p-value > 0.75

Kolmogorov-Smirnov Test
  Test Statistic        = 0.163
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points   = 24
Min Data Value          = 126
Max Data Value          = 648
Sample Mean             = 334
Sample Std Dev          = 160

        Histogram Summary

Histogram Range         = 126 to 648
Number of Intervals     = 5
```

NORM(16.2, 5.22)



```
        Distribution Summary

Distribution:   Normal
Expression:     NORM(16.2, 5.22)
Square Error:   0.019714

Chi Square Test
  Number of intervals   = 3
  Degrees of freedom    = 0
  Test Statistic        = 1.13
  Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
  Test Statistic        = 0.118
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points   = 24
Min Data Value          = 5.5
Max Data Value          = 28.1
Sample Mean             = 16.2
Sample Std Dev          = 5.34

        Histogram Summary

Histogram Range         = 5 to 29
Number of Intervals     = 5
```

-0.001 + GAMM(3.73e+004, 0.534)



```
        Distribution Summary

Distribution:   Gamma
Expression:     -0.001 + GAMM(3.73e+004, 0.534)
Square Error:   0.007275

Chi Square Test
  Number of intervals   = 2
  Degrees of freedom    = -1
  Test Statistic        = 0.932
  Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
  Test Statistic        = 2.23
  Corresponding p-value < 0.01

        Data Summary

Number of Data Points   = 24
Min Data Value          = 0
Max Data Value          = 7.3e+004
Sample Mean             = 1.99e+004
Sample Std Dev          = 2.05e+004

        Histogram Summary

Histogram Range         = -0.001 to 7.3e+004
Number of Intervals     = 5
```

Appendix C

Summary of T-test hypothesis testing

Summary Values		
n		30
$\sum X$		346.79
$\sum X^2$		5297.8207
SS		1289.0439
variance (inferential)		44.4498
standard deviation (inferential)		6.6671
standard error		1.2172
sample mean		11.5597
hypothetical population mean		125
difference		-113.4403
t		-93.1977
df		29
P	one-tailed	<.0001
	two-tailed	<.0001

Appendix D

Momentary shifting bottleneck plot