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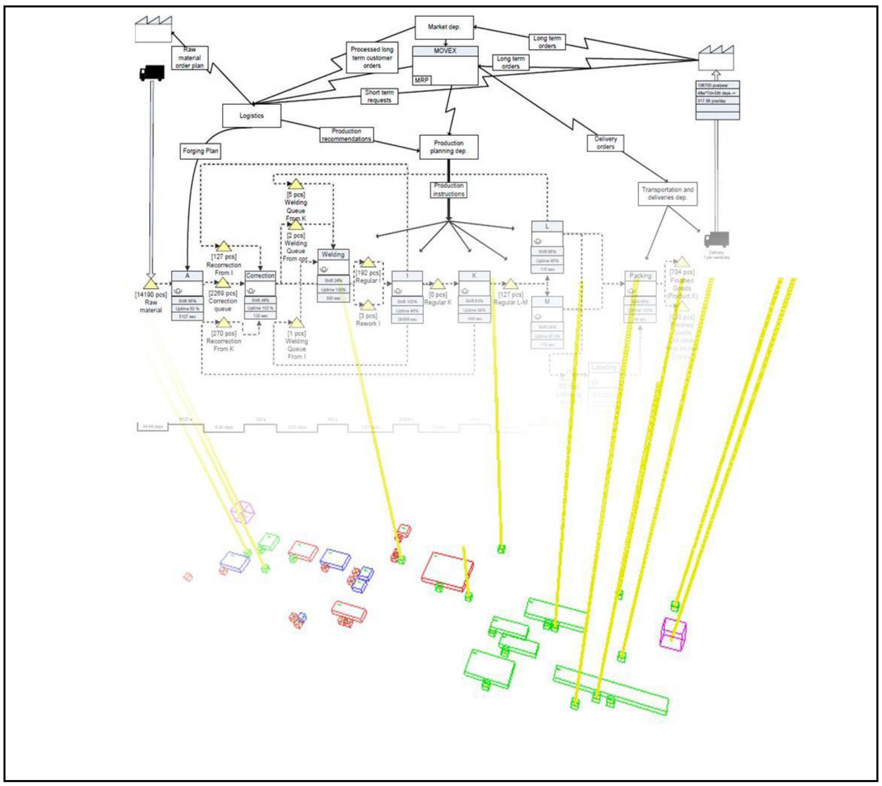

An assesment of production system dynamics

Evaluating WIP using discrete event simulation and value stream mapping

Master of Science Thesis in Production Engineering

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Abstract

This report covers a master thesis project carried out at Chalmers University of Technology. The purpose of the project was an attempt to combine Value Stream Mapping (VSM) with Discrete Event Simulation (DES) to a single tool used to solve problems in industrial applications. The idea behind this was to combine a simple, well known and static tool as VSM with the more complex and unused method of DES. To do this combination a case study was done at a forging company in Sweden, manufacturing cranks and front axle beams in a 16000 metric ton forging press. The focus of the study was to identify the levels of work-in-process (WIP) in the system and identify how the dynamics of the production system affected them. In the study, a DES model was used to identify problem areas and to compare the WIP levels resulting from different forging plans. In addition to the DES model a VSM was done, in an effort to both reduce WIP in the system and to increase the value adding time. The mapping also showed possible synergies between the two methods, which are used in the creation of a framework for a new methodology. The final result of the study was a new method, combining VSM and DES. Also, a forging plan designed to reach the set target output was created and tested to assist the case company.

Keywords: Discrete event simulation, value stream mapping, dynamic, WIP.

Contents

1 Introduction

This report treats a project carried out as a master thesis work at Chalmers University of Technology, the goal of the project being to research the possibilities of combining the Lean tool Value Stream Mapping (VSM) with discrete event simulation (DES) to a new way to approach challenges. To achieve this, a study was done at a case company which meant the goal of the project became twofold. In addition to finding a solution to the initial question, the study at the case company also meant fulfilling their wishes with regards to their own production facilities.

The reason for pursuing a new method involving both discrete event simulation and value stream mapping is that relatively little research has been done on the subject. Also VSM is a well known tool and widely used while simulation is still quite unknown. Combining the two would bring new light to the possibility of using simulation in industrial applications.

1.1 Background

The study was done at a company manufacturing front axle beams and crankshafts for trucks, the focus of the study was the production lines originating from a forging press with a capacity of 16000 metric tons. Both crankshafts and front axle beams are forged in the press, the products are then depending on customer specifications processed by varying machinery including heat treatment, cooling, straightening, blastering, drilling, welding and painting.

The production flow is illustrated in Figure 1.1.1. Production starts by pressing the raw material in A, and then depending on if it is cranks or beams being manufactured enters either the beam part of the flow shown in the upper part of the figure, or the crank part in the bottom.

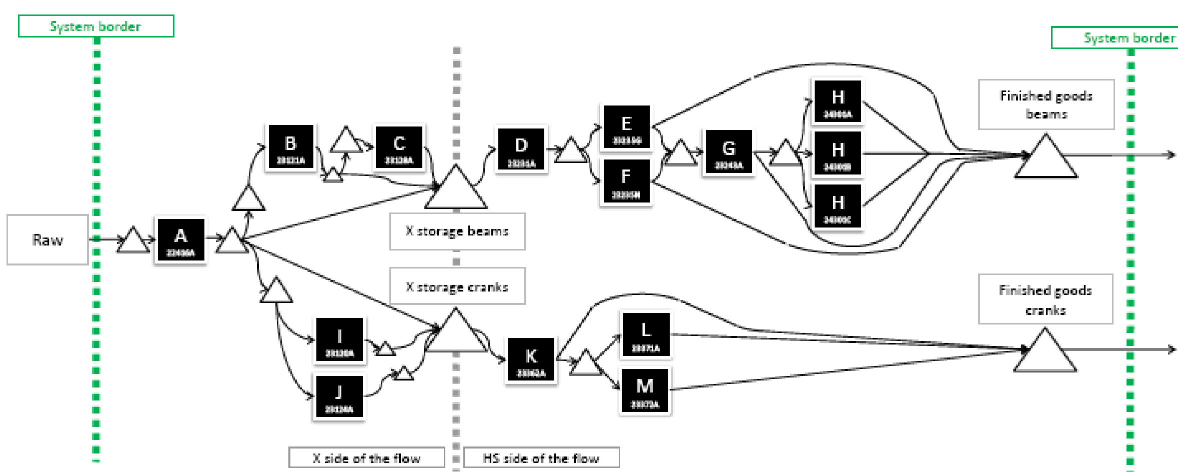


Figure 1.1.1 Production layout showing the two flows.

Due to certain circumstances, the number of different articles made at the company has doubled and a few new machines have been added to the production facilities. These changes are a challenge for the case company since a larger volume and twice as many articles complicates the production lines. The case company wishes to investigate the possibility of reducing the work-in-process (WIP), that is, the number of units that are in production. Both a DES model and VSM are tools that can be used to accomplish a reduction of WIP, in this project AutoMod was used in the creation of the DES model.

1.2 Purpose

The main purpose of this master thesis project is to combine VSM and DES to a new method that can be used in industrial applications. To do this, VSM and DES must first be compared, the purpose of the comparison is to highlight the upsides and downsides with each method, and then try to combine them both to a method that compensates for their respective weaknesses. Combining a well known Lean tool (VSM) with simulation, which is not as well known or widely used in industrial applications presently, would increase and diversify the knowledge in production development . Another important aspect of this project is to emphasize the importance of system dynamics and thus demonstrate the lesser known weaknesses of the well established VSM method.

The purpose of the company study was primarily to reduce the WIP, from the original level of an amount equivalent to 22 days worth of production to 14 days worth of production. Also, the DES model was used in an effort to identify bottlenecks in production, by doing this improvement work can be properly directed and hopefully lead to an increased output. Results from a dynamic model can show how changes to the production plan or a change in customer orders affect the production system, creating a model that can assist the company in such matters will also be done.

1.3 Objectives

The objectives will be to provide the company with information on how to reduce the WIP in their production system using the tools of discrete event simulation and value stream mapping. Information about how changes in customer orders and the production plan affect the system will also be provided with assistance from the DES model.

1.4 Problem definition

Since the project will have two different targets, the theoretical comparison between DES and VSM and the more straightforward reduction in WIP at the company, it is natural that the main question formulation also has been split in two; one main question concerning the WIP reduction and one concerning the comparison and possible combination of DES and VSM.

To answer these questions a dynamic model was created and a Value Stream Mapping was performed and combined with the simulation model to evaluate the present and possible future situations.

The first question concerns the WIP and the possibility of reducing it. To make a reduction possible it must first be established how the dynamics of the system affect the WIP levels. For instance system dynamics can be influenced by using philosophies concerning leveling. How will a large number of articles and different batch sizes affect the WIP of the system? The manufacturing flow can also be affected by bottlenecks in the system, will it be possible to identify these bottlenecks using the simulation and thus decrease the WIP levels?

- What are the levels of WIP and how much do the dynamics of the system affect these levels?

The second question concerns the possibilities of using VSM and DES in tandem to take on challenges in industrial environments. A comparison between the methods will show if the results from the two correspond and if strengths from one of the methods can act as a complement for weaknesses of the other.

- How can a combination of a dynamic DES model and a VSM help a manufacturing company reach desired levels of WIP?

1.5 Focus and delimitations

The main focus of the project will be to try to evaluate different ways to combine discrete event simulation with value stream mapping, while a comparison between the two methods also is interesting, focus will be put on trying to create a new method to approach production issues in industry. The study at the company will be focused on reducing the WIP levels and recommendations concerning other issues will be secondary. The study will focus on events inside the factory, thus, recommendations on changes in the supply chain will not be made. Also, only the heavy forging line, originating from the 16000 metric tons press, will be evaluated.

The focus of the VSM will be to create a current state map, creating a future state map and an improvement plan for reaching the future state will not be the focus, since the goal is to combine the DES and VSM. Recommendations based on the current state map and Lean productions theories can still be made though.

2 Theoretical Background

There are three focal areas of this study; discrete event simulation (section 2.1), Value stream mapping and its principles (section 2.2) and the dynamics of a production system (section 2.5). These are what define the framework for the entire project and must therefore be given a proper theoretical description. There are also some additional theories and principles that must be added to the list to make this subject coherent, as for instance how the worldviews of performance indicators can affect production control. All the required theories should be mentioned in this chapter.

2.1 Discrete Event Simulation

Simulation is defined by Banks (1998, s. 3) as an "imitation of the operation of a real-world process or system over time" and uses observations of the process' history to learn the operations characteristics. Simulation can be used to evaluate future implementations or changes in the current setup. Both existing and conceptual models can be assessed (Banks, 1998, s. 4).

A model is a representation of a system that should have clear boundaries, but could contain system components described in various detail. More on which components can be located in this study's model can be found in the methodology chapter. Here, discrete event models are used and they can be contrasted to mathematical, descriptive, statistical or input-output models. They represent the system's inner workings and not only the output that comes out from a given input. Discrete event models and their incorporated components are defined to a sufficient level of detail to represent the system and to meet the objectives of the study (Carson, 1993).

Various advantages of DES can be found and Banks (1998, ss. 10-12) mentions most of them. Among many, it eases decision making and correct decisions will be made more often, it reduces the time to analyze phenomena and gives a broad yet deep understanding of the system. It enables the analyst to understand the big "why" and help diagnosing the problem. Not least, you can explore possibilities using DES.

Banks (1998, s. 12) also gives four examples of disadvantages of DES, all of which must be discussed in this project. They are; *Model building requires special training*, *simulation results may be difficult to interpret*, *simulation modeling and analysis can be time consuming and expensive* and *simulation can be used inappropriately*.

In this project a discrete event model of the flow of products in the company's heavy forging line was created using the program AutoMod and its own programming language. Knowledge about DES and AutoMod was gained in an earlier course at Chalmers, without such specialized training it would have been difficult to use DES in a project such as this. The input data to the model was then differentiated in order to investigate how changes would affect the system and evaluate which new scenario would be best to implement.

2.2 Value Stream Mapping

Value stream mapping (VSM) is a Lean production tool developed by Toyota in 1995 designed to identify and eliminate waste, called *muda*, in the value stream (Hines, Rich, Bicheno, Brunt, Taylor, & Butterworth, 1998). Waste in the Lean manufacturing sense is unnecessary activities that cost resources without adding anything to the creation of the product, i.e. unnecessary transports and overproduction. Originally there were a total of seven different types of *muda*, but later an eighth type has been added.

To understand what VSM is, the concept of the value stream must first be established. A product’s value stream is all the events occurring when it moves through the supply chain, from raw material provider to the end user. VSM divides these events into value adding activities and non value adding activities. The value adding activities are operations that directly provide value to the customer, while the non value-adding do not. For instance cutting through a log is value adding, but cleaning the sawdust and moving the log into position to be cut are non value adding (Plenert, 2007). A VSM can be performed on a product’s entire supply chain, but most of the time it is confined to the limits of the company. That is, the material is traced from when it arrives from the supplier until the finished product leaves the factory (Rother & Shook, 2003, s. 9).

The main objective of the VSM process is to create a current state map of the value stream, showing not only product flow but also flow of information within the company and possibly between companies. Before creating the current state map a decision has to be made on what product or product family to map, since it is too time consuming to create a map for every single article. The product chosen should preferably be of large volume and must be important to the company, mapping a product of little importance to the company would be a pointless endeavor (Plenert, 2007). The map is constructed by visiting the shop floor, measuring times and noting how products move between processes and buffers. The most important total measurement values in VSM are cycle time, value-added time, lead time and throughput time (Rother & Shook, 2003, s. 17). The basis for improvement of the current state map is a number of Lean principles, the major ones used are presented in section 2.2.1 to 2.2.5. A future state map can then be constructed, showing how a new improved layout would look. Finally an improvement plan should be created, where the suggested improvements and the procedure to implement them are presented to ensure that the future state is reached in the best possible way. The VSM done in this project only concerned one important product group and its movement within the factory, and only a current state map was created. A future state map and the improvement plan accompanying it was not created, since the focus was not to carry out a complete VSM project.

Value stream mapping is a simple tool to use and no special education is required, even though a deeper knowledge of Lean production is advantageous when improving the current state map. Additionally there are no expensive or advanced tools needed, a large piece of paper and a pen are everything that is required and completing the map is a relatively fast process since it only requires one or a few visits to the shop floor.

The speed of the VSM process can also be a downside however, since the map is constructed based on a single visit there is a risk that the value stream map will be done under extraordinary circumstances. This is especially true if there is large variation in the production processes and of customer orders, the output total for the day might still be reasonable but the few items studied will not be representative for the average production rate.

2.2.1 Lean production

The basis for the improvement plan and the future state map is Lean production theory, a short introduction to what Lean production is and the most important concepts are presented in this chapter.

Lean production is the name given to Toyota production system (TPS) in the western world, it was introduced in 1990 when *The machine that changed the world* was first published (Shook & Dennis, 2007, s. chapter 2). Toyota themselves started creating their production system after the Second World War. Because of the war and the subsequent American occupation, Toyota had to deal with issues that were not affecting companies in the west at the time. For instance credit was extremely expensive and thus no investment in expensive machinery could be made, also a lack of skilled labor combined with strong unions lead to a culture with life-time employment for workers (Shook & Dennis, 2007, s. chapter 1). Out of this a system with a low level of capital investment and large involvement of employees was born, unlike in batch-and-queue systems focus was shifted from machine efficiency and towards creating value for the customer. With guarantees of life-time employment Toyota was able to implement a system of continuous improvement, *kaizen*, where everyone involved strives towards improving the processes and eliminating *muda*. Over the years TPS has evolved and new ways of identifying and eliminating waste have been introduced, value stream mapping is one of those tools.

TPS did not gain much attention in the western world initially, since companies in the west did not face the same difficulties of fierce competition and expensive credit that the Japanese companies did. However in the late 80s and early 90s the economic climate in the west changed and more attention was paid to how successful Toyota's business model had been and a number of books were released, as for instance *Toyota production system: beyond large-scale production* (Ohno, 1988), *The machine that changed the world* (Roos, Jones, & Womack, 1990) and *The Toyota way* (Liker, 2004). In these books the name Lean production was given to what initially was Toyotas own production system.

Knowledge of Lean production theories has been important in this project since VSM is a Lean tool, and without knowing the background the risk if misusing the tool would be greater. Also, suggestions for improvement of the current system have been based on the theories of Lean production.

2.2.2 **Waste and value**

In Lean production the goal is to create more value using fewer resources and in order to do this, activities that use resources without creating any value for the customer must be removed. In short these activities are waste, or as it are called in Japanese, *muda*. By adopting the Lean approach the waste can be eliminated and replaced with value-adding activities instead (Womack & Jones, 1996, ss. 31-32). Taiichi Ohno, the creator of Toyota Production System defined seven different types of waste:

- Unnecessary transport of products
- Unnecessary motion of people
- Inventory
- Waiting
- Overproduction, producing more units than the customer requires
- Over processing, this can be both unnecessary process steps and extra processing that must be done due to poor equipment
- Defects

An additional type of waste, manufacturing of incorrect products can also be added (Womack & Jones, 1996, s. 15). This is not a quality issue and instead means that the company has produced a product or service that the customer does not need, or has produced a product with features that add no value for the customer.

Ohno thought that overproduction was the most severe type of waste, since that it is what creates many of the other types. For instance extra inventory and additional waiting are both caused by overproduction. In extreme cases overproduction also causes unnecessary transport and motion if operators have to navigate through a shop-floor clogged by excess inventory (Liker, 2004).

To define which activities are value-adding and which are not, it is important to focus on what the customer wants, since he or she is the one who ultimately defines what value is. Too often companies tend to focus on what equipment and conditions they have available and create a product trying to "maximize" the use of what they already have. Instead the focal point is the wants and needs of the customer, if the customer wants a product that has rendered an expensive piece of equipment obsolete then let that be the case (Womack & Jones, 1996, ss. 17-18). It should however be mentioned that customers have needs and expectations that they are not aware of themselves and if a company is able to fulfill those unspoken needs much can be gained. (Bergman & Klefsjö, 2009)

2.2.3 **Buffers and Work-in-Process**

Inventory is the products that are yet to be delivered from the producer to the customer. The products can be completed and stored in a finished goods warehouse or they can also be incomplete and stored either in production buffers or be processed in machinery. The products that are incomplete are called work-in-process (WIP), as shown earlier in section 2.2.2 inventory is one of the seven wastes and that means that WIP should be kept as low as possible. This is because inventory causes costs in the form of interest on the capital tied up in the stored products. Another risk is that if the product goes out of fashion a larger quantity of units has to be scrapped than if inventory was kept low. Large quantities of inventory can also require extra space which means higher rent or that products are placed in locations that are not meant to be storages which causes confusion.

The presence of large buffers is also a hindrance to improvement, with large buffers the following process is not directly affected when a machine breaks down since production can continue by processing products from the buffer. This buffer only serves to hide the inadequacy of the first machine, without the buffer the problems with the first machine would be clearly visible, a removal of the buffer would also create an incentive for the operators in the first machine to improve their process since the colleagues in the following process would be directly affected by a breakdown (Liker, 2004).

The ultimate target is to achieve a production process with one-piece flow, where a product moves from process to process without ever waiting and then is directly transported to the customer. This production process would be void of both buffers and stock, however this is not achievable in all fields of production, for instance a supplier delivering spare parts at moment's notice needs a finished goods inventory. Machines that require long setup times require some kind of buffer and even though the Lean approach strives to reduce setup times it is not possible to eliminate them completely.

The main reason for having buffers is variation (Wilson, 2009, ss. 44-47), the larger the variation the larger the buffer must be. If three processes organized in a line all have the same cycle time, 60s, with zero variation there will not be any need for a buffer. If instead the middle of the three processes has the same mean value but with a variation of +-10s there must be a buffer installed before and after the middle process to achieve the original takt time of 60s. Without buffers there would be starvation either in the last or middle process because of the variation in the middle process (Wilson, 2009, s. 45).

So while inventory is *muda*, it is in many cases a necessary waste and removing the buffers completely without considering the consequences can in many cases have a negative total effect.

2.2.4 Just-in-time and Flow

The just-in-time (JIT) philosophy strives towards producing the right amount, which should arrive at the right place at the right time. According to Shook and Dennis (2007, s. 67) the JIT system has four rules:

- Do not produce something unless the customer has ordered it.
- Level demand so that work may proceed smoothly throughout the plant (*heijunka*).
- Link all processes to customer demand through simple visual tools (*kanbans*).
- Maximize the flexibility of people and machinery.

Heijunka, leveling the demand and production, will be dealt with separately in section 2.2.5 since it can be done without implementing a JIT system.

When using JIT the focus will be moved from the old push system where production is planned after a schedule that is based on an earlier estimation of customer demand. Instead a pull-system will be implemented, where production only starts when the customer has used a product, the customer in this case can be the following process step within the factory or of course the end-user depending on what process is considered. Points one and three are closely related, since the *kanban* system is a way to stop overproduction and send a signal to start production when a customer has ordered a product.

Kanban is Japanese word, literally meaning billboard, the original and most common *kanban* is a rectangular card, but it can be practically anything, a marking on the floor or an electronic signal (Shook & Dennis, 2007, ss. 74-76). When a customer uses a product the *kanban* card is sent downstream in the supply chain as a signal to start production of what just has been used. Without a *kanban* signal production is not allowed to start and thus overproduction can never occur. This creates a pull system, where production is based on what the customer truly demands and not a scenario where the producer tries to force demand by price campaigns to sell large amounts of inventory created by using a push system. The optimum would be to produce one single unit when a unit is consumed, and thus creating a one-piece flow. In reality this is seldom possible, many kinds of products must be produced in batches because of the nature of the production process, i.e. in a production process with a cycle time of only a few seconds but a setup time of several hours batches of one unit can never be justified.

In a pull system scrap and rework rates must be kept low, much lower than in a push system with large batches. This is because of the fact that if a unit is scrapped in a one-piece flow, a new product must be started from the start of the production chain. In a batch-and-queue system where an excessive amount of units are produced in each batch, scrapping one unit will not have any impact on the lead time. So to accommodate these demands processes must be stable and changeover times kept at reasonable levels in a pull system. (Shook & Dennis, 2007, s. chapter 5)

However, it should be mentioned that push systems are used even at Toyota (Liker, 2004, s. chapter 9).

At the case company, there is currently a backlog and the bottleneck is placed first in the production chain, or at least it is assumed to be, which means that a pull system probably will not be a great improvement on productivity. Additionally, some processes require long setup times which are not fitting for a pull system.

2.2.5 Leveling (*Heijunka*)

As stated earlier the optimal production chain would be a one-piece flow, also focus should be on delivering what the customer wants. A build-to-order production system achieves these goals and in theory would be an excellent system, provided that customer orders do not change with regards to both quantity and type. However this is not the case in the real world, customers change what they want even after ordering a product and total quantity varies during the year (Liker, 2004, ss. 115-117). Thus a build-to-order system can lead to large amount of overtime and stress during hectic periods while equipment and workers are idle when demand is low. Higher amounts of inventory and capital investment will also be required, since they must be calculated for the maximum possible level. To combat these issues Toyota introduced *heijunka*, leveling the schedule, where the pace of production is held constant.

Liker (2004, ss. 117-118) illustrates how *heijunka* can be implemented in a facility with batch production, much like the one currently used at the studied company. The example is however taken from a plant assembling engines and not a pure manufacturing industry. In the example a medium-sized product is produced Monday-Wednesday because it is the largest product type, then a small-sized is produced since it is the second largest volume and finally the small volume, large-size is manufactured, Liker has three issues with this kind of batch production:

- Customer demand is unpredictable, if the demand varies and customers order many large sized products early there will be a problem since they won't be produced until later in the week. If demand is instead low and fewer medium-sized products are ordered there will be excess inventory because they have already been produced.
- The use of resources will be unbalanced, it is likely that different product types require different amount of labor and machinery. Thus there might be stress during the first days and then workers are idle during the end of the week when small and large products are made.
- There will be an uneven demand on the suppliers since they too will have to adjust to the uneven schedule. When the company then tries to adjust to the varying customer demand a large strain will be put on supplier who either will have to keep large inventory or increase their production on short notice. The further one moves along the supply chain, the larger these effects will be; this is called the bull-whip effect.

All of these issues can be resolved by replacing the batch production with a leveled production where small, medium and large products are produced intermediately. In the new leveled production all three different products will be produced every day, and each day the production will be identical. The new schedule will require more changeovers, so in order to implement *heijunka,* setup times have to be reasonably short. At the case company, the setup times are long and reducing them is not a part of this project. However in relation to the batch sizes, ranging from a few hundred up to approximately 2500 products, they might be manageable (Liker, 2004, s. 120).

Coleman and Vaghefi (1994) also stress the need for short setup times when implementing *heijunka*. They also point out that an effort to implement *heijunka* will not only level the workload with respect to different days, the workload of each machine and operator will also be leveled. When the load carried by each worker differs there will be a problem of the most skilled and senior workers trying to hold down the easiest jobs. Not only does this create a poor work environment but it also hinders improvement work since there is no cooperation and the most skilled staff is stuck with easy tasks and has no incentive to improve the harder tasks that require longer time.

In a study done in a purer manufacturing environment it was shown that the implementation of *heijunka* was still viable, finished goods stock was reduced and operational efficiency was improved while maintaining a high service level (de Araujo & de Queiroz, 2010).

2.3 Theory of Constraints

In 1984 Eliyahu Goldratt (The goal: a process of ongoing improvement) proposed a methodology on how to work to streamline a manufacturing flow. During the authors' time at Chalmers this has been a reoccurring subject, generally known as Theory of Constraints (TOC). It has since the 80's become a recognized methodology in companies world-wide and was considered to be the primary tool when the authors first learned to analyze an AutoMod output. In the course Simulation of Production Systems (Laring, 2009) the authors were presented to the following methodology, originally interpreted from Eliyahu Goldratt:

1. Find the bottleneck that limits the system
2. Maximize the utilization of the bottleneck
3. Subordinate all other resources to the bottleneck
4. Exploit the bottleneck further until it no longer is a bottleneck
5. Start over from step 1.

This approach is used to eliminate or at least reduce bottlenecks in a system, by doing this the total output of the system will be improved since the limiting bottleneck has been improved. However, this is primarily used in a push-oriented system where the main target is to increase the output of the system and where things such as a reduction in WIP and continuous flow are secondary.

2.4 Performance Indicators

The concept of productivity has been around for a long time, and it is still one of the most valuable concepts for manufacturing companies across the globe. Yet productivity is not that straightforward to measure, something that has been discussed in Maynard's Industrial Engineering Handbook (Smith, 2001) and Niebel's Methods, standards, and work design (Freivalds, 2009) among many other books. Smith (2001) describes the importance of productivity as a measurement of performance and concludes that there are a lot of misperceptions in the subject. For instance, productivity is usually measured as the relationship between input and output but is more seldom put in comparison to the marketplace needs. In the same chapter of that book Smith writes about measuring productivity in a broader sense and gives us some examples of measurable indices, for instance *Average production response time (lead time)* and *Average level of work in process (WIP)*. These performance indicators are usually weighted according to their relative importance and measured to see the success rate of the company's work towards meeting their objectives (Smith, 2001, s. 2.1.6).

Performance indicators must be used as they originally were intended to, as pure indicators of how the organization works. A common mistake in producing companies of today is to make changes in the manufacturing process, layout or personnel to chase required values of indicators that possibly are misleading, often with sub-optimization as a result.

An exceptionally valid remark made by Smith is the point about comparing indices with customer demands, something that is immensely connected to the subject of this project; dynamics of the manufacturing system. In this project, the need to measure Key Performance Indicators (KPIs) is large, but mainly to evaluate possible future solutions in comparison to the current setup. They also play a big part in the evaluation of the analysis tools (DES and VSM) since they differ remarkably in character between each other. For instance, in a DES study, it is possible to follow the variations of the indicators, or get an average value. From the VSM only a single snapshot of each indicator should be extracted (Donatelli & Harris, 2001). Just as with Lean theory it is important to be knowledgeable about KPI theory, since when being aware of the pitfalls of KPI greatly reduces the risk of misusing them and arriving at an incorrect conclusion.

2.5 Dynamic and Static Systems – The Combination of DES and VSM

First of all, the authors feel that the meaning of the words dynamic and static needs to be explained in the context of this project. Therefore a dictionary is used;

The Oxford Pocket Dictionary of Current English (2009) gives the following definition of the word *Dynamic*:

> *Characterized by constant change, activity, or progress (Physics) of or relating to forces producing motion. Often contrasted with static.*

Basically a dynamic system should thus be a system characterized by constant changes, and that could mean in any sense of activity. Such a system's variables can change without external influence and is affected by its own history. Changing an input variable does not have to immediately affects the output of a dynamic system, in contrast to a static system where output is directly dependant on the input to the system (Gustafsson, 2007). Britannica (Encyclopædia Britannica, Inc., 2011) gives more information on dynamical systems theory and chaos and conclude that *one of the most important theoretical developments has been the qualitative theory of differential equations* which is a method to write general properties of solutions to dynamical systems without writing any explicit solutions. Without going into detail, the theory is about collecting and combining local analytic information to describe global characteristics of a system using differential equations. Something very similar to what the aim of a DES model is where the simulation team uses a break-down of the system to smaller pieces. These sub-sections can then be analyzed and reenacted in order to make the computer reconstruct a model of the entire system.

2.5.1 Exemplifying system dynamics

In this project, the difference between a dynamic and a static system is more a concern of what gives the system its randomness and how the system performs under different conditions, still there are a lot of distinctions between the two that must be discussed in order to get the reader to fully understand the problem. In order to exemplify these differences some fictional examples with hypothetic questions are now given:

2.5.1.1 Example 1 – Is static planning realistic?

Many companies use some kind of ERP (Enterprise Resource Planning) system where they give static input, for instance batch sizes, cycle times etc. The system then calculates the lead time of the batch (or equivalent) and translates that into a starting time of each order. These systems can normally combine various inputs and project the most efficient response from that. However, it is very rare that they include randomness or variations in the calculations, which thus are static. ERP systems seldom consider that highly distressed systems often are clogged by an excess of articles flowing through the system, a well known phenomenon in the manufacturing world. Besides, calculations of that sort never take shared resources that support parallel flows, such as maintenance personnel, forklifts, production leaders and managers etc. into consideration. Is a static system of that sort realistic or could the lack of those support functions affect the system as a whole?

2.5.1.2 Example 2 – Calculating with scrap rates

If a production manager can give the rejection rates for a process, or even an article number in that process, the feedback from that process is often considered to be adequate. That might be the case, but using these numbers to forecast production output is very risky since they can vary greatly from batch to batch. What if the output of three different starting batches of 100 pieces were 97, 72 and 98 pieces respectively? Is it valid to expect a scrap rate of 11 % per batch? In addition to that, if batch production is applied, must batch sizes be corrected in agreement to the output of the previous batch? If static planning is used, what happens when an output is expected to be 89 pieces but only is 72? Is the answer to always forecast an output of the mean or the lowest value?

2.5.1.3 Example 3 - Static processes?

This example is closely connected to the two above, but gives another edge to the problem; in the same way as scrap rates often is forecasted, most ERP systems use a static availability or uptime of the resources. They also assume that the process time is constant for all products within an article number for each resource. Is it fair to suppose that a machine will perform equally well or bad during the entire maintenance cycle? Let us say that a manufacturing cell consists of two machines that produce with the same process time. They are put in a serial flow and machine A has an average availability of 85 %, whilst the same number for machine B is 75 %. However machine A's availability is at 90 % directly after every maintenance and then linearly drops to 80 %. Machine B's availability after maintenance is also as high as 90 %, but drops to 60 %. It also has to be maintained more than twice as often as machine A. The maintenance procedure lasts half a day for each machine. A probable diagram of the machines availabilities is shown below.

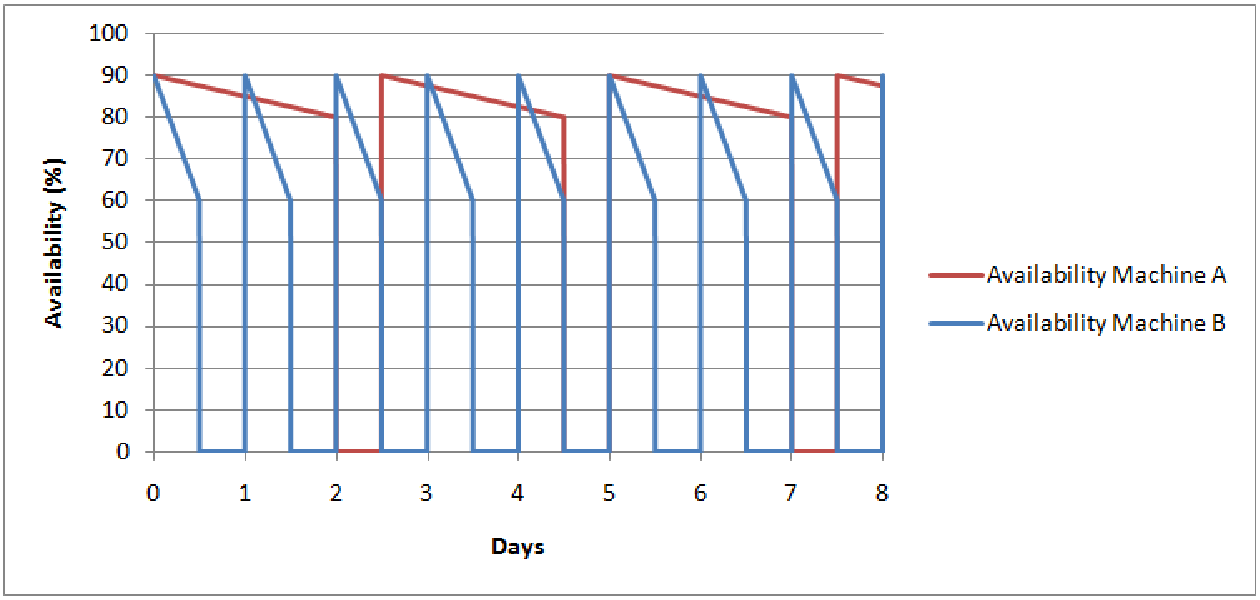


Figure 2.5.1. Probable availability diagram of the above defined system.

Will the availability of the cell still be 75 % (as machine B is the ordinary bottleneck)? In this case, the obvious answer is 'no' even though the diagram shows a very surreal linear system. Imagine the differences of a more reality like system with even more variation.

2.5.2 Impact of system dynamics in DES and VSM

There are of course more aspects of dynamic systems then the above mentioned, but these can give a clue how different methods perform when it comes to analyzing manufacturing systems. Dissimilarities in the essential characteristics between DES and VSM are partly what make this topic captivating. VSM as a tool is easily performed, fast and might be very accurate but it has a few flaws that must not be forgotten. Most important for this project, it does not consider any variations since it is only a snapshot of reality (Donatelli & Harris, 2001). DES, on the other hand, is a method that is much more time-consuming but can give advantages in terms of including system dynamics. The dynamics of a DES system is provided by stochastic variables which are impossible to predict (Gustafsson, 2007). In this case probability distributions are used to define the stochastic variables. If time is used wisely to recreate the dynamics of the real manufacturing processes there is really no competition in the Lean or six sigma tool box available that can measure up to simulation, in the sense of analyzing dynamic shop floor organizations (Ferrin, Miller, & Muthler, 2005).

This project is not the first of its kind, some researchers have evaluated the combination of simulation and VSM with various conclusions as result. In fact, Solding and Gullander (2009) use both AutoMod and Excel, which are two important tools in this project, to evaluate a combination of DES and VSM. McDonald et al (2002) find that simulation can be a very important part of VSM, especially when the product complexity leads to variations in process steps, setup times and such. Donatelli and Harris (2001) conclude that simulation adds an extra dimension to VSM, time, and that the two are a “natural combination”. In those studies no integration of the two methods is done, but they are seen as complements to each other. Narasimhan et al (2007) gives a framework for a simulation aided VSM and proves the success of it in an engine test plant. Lian and Van Landeghem (2007) have an entirely different approach and instead create a VSM based model generator which enables the user to utilize a VSM inspired interface to produce a simulation model. All of the above mentioned researchers illustrate the possibilities a VSM is given when the dynamics of a simulation is supplied.

3 Methodology

In this project two analysis tools are of great importance; AutoMod and Value Stream Mapping. AutoMod is a discrete event simulation (DES) tool which simulates a model of the reality with a state variable that only changes at a discrete set of points in time (Banks, Nelson, & Nicol, Discrete-Event System Simulation, 2010, s. 16). Value Stream Mapping (VSM), on the other hand, is a tool used to map all the actions needed to bring a product from raw material storage to paying customer (Rother & Shook, 2003, s. 3). In this chapter, these methods and their inherent steps will be described. A few other complementary methods and tools will also be addressed to ensure that every step of the project is explained.

3.1 Project approach

The first step in this master thesis work was to find a suitable company and project to take on, that the project would involve simulation and production engineering related theories was decided before contact with companies was taken. Inquires were then sent to a number of companies that seemed fitting and a positive response was received from the case company. When a company had been found, a clearer definition was established with regards to the production facilities and challenges that the case company faced. These challenges then had to be translated into a relevant problem formulation together with the more scientific issue of combining VSM and DES. With the project now established the next step was to create a project plan where the timeframe for the different tasks in the project was set. The original intention was to start with the VSM to use it as input for the conceptual model. However the level of detail of the DES model became too deep which would have required a total of fourteen different value stream maps to be made. This would have required far too much time so the point of beginning with the VSM was moot and instead work on the DES model was initiated.

The creation and validation of the conceptual model is the first step of any simulation project, so too in this case. The case company provided assistance in the creation of the model which was necessary to correctly identify the different flows of products in the factory. When the conceptual model was complete the next step was to gather data for the computerized model as well as the VSM. The case company provided stop logs as well as other recorded data, this data then had to be processed and cleaned to make it correct and usable in the models. With data gathered and processed and the conceptual model complete the translation from conceptual to computerized model began. The computerized model was then verified and validated to make sure that it was a close enough approximation of the real system. The model was then used with real historic input data of both production and sales. In some cases, data such as stop logs was missing; this data had to be gathered by conducting interviews and making inquiries and then use these approximations as input data.

In tandem with the creation of the computerized model the VSM was started. The first part of the VSM was identifying a suitable product group which then could be mapped. When the product group had been identified, its theoretical flow was drawn. After this the products where studied in the reality and flows of products and process times and buffer levels where measured. Finally, the information flows within the company were mapped.

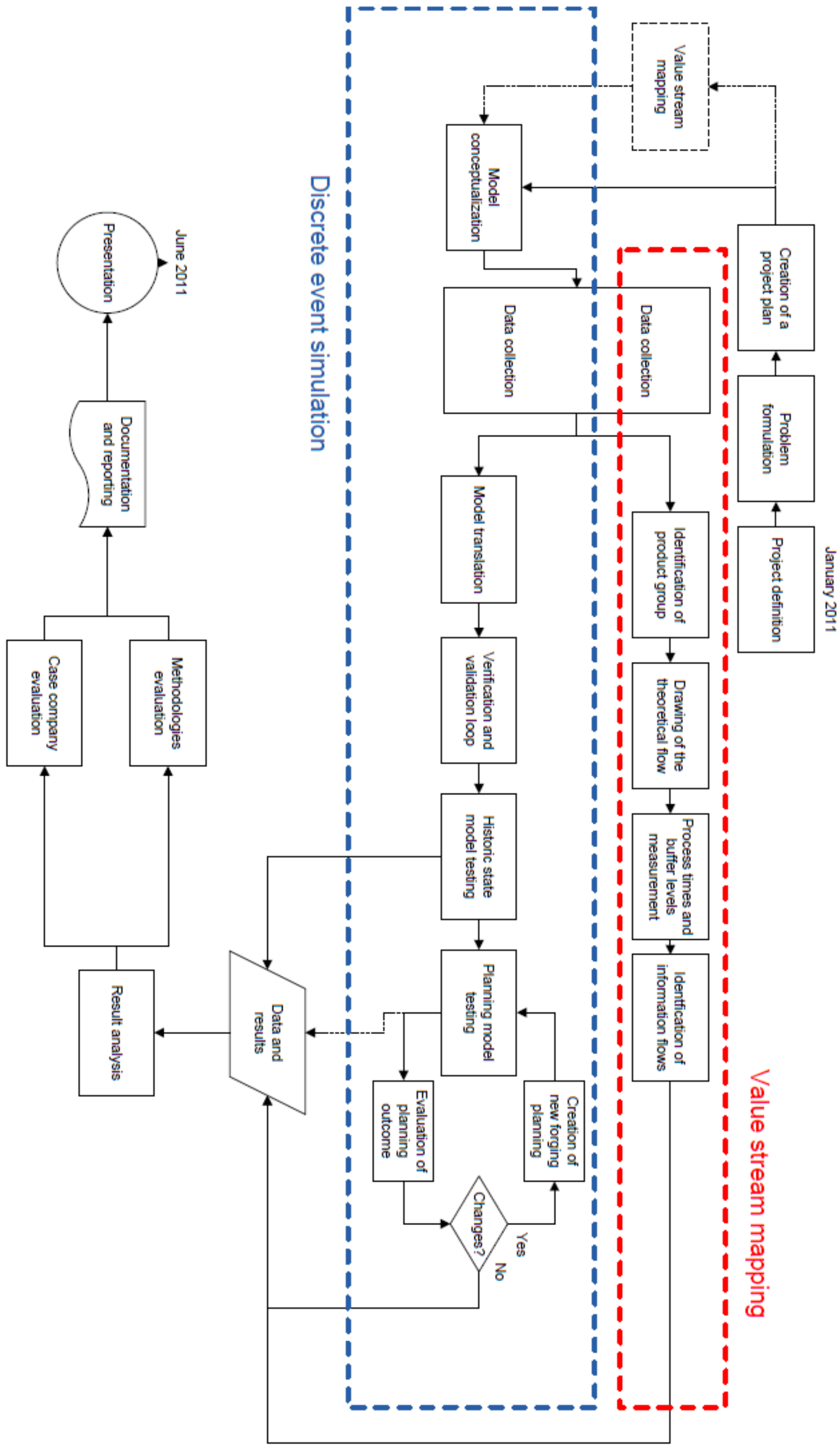


Figure 3.1.1. Flow chart of the project execution

The complete DES model was then used for testing different scenarios; different production plans were constructed and then ran in the model. How the system was affected with regards to WIP, queue levels etc. was then evaluated to see which plan performed in the best way.

The final part of the project was to analyze the results and present them to the case company and finally evaluate the possibility of combining the methods.

3.2 Simulation of the production layout

DES simulates the reality in a discrete set of points in time, as mentioned in section 2.1. The element of time thus plays a crucial role in the creation of the models, which preferably should be dynamic. However, it is not necessarily so that a model created in a DES tool as AutoMod is dynamic, it lies in the definition of the state variables. Usually simulation is used to include the dynamics of a system, but if the state variables are kept constant the result will be a static model. This project will contain models of both approaches since a part of the problem formulation needs a static model to be analyzed.

The model itself, or imitation of the real system, is built up by entities that represent different objects. These entities are then given definitions that make them function as they are supposed to. The entities can either be static or dynamic in the sense that they can move throughout the system or be stationary and may be ascribed attributes that pertain to every single entity (Banks, 1998, s. 4).

There are several different types of entities. A machine located in the shop floor in reality can be resembled by a resource in the model. The resources specified in the model are then an entity that can be ascribed attributes to be utilized in a reality-like manner. Note that resource entities give a service to dynamic entities flowing through the system. For instance, when a stamping operation of an axle beam is performed in a forging press, the press is the resource entity and the axle beam is the dynamic entity flowing through the process. Dynamic entities of that kind are in AutoMod called loads (Banks, 2000).

Another very common type of entity is queues. They are the “physical” place where loads can be located in the model and a load must always be in one of these queues. One specific queue where all loads are created is called space. Space can also, incorrectly, be used as a buffer between full queues. To control the waiting and activities of loads order lists can be used. Loads can namely be caused to wait on and be ordered from such lists, thus eliminating the problem of creating loads to already full buffers.

The above described features of a DES software makes it very suitable for simulation of a manufacturing process were the system itself is built up by resources and queues and with discrete elements flowing through the system. It is possible to create very complex systems with simple building blocks. However, when creating models in software as AutoMod one must be certain to work efficiently and in a structured way. In this project, Banks’ methodologies have been chosen and will thus be presented further.

Jeffrey Banks (Banks, Nelson, & Nicol, Discrete-Event System Simulation, 2010, ss. 16-21) defined twelve steps that can be followed in order to create a sound simulation project. He then explains what is required in every step and how the steps should be performed. The group members were educated in this methodology while studying at Chalmers and therefore it was also applied in this project. There are a few critical steps in this methodology, which can be preformed differently or using various methods and the group have chosen to only write explicitly about these steps. The steps are: Model Conceptualization; Data Collection; Verification & Validation and Production Runs & Analysis.

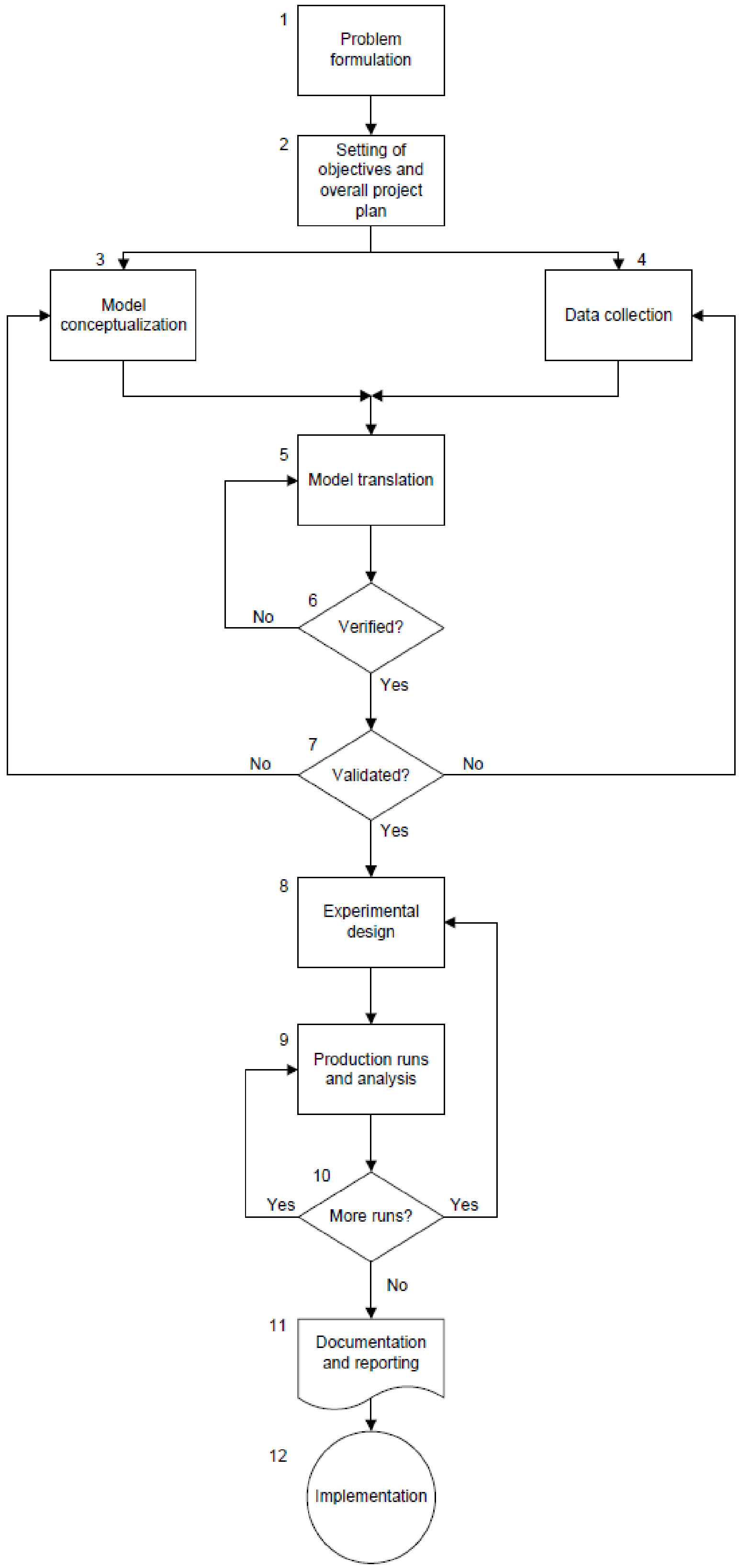


Figure 3.2.1. Banks' twelve steps for a simulation study (Banks, 1998, s. 17)

3.2.1 Model Conceptualization

A conceptualization of the reality in mathematical and logical relationships should be created to fully understand the flow structures of the entities in every simulation model. It is beneficial to start by doing a simplistic model and then add more complex logic to it to make it more realistic. By doing so, the followers of the project will gradually gain knowledge of the model (Banks, 1998, s. 15).

This project started off by having a discussion about what the problem was and how it was possible to analyze it. The group members got some information about the processes and the factory layout before going on a short, guided tour of the factory with the supervisor at the company. After walking through the plant a more thorough discussion about the problem was possible.

After having defined the problems and how to analyze it, the group was handed a simplistic flowchart in an Excel-file. One could say that this is the very first conceptual model of this project. It gave the group members an insight in the production flow, and was a good basis to start from when trying to understand the logic of the future simulation model.

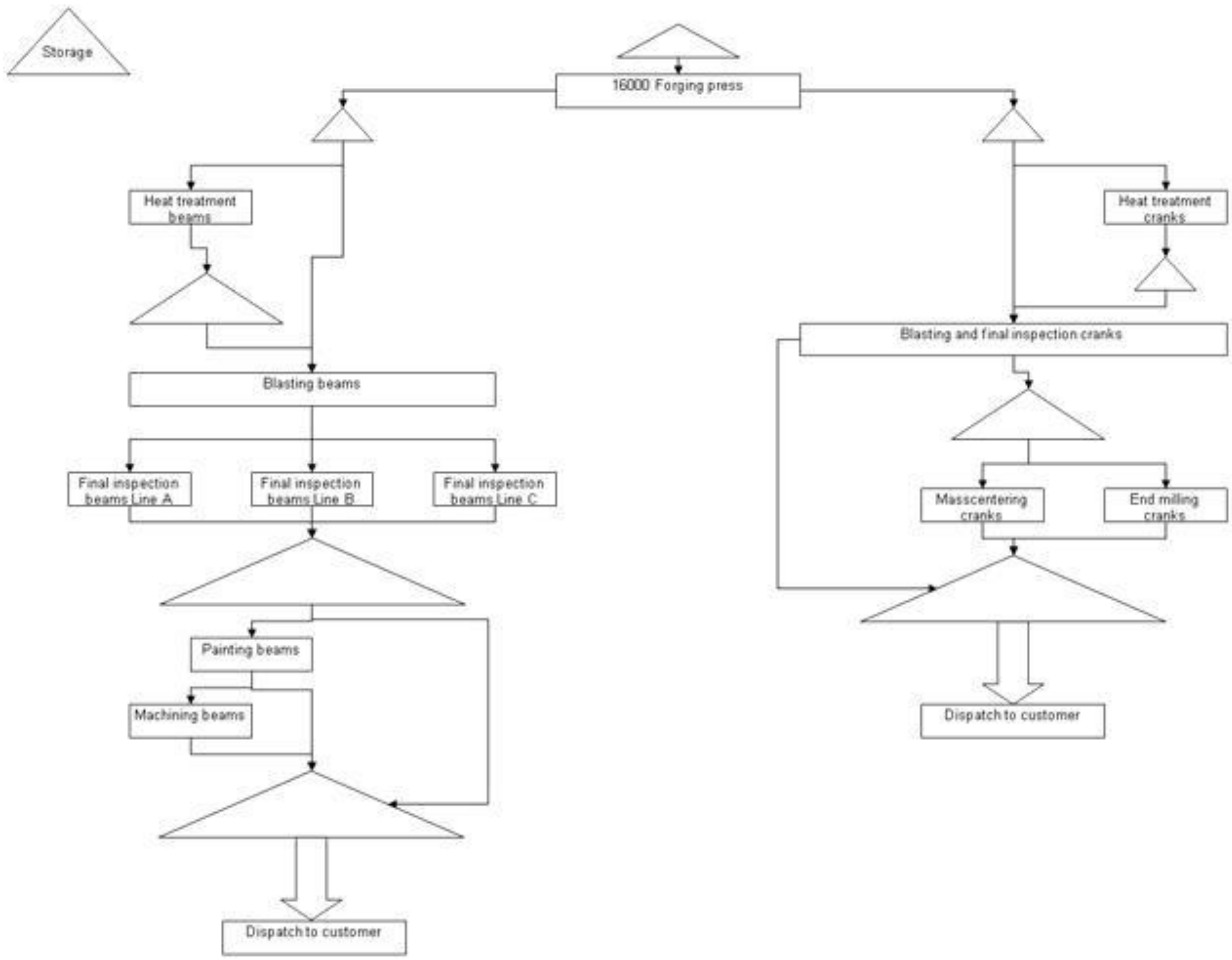


Figure 3.2.2. The first conceptual model of the project. The text printed in the picture is not of importance (contains names of the processes). Supplied by a supervisor at the case company.

The next step was to understand, clarify and in some cases simplify the real production logic into applicable model logic. This was done using simple tools as drawing on a printed layout of the factory and discussing possible logic scenarios with the supervisors at the case company. Many questions that were too tricky to answer by the supervisors were also answered by persons in charge of the processes, as for instance the shift leaders.

3.2.2 Data Collection

When step 2 is finished it is possible to start working on data collection and management. A list of required input data can be sent to the client. The data can either be retrieved from some kind of logging system or if no logs are available be collected by doing measurements and interviews on site. The data can then be translated into the model in a few different ways. Law and McComas (1999) describe the input modeling as one of the most important activities of a successful simulation study. They conclude that each source of randomness must be represented by a valid probability distribution and that there are two common pitfalls that can lead to bad input modeling. One of them is incorrect modeling of random machine downtimes, which often occurs when a new system is simulated. It is difficult to analyze a non-existing machine and therefore incorrect assumptions are made resulting in a simplified model that has a too high output. In this project, problems with entirely new machines have not been an issue, but most of the machines did not have a stop log associated to them. In those cases, the project group and one of the supervisors performed interviews with operators on the shop floor. The interviews were unstructured and had no direct questions about exact downtimes, instead the group tried to ask questions that made the operators reason about the stops. In that way, more credible values of the length of stops, number of stops etc. could be obtained (Denscombe, 2007). These values were then related to the budgeted availability numbers given by the planning department before they were introduced in the model.

However, the most important resource – the forging press – had an associated stop log which was prosperously filled in. The group members, as model builders, had to gather and manage the raw data for the process times. This activity can contain several problems, some mentioned by Williams (1994). For instance, the data sources might not be specific enough when defining the cause of the stop. This put demands on the project group’s data management, in particular the cleaning of data. The log was cleaned from maintenance slots, material shortages and unspecific data and analyzed with ExpertFit.

The other pitfall brought up by (Law & McComas, 1999) is replacing a distribution by its mean. This is a very important subject when it comes to discrete event simulation of manufacturing flows which are queuing-type systems. The variability of the probability functions has a tremendous impact on the flow through the queues and replacing them with constant mean values increases the output levels immensely. It was clear to the group members that this problem had to be kept in mind during the project and a focus on a valid data management process were kept all along.

3.2.3 Verification & Validation

When using simulation, discrete-event as well as other types of simulation, it is of outmost importance that the model created is an accurate representation of reality. To ensure proper behavior of the model it must be verified and validated, while the terminology is not universally defined, the verification process is concerned with making sure that the code of the model is free from errors and behaving correctly. The validation process is aimed at assuring that the simulation model itself conforms to reality and that it possesses the accuracy required. Kelton (2000, ss. 697-698) defines them as: "Verification is determining that a simulation computer program performs as intended, i.e., debugging the computer program. Validation is concerned with determining whether the conceptual simulation model (as opposed to the computer program) is an accurate representation of the system under study".

Thus a model can and should be verified until the code is flawless but the model cannot be validated until “perfection”, since a perfect model would be reality itself and a model is always a simplification of the real world. A model also has to be validated for a number of different conditions since the model might be valid in some conditions and invalid in others. To check if the model is valid for a set of conditions the output variables must first be identified, if the output then is within an acceptable range the model can be said to be valid for that set of conditions. (Sargent, 1998)

Validating a model is a time consuming process and since the model never can be perfect, a balance between accuracy of the model and the cost of validation must be found. Ensuring that the model is valid for its intended purpose is the highest priority. The importance of validation increases with the complexity of the model, so the validation of a very complex model can be a long process. (Jagdev, Browne, & Jordan, 1995)

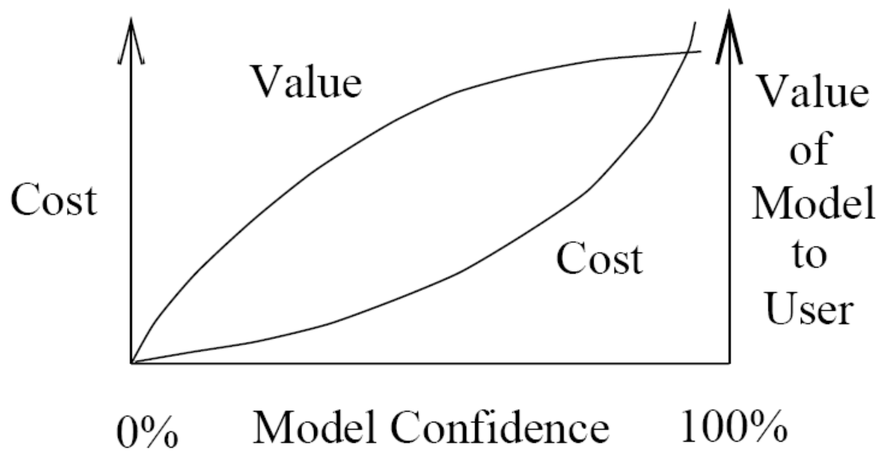


Figure 3.2.3. Model confidence as described by Sargent (Verification and validation of simulation models, 1998).

3.2.3.1 Model Verification

The verification process of a computerized model checks that the code is correct and that the implementation of the conceptual model is properly done (Sargent, 1998).Verification should take place before the validation of the model since it is unnecessary to make changes to the conceptual model before assuring that the code is correct (Jagdev, Browne, & Jordan, 1995).

To facilitate the process of correcting errors in the code it is important that proper programming procedures are used during the creation of the computerized model. Sargent (1998) also states that using a specific programming language instead of a generalized one will yield fewer errors. In this project AutoMod, that has its own programming language, has been used and thus the errors should have been kept to a minimum in that regard.

After assuring that the code is without errors the behavior of the model was checked, this was done by initially going over the code and checking that the statements were corresponding with the conceptual model. According to Sargent (1998) this is a part of the static verification of a model, additionally there is also a phase of dynamic testing. This can be done in three different ways, a top-down approach, a bottom-up approach and a mix of the two.

Common testing techniques that have been used are tracing, investigation of input-output relations and reprogramming of critical parts of the model. Tracing is a technique where a single load is run though the program to make sure that no part of chain is being skipped or passed too many times. The input-output check is checking that there is a reasonable correlation between the input and the output, for instance an input of zero would yield an output of zero, and output would most likely increase with an increase of the input. Reprogramming critical parts of the model means that an error deliberately is added to an important part of the code, this should affect the output and other variables of the model greatly. If not the case, something is most likely awry with the logic of the model. It is important to keep in mind that errors might also be caused by the conceptual model or the data and not just by the computerized model (Sargent, 1998).

3.2.3.2 Validation and validation techniques

Validation of a model is most of the time done by the modeling team themselves. However a third, independent, party can also be part of the validating process. Either they can validate the model during the process of model creation, or they can be brought in when the model is completed and validated by the modeling team. In this case the third party is responsible for making sure that the validating process itself was correctly done (Sargent, 1998). In both these cases the final decision if the model is valid is a subjective decision, a third process that strives to be more objective is using a process where parts of the model are given numerical scores. For the model to be valid the total score must be higher than a predetermined value. Sargent (1998) however is critical of this approach since the process might seem to be objective, but the subjectivity is actually only hidden since the scoring of the individual parts is still a subjective procedure. He also points out that a model might receive a total score high enough to pass while still having a big flaw that needs to be corrected.

In this project no third party has been consulted and the validation and verification of the model has been conducted by the project group itself.

The development of a simulation model can be divided into different parts, first the conceptual model is created by analyzing and interpreting the real system. Then the conceptual model is implemented into a computerized model by using a programming language, in this case AutoMod’s own. Conclusions can then be drawn from running the model using real world data and analyzing the results in an experimentation phase (Sargent, 1998). All parts of the model must be validated, from the conceptual model to the data needed to run the experiments on the computerized model. To validate the conceptual model, face validation has been used. This means that people knowledgeable about the real system have studied the conceptual model to confirm that its logic confirms with reality. Another validation technique used is historical data validation where output from the computerized model is checked towards real historical data. Cautioned must be used when using this validation techniques, because an incorrect output can mean that there are errors in the code or that the conceptual model is incorrect. A worst case scenario is of course that there are flaws in both.

3.2.3.3 Verification Techniques

In order to verify the model a number of different techniques have been used, there are more techniques available but due to the nature of the project and the model the following were chosen.

Animation: A model created in AutoMod can easily be shown graphically in the program itself and when a run is made the graphic model is always shown. By studying this animation, flaws in the system could be identified, for instance if a process had no downtime or if loads got stuck in a specific place. This technique was used continuously because, as mentioned, the graphics were always available.

Event validity: Certain events in the model were tested and it was made certain that the outcome was similar to the outcome of the same event in the real system. This was used when trying to create a backordering function, because as it turned out AutoMod's own backorder system did not work as was expected.

Fixed values: This is a process where input values were kept constant to make sure that there was no strange behavior in the model, for instance if the input into the system was set to zero the output also had to be zero. The use of production plans in the model runs meant that the input always was fixed, so if the output differed there would have been something wrong in the model.

Internal validity: Here the variability of the model output was tested by doing a number of runs and checking that the variability of the model was reasonably low. A too high variability can mean that the model is not dependable.

Operational graphics: As the model was run different key values, such as queue numbers and total loads in the model were checked for consistency with the real system and reasonable behavior. The system's real queue values were obtained in the VSM, therefore this technique was also used as a type of validation technique in the evaluation phase. However it is important to keep in mind that the VSM does not necessarily represent an average image of reality.

Traces: A single load was run through the system to check that the logic of the computerized model is correct and no steps in the chain were skipped. In AutoMod there is a built in debugger which was used to check that certain procedures were functioning as intended.

3.2.4 **Production Runs & Analysis**

This is the step where the runs are made and results gathered and analyzed. In this project, AutoStat is the main tool used in this step, at least when it comes to analyzing different outputs in a statistical comparison, as for instance when the current setup is evaluated according to the Theory of Constraints. An important part of the project has also been looking at how changes in the production plan affects the levels of WIP and the delivery precision. When performing such an analysis, the company and the project group wanted to follow the production performance indicators and WIP levels all through the run and plot the changes in Excel. Therefore, those runs have only been performed in the regular AutoMod Runtime window, and values were extracted to Excel-files from that.

3.3 Creation of the Value Stream Map at the case company

The Value Stream Mapping was done together in cooperation with the case company, which meant that certain wishes on their part were considered when choosing which product group to map.

The value stream mapping process itself can be divided into four different phases (Plenert, 2007):

- Preparation
- Current state map
- Future state map
- Improvement plan

In this project a future state map and the improvement plan for reaching the future state in the best possible way have not been included, since the focus has been improvement using the simulation and the comparison between the DES model and the current state of the VSM.

The first step of the preparation phase was to identify a suitable number of products or product groups to map. The decision was to map heat treated cranks, one of the four major product groups. As mentioned this is a crucial step in the VSM process, since choosing the map a product group of little volume or importance will cost a lot of time but return very little. The heat treated cranks are quite large in volume and contains one of the most important and large products. Another possibility would have been to map all four product groups, but that would have taken too much time without giving much additional information. Additionally, recent demands from customers meant that there was reorganization in the flow of beams, which meant that a VSM of that flow would not have been representative for a normal production state. This, together with a few other desires of the case company meant that heat treated cranks was the product group mapped.

Before gathering data for the current state map, the theoretical flow of the heat treated cranks had to be established to draw a rough picture of what the flow should look like, and to easier spot possible errors in the flow.

Data for the current state map was then collected in the usual way, by paying a few visits to the shop floor and doing measurements. Process times and cycle times were measured and the number of products in buffers was counted. By following the cranks throughout the production the flow, including possible rework, was identified.

The current state map of the product flow was then constructed from the gathered data. Missing from a complete current state map was still the information flow for the production chain. Mapping the information flow could not be done by visits and measurements; instead the main focus was speaking to those responsible for customer contacts and raw material orders. People with knowledge about the material planning system and the general production layout were also consulted. Since the process is not as straightforward as the one mapping the material flow, it is more likely that there will be a few errors. However, the information flow mapping was done over a longer time than the material flow, and thus variation will not be an as important issue.

3.4 Comparison between VSM and DES

When a VSM analysis as well as a dynamic simulation model had been created, it was time to compare these two in various areas to see which strengths and weaknesses both methods have. To do this, different points of comparison had to be defined. Out of these points, or indicators, some cannot be objectively judged. Therefore, not only statistical comparisons are valid, but a subjective evaluation technique was also needed.

3.4.1 Statistical Comparison

In order to measure, compare and validate the output of the methods used, a statistical approach was used. Indicators given in the VSM analysis have been compared to the dynamic responses from the DES model using mean, standard deviation and confidence intervals. These indicators are:

- Queues (WIP)
- Production lead time
- Finished goods storage

This process is closely connected to Sargent's proposed validation technique *Operational graphics* since the group compares the output of the DES model to real indices. It is however important to remember that it is not certain that the DES model is incorrect just because the outputs differ a lot. If the simulation model has been correctly validated and verified, this is instead a strong indication that the VSM results may be far from the real average value.

3.4.2 Subjective Comparison

The group members believe that only a statistical analysis of the output would not supply a sufficient basis to evaluate the two methods and therefore observations made during the analysis must be taken into consideration. These observations can be made by the group members, as analysts, or by people outside of the group. To collect information from other people, ordinary conversations held in the project have been very proficient. No structured interviews were held to get more information in this subject, since it is the opinion of the project group that a person must attain a certain level of knowledge of the results before making any valid contribution to the comparison. It is generally difficult to reach that level of knowledge when being outside the group of analysts.

Another subjective point of comparison is the actual results of the two methods. The comparison between the two results themselves is not subjective, it is just the matter of saying if the result is the same or not, it is more that the results from the methods are more or less subjectively made.

For instance, as presented by Plenert (2007), the outcome of a VSM analysis should be a future state map and an improvement plan. Both subjectively created by the analyst. The result of the DES analysis is vastly dependent on the methodology used to evaluate the model, and is always contingent to what changes have been tested by the analyst. It is possible to say that when comparing improvement plans, or anything of that sort, originating from any kind of analysis there will always be some subjectivity. Therefore, in this project, two separate improvement plans were not created. Instead, one improvement plan was created when the entire analysis process was finished, containing results from both the VSM and the simulation study.

3.5 Combining the advantages

The two methods used in the project were also combined in an attempt to create a tool that uses advantages from both methods. First off, the wanted features of the new method were defined, mainly by brainstorming activities by the group. When the method had been defined and created, it had to be tested and evaluated to see if the requirements were met.

3.5.1 Evaluation of the new method – Case study

It is of great importance to understand that this method is made for a forging facility in Sweden. Consequently, it is not certain that it is applicable for other research areas or even other forging facilities. It is therefore necessary to explain the current situation in depth so that no readers of this report gets the misperception that this is a general tool, even though the aim of the tool is to make it as general as possible.

The case company has a forging facility located in Sweden where they produce crankshafts and front axle beams for trucks, buses and other large vehicles. There are a total of 61 article numbers included in this project, most of them seldom produced and a few produced in a very significant volume. The articles are quite evenly distributed between the two product families (crankshafts and beams), but all articles are forged in the large forging press located in the beginning of the manufacturing flow.

There are a total of 13 sets of machines or production lines numbered from A to M in the flow. A being the forging press, B-H processing beams and I-M processing cranks.

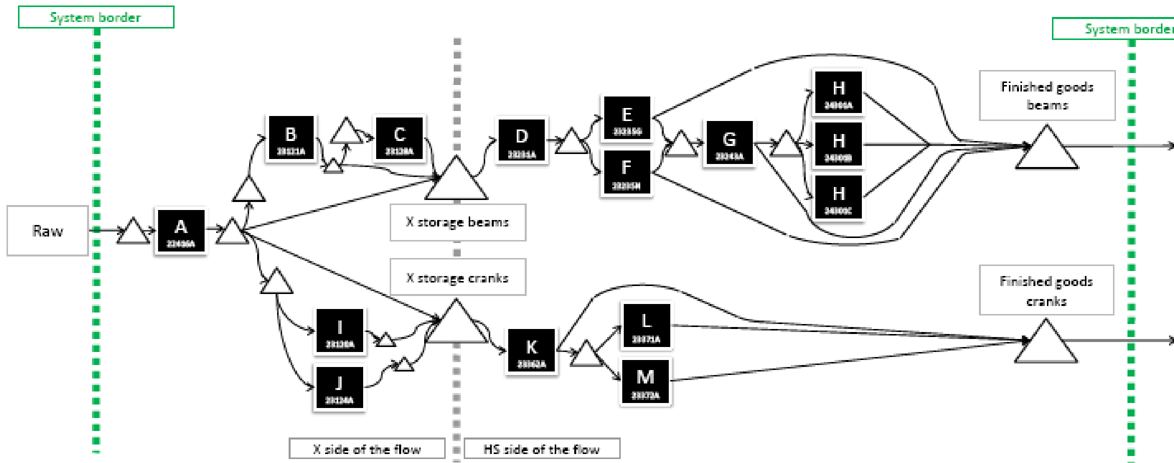


Figure 3.5.1. Flow chart of the manufacturing at the case company.

Without being too specific, confidentiality is an issue, the process times varies a lot between the different processes. The forging press (A) produces in a one-piece flow at a pace of about 35 seconds a piece while the different heat treatments (B, I and J) can take up to 14 hours but can handle more than 150 pieces at a time. The setup time for the forging press is comparatively long and it also the presumed bottleneck which makes rather large batches viable. Because of the large batches, the WIP within the two different product families varies a lot since one subsystem is draining while the other is filling up. That phenomenon is something that needs to be considered when drawing any conclusions from the use of a possible new method and for future research, given that in this specific case the variations will be very big and a combination of VSM and DES will thus be beneficial. Maybe more so than in most other cases subject to less variation.

3.5.2 Interviews

In cases like this, when the purpose of the data collection is to map people’s opinions, feelings, emotions and experiences of a subject, interviews are normally very effective (Denscombe, 2007, ss. 173-175). To evaluate the new method and to investigate the response from it, unstructured interviews were held with leading people at the case company. The interviews were held using Denscombe’s (2007, ss. 192-196) guidelines.

3.5.3 Statistical Analysis

To fully evaluate the new method, which is simplified in comparison to a DES analysis, a statistical analysis must be made. It is essential to see how much is lost in the transition from a fully dynamic DES model to the new method and if these losses play a significant role. This can only be done by comparing different indicators specified by the project group and the supervisors at the case company. It is of course important to remember that these indicators are case specific and cannot be generalized, as described above, even though focus will be put on analyzing WIP levels and lead times.

4 Results

This chapter reviews all the results from this study in order to later be able to analyze them. Firstly the simulation model and its parts and functions are assessed. Secondly, the more numerical results are given in two separate subchapters; sections 4.2 and 0, each describing outcomes from the different simulations and the value stream mapping respectively.

4.1 The DES model and its structure

The simulation model used in this project must be examined and understood in order to recognize and comprehend the output from it. Hence, the various components and structure of the DES model are reviewed here.

First of all, a list of all articles was created by a supervisor, with their designated flow through the machine groups respectively marked by X:s in the manner shown in Table 4.1.1. Secondly, a printed factory layout served as a conceptual model drawing with every machine marked with its given letter (A-M). The possible storage areas were also plotted in this drawing, each one given a queue name to show which products that could end up there; for instance a WIP queue between machine A and machine B would be called Q_WIP_A2B. The third step was to place the resources in the graphical interface of AutoMod according to the layout.

Table 4.1.1. List of products with their utilized machines marked by X.

	Machine A	M. B	M. C	M. D	M. E	M. F	M. G	M. H	M. I	M. J	M. K	M. L	M. M
Product 1	X	X	X	X	X	X	X	X					
Product 2	X	X	X	X			X	X					
Product 3	X		X	X	X			X					
Product 4	X								X	X	X	X	X
Product 5	X								X	X	X	X	
Product 6	X										X	X	

When all the products where mapped in a list similar to the one in Table 4.1.1, the group created a flow code for every product to see how many unique flows were to be simulated and to be able to start writing the model logic. Product 1 in the example above would thus be given ABCDEFGH, Product 2 would have ABCDGH and so on. This case gave the project group 61 articles divided between 14 different flows to work with.

After the above declared steps, the model translation could begin. The model was built in modules; every machine has the same basic code (with minor changes made for each machine) and all WIP queue logic, which sends the product to the correct queue/process, is basically the same. Simultaneously, Excel-lists containing process times, rejection rates and setup times were created in a manner so that they were suitable for the model to read.

The result of the efforts described above is a model that needs two different inputs; a forging planning and a delivery list. The forging planning is an Excel-list with five columns containing data about *batch number*, *article number*, *flow code*, *batch siz*e and something called *simulation based article number* which indicates the field in the vectors containing process times etc. that are related to the specific article. The delivery list is a list of which orders demanded products from an in-production storage called *X storage*. At this point the products are also given a new article number which calls for a few extra input fields. The columns in the delivery Excel-list is thus; *batch number*, *old article number*, *new article number*, *new batch size, time to next order, old simulation based article number, new simulation based article numb*er and *safety time*. The *safety time* denotes an expected time it takes for the product to pass through the remaining processes and be available for shipping. It is essentially a planning tool that the planner uses to show how much time before customer demand arises that a product must be ordered from the in-production storage.

Since these two lists are controlling the entire simulated system in terms of how much and which products enters and leaves the system it is very important that they correspond to each other. If not the correct mix of products is created, too few products will be available for the customer thus creating a backlog. The model holds a few variables that can show shortages and delays, most of them will be announced in section 4.2.

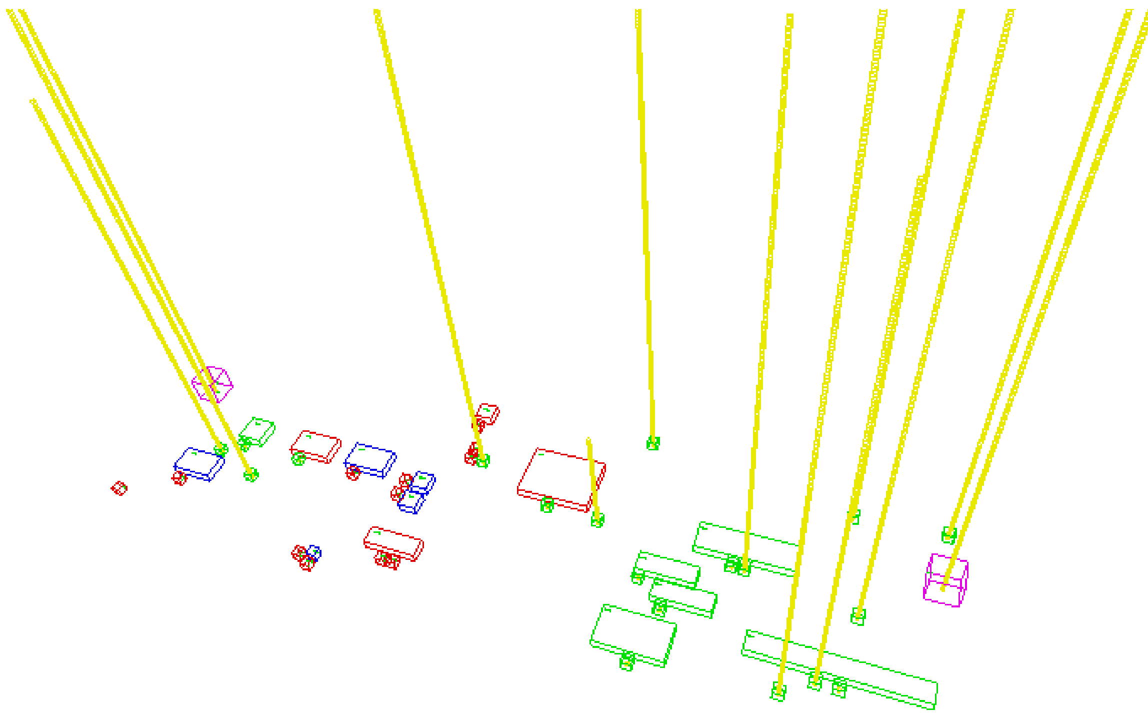


Figure 4.1.1. Picture of the graphical run-time window during a simulation.

4.2 Results from the DES model

The first simulation step of this study was to reenact an old forging planning together with its corresponding deliveries list, a part called *Historic state model testing* in the Project approach description (section 3.1). This was done using a list of the output from the forging press starting in November 2010 and ending three months later. A delivery list from the same period was also handed to the project group from the sales department at the case company. The lists were cleaned from a low number of excluded articles and set to fit as model input.

In order to get a valid result and to include most of the dynamics of the systems five repetitions of a four weeks long period were simulated, each one with a warm-up time of two weeks. Consequently, the third and fourth week of November 2010 and the first two weeks of December 2010, should have been simulated.

There are a few different parameters that one could look at when evaluating bottlenecks. In a simulation project like this, modeling a batch-and-queue system, looking at queues and resource utilization are normally the most efficient.

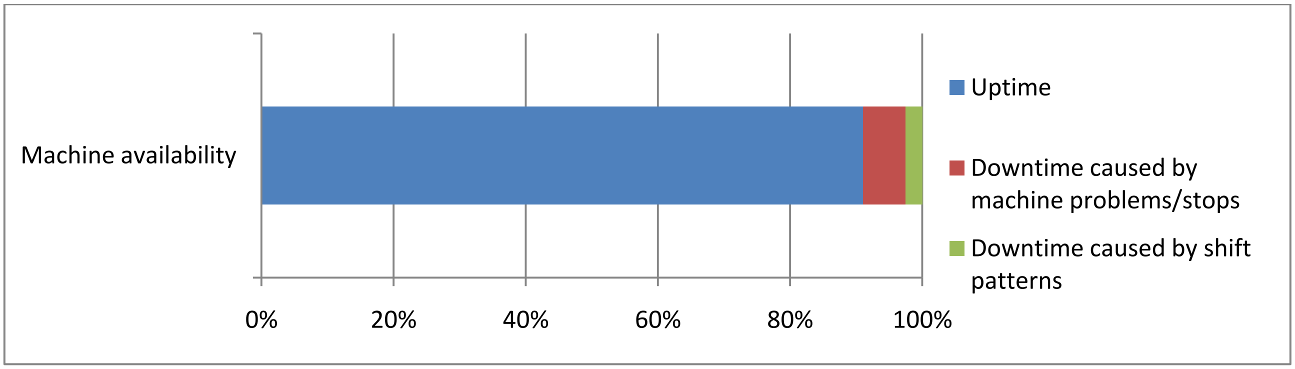
In Table 4.2.1, the three rightmost columns is not an output from AutoStat but is added by the project group. The columns are added to see how much time of the production simulation, nominally, every machine is down because of either the shift pattern or the stops caused by machine problems. The column to the far right is a calculation of how much of the nominal uptime every machine has been able to produce (not starving). It is basically a measurement of how much of the uptime is used for producing. This provides information of how close to being the regular bottleneck a machine is; *utilization during nominal uptime* around 1 means that the machine is highly strained.

The reason to that some of the machines have an *utilization during nominal uptime* higher than 1 is of course that the dynamics of the downtimes are very influential when running a simulation over a month’s production. To be exact, some machines have not had that many stops yet and the simulated uptime is therefore higher than the nominal, still it gives valuable information about how the machine is performing.

Table 4.2.1. Utilization of the resource according to an AutoStat simulation of four weeks of production (after two weeks warm-up time). Nominal downtimes caused by stops and shift patterns is added to the calculations in the rightmost parts of the table.

	Utilization output from AutoStat (5 runs)							
Resource	Average	Std. Dev.	Min.	Max.	Median	Nominal stop down	Nominal shift down	Utilization during nominal uptime (Average)
A	0.564	0.020	0.539	0.588	0.562	0.448	0.048	1.119
B	0.862	0.011	0.847	0.873	0.860	0.060	0.024	0.941
C	0.163	0.001	0.162	0.163	0.163	0.090	0.762	1.098
D	0.749	0.017	0.730	0.775	0.743	0.090	0.036	0.856
E	0.626	0.016	0.608	0.647	0.625	0.090	0.036	0.716
F	0.594	0.017	0.577	0.620	0.593	0.060	0.012	0.640
G	0.589	0.011	0.576	0.600	0.590	0.060	0.036	0.652
H (A)	0.292	0.010	0.286	0.310	0.288	0.100	0.345	0.526
H (B)	0.291	0.008	0.280	0.302	0.291	0.100	0.345	0.524
H (C)	0.186	0.007	0.179	0.194	0.182	0.100	0.762	1.345
I	0.840	0.002	0.837	0.841	0.840	0.150	0.012	1.002
J	0.000	0.000	0.000	0.000	0.000	0.020	0.128	0.000
K	0.334	0.008	0.323	0.346	0.334	0.010	0.369	0.538
L	0.355	0.007	0.350	0.366	0.352	0.050	0.333	0.576
M	0.070	0.007	0.059	0.079	0.071	0.025	0.762	0.328

Table 4.2.2. Typical proportions of a machine's nominal availability (machine B shown).



Other important indices can be found in the WIP queues; both levels of WIP and how much time products in average spends in them are good indications of which processes are possible bottlenecks. For the readers to understand the flow of products between the processes and to clarify where the WIP queues are located, a simplified map is presented in Figure 4.2.1. Note the technique of naming WIP queues; a WIP queue between process A and B is called *A2B* and so on. Queues named *X storage* is from where the delivery list orders and renames articles. The X storages can therefore be seen as in-production storages more than WIP queues and are thus not included in Table 4.2.3.

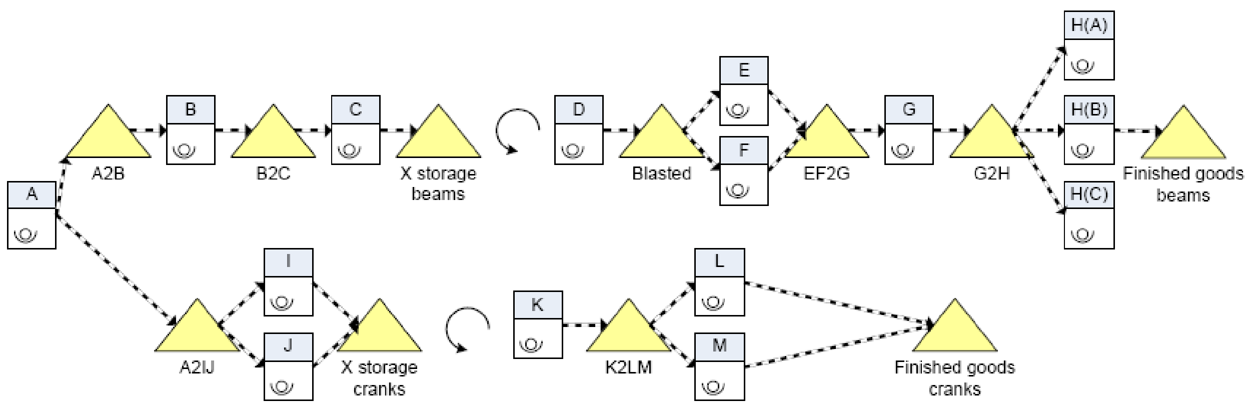


Figure 4.2.1. Simplified mapping of the production flow with assigned queue names.

Figure 4.2.1 shows a generalized map of the production flow, starting from the forging press (Process A). The flow is then divided in two, the topmost being the flow of beams and the one below the flow of cranks. Statistics for all WIP queues are given in Table 4.2.3.

Table 4.2.3. Average time spent in (per product) and average number of products in WIP queues.

	Average time in queue (h)					Average number of products in queue (pcs)				
Queue	Average	Std. Dev.	Min.	Max.	Median	Average	Std. Dev.	Min.	Max.	Median
A2B	66.0	5.8	57.9	71.9	68.3	1325.1	162.1	1123.3	1503.4	1324.7
B2C	186.1	9.1	172.0	194.2	186.2	548.5	26.4	506.1	573.3	550.7
Blasted	9.2	0.3	9.0	9.5	9.1	209.7	11.4	200.3	225.4	203.1
EF2G	55.7	1.1	54.5	56.9	55.4	823.8	23.6	794.9	843.8	837.5
G2H	40.6	1.1	38.8	41.9	40.9	154.4	4.7	147.4	160.2	155.1
A2IJ	114.3	11.7	100.5	131.6	112.2	1572.3	219.5	1338.5	1917.1	1558.9
K2LM	11.1	1.7	9.5	13.7	11.3	245.1	41.1	208.1	311.4	243.9

Only presenting statistics from a dynamic system like the one described would be a fundamental mistake in a study like this one, since the focus should be immersing in the difference between dynamic and static systems. The numbers of Table 4.2.3 originate from results of five different runs. In these runs, the time every load spends in a queue is added to a sum and divided by the total numbers of loads that have been in the queue, thus giving an average. The other value (average number of products in the queue) is based on how many loads are in the queue at every discrete point of time in the model, and from that the average is calculated. The tabulated values are therefore average, standard deviation, minimum, maximum and median out of these five averages. To see the effects of the system dynamics it is necessary to go even deeper into the system. In this project that has been done by plotting queue levels all along the run time, see Figure 4.2.2 for an example of such plots.

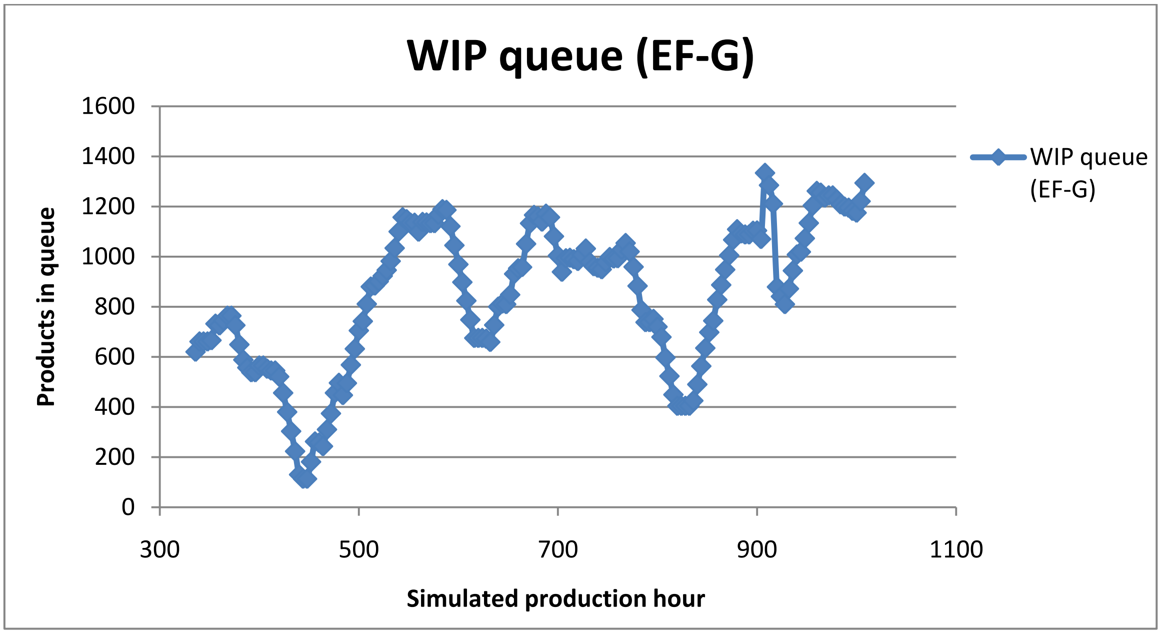


Figure 4.2.2. Plot of one of the WIP queues derived from a four week production simulation (two weeks warm-up time)

Valuable information can be obtained from Table 4.2.3 and figures like Figure 4.2.2. Table 4.2.3 shows that there has not been large variation in the average of the level in WIP queue *EF2G* and Figure 4.2.2 gives an example of how the levels can vary during four weeks of production. Note that the plot is derived from one single run, and is thus the actual simulated value of the WIP level.

All the plots from the simulation must be put in comparison to each other and seen as a whole when evaluating the bottlenecks and production planning. They can all therefore be found in the Appendix.

The next step in the simulation approach was to test new production plans, this is called *Planning model testing* in section 3.1. To spot the full effects of a new production plan the pull from the customer order list had to be removed. Keeping the order list would mean a smoothing of production and thus hiding possible bottlenecks and overproduction. Besides, to test a new production plan the original way, a corresponding customer order list would have had to be created. However since the project group could not get access to accurate customer information, such a plan would have run the risk of being incorrect. The reason such information was unavailable is simply because that the case company's customers themselves are unsure of future demand, in fact they tend to want to change orders even at short notice. So creating such a plan would have been near impossible. Testing the production plan with a push approach provides valuable information about a worst case scenario, with no leveling and thus higher peaks and deeper dips.

In total twelve different forging plans were created in cooperation with the case company, assisting the project group in the task were the Lean manager, Lean coordinator, logistics manager and the production planners. The plans were run through the model and the levels of the WIP queues were plotted every four hours in the same manner as in Figure 4.2.2.

Most of the plots are quite easy to grasp; the y axis represent the amount of products in queue and the time is given along the x axis. It is however more intricate to extract valuable information from the plotted data, a walk-through of all the plots from one of the forging planning runs will therefore act as a guide:

First of all, the data in the following plots comes from the 5th planning model, which is based on what the case company was going to start to produce in the beginning of May 2011. Note that from all buffers that act as nodes (both *X storages* and *EF2G*) only entire batches leave simultaneously. An effect of this is that levels in these queues might be higher in the plots than they necessarily would be in reality, since it is in reality possible to start processing the batch when the first product arrives at the queue.

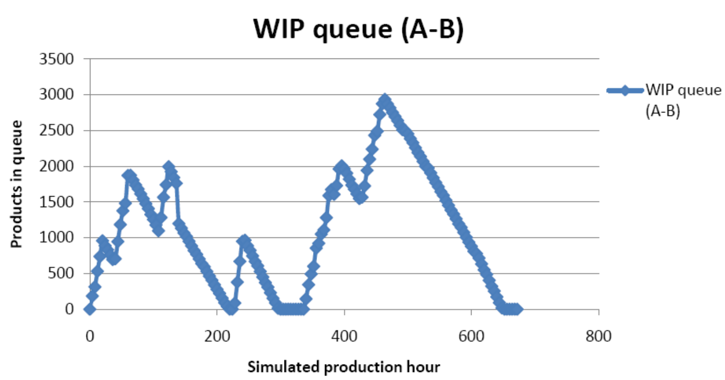


Figure 4.2.3. WIP queue level between process A and B.

The first plotted queue is the one located between the forging press and the heat treatment for beams. The heat treatment is a very time consuming process and as seen in the plot, a lot of products is in average waiting in the queue before it. Hence, it might be one of the bottlenecks affecting the systems output. It is also important to note that, using this forging planning, there is a risk that the heat treatment will be starved a few of times (after about 220, 300 and 650 hours)

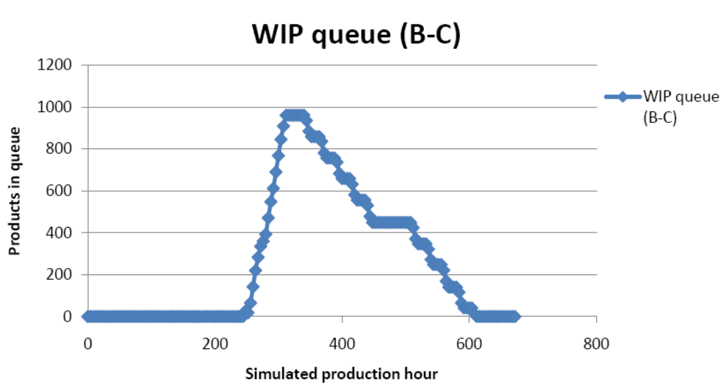
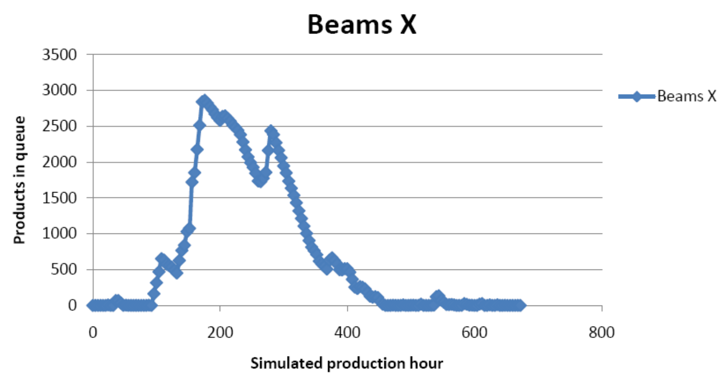


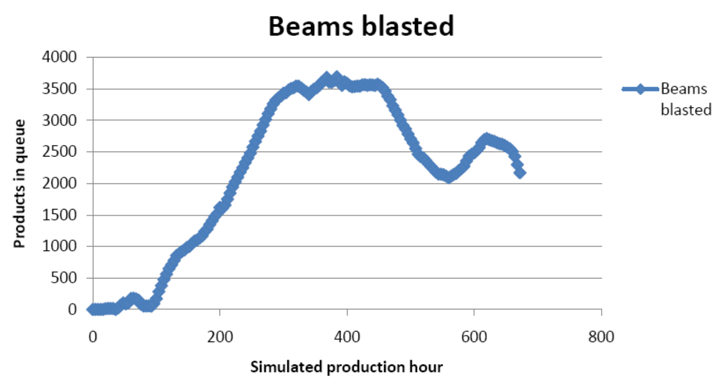
Figure 4.2.4. WIP queue level between process B and C.

This queue is located before a quite special process; a type of performance test which is run by a day-time shift and only applies to a few article numbers. The shape of the plot is therefore expected. Still, it can show if the process needs more resources with the current planning or if it can cope with the demand.



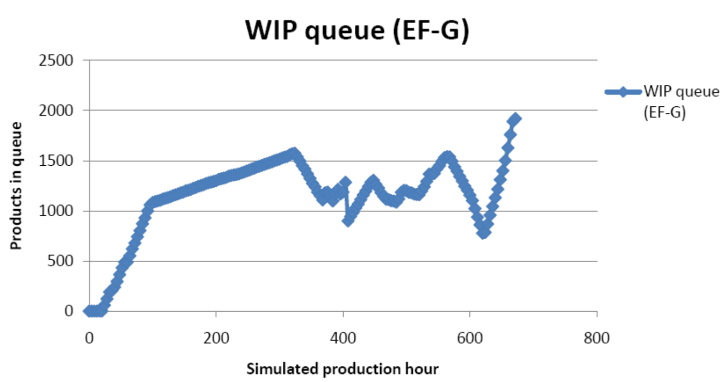
The X storage is during the *Planning model testing* not working as an in-production storage but is simply a buffer queue, just like the other queues. It is supplying process D (blasting), which is a process all beams goes through, with products.

Figure 4.2.5. WIP queue before process D.



The *beams blasted* queue is named differently from all of the others for a reason; it is easier for the analyst to have a reference queue when showing the results for people that are not familiar with the coding but have good knowledge of the flow. If all queues were named after the process letters, more time would be spent trying to understand where the queues are located than actually analyzing the plots. At least now there is a natural starting point. It was chosen because all beams passes through this queue. It supplies processes E and F with beams.

Figure 4.2.6. WIP queue between process D and processes E and F (called blasted queue).



Some of the products leave the manufacturing flow after processes E and F. This queue acts as a node for those continuing on, before process G.

Figure 4.2.7. WIP queue between processes E and F and process G.

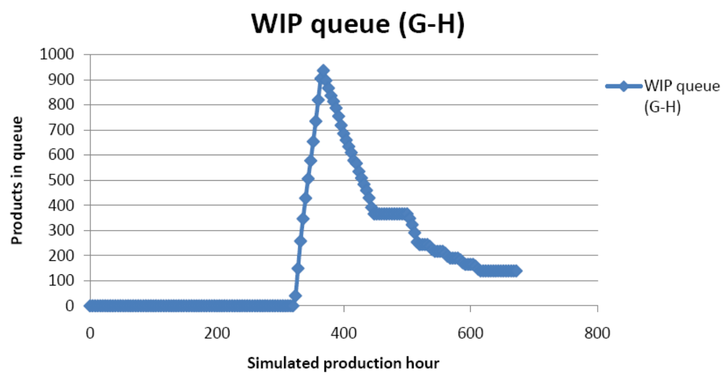


Figure 4.2.8. WIP queue between process G and H.

This is the last queue before the beams leave the production for *Finished goods storage*. Plots of those storages are presented after the WIP queues in the crankshaft flow.

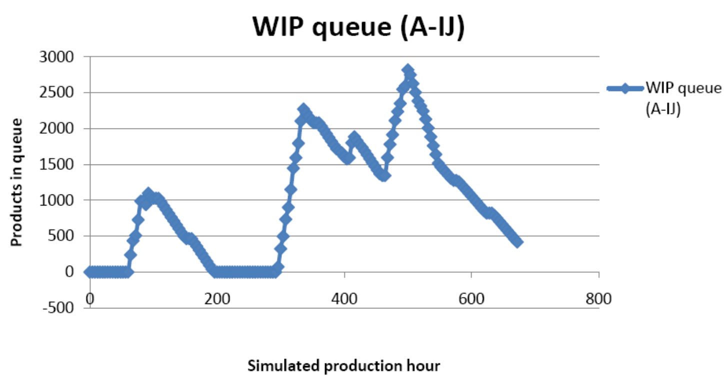


Figure 4.2.9. WIP queue between process A and processes I and J.

The first queue in the crank flow is situated between the forging press (A) and the two heat treatments available for cranks (processes I and J). The plot is pretty similar to the corresponding one in the beam flow, with quite high levels of WIP, yet some starving occasions.

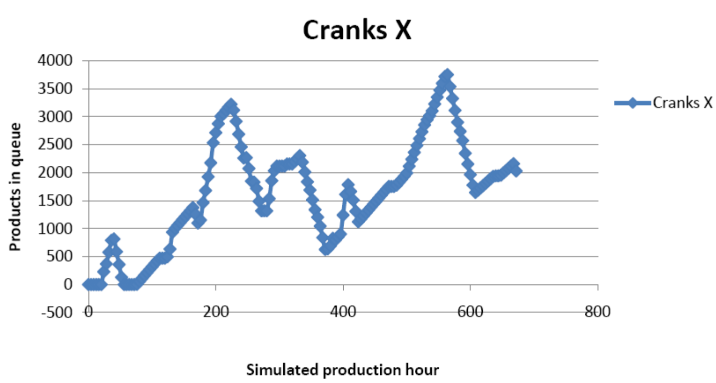
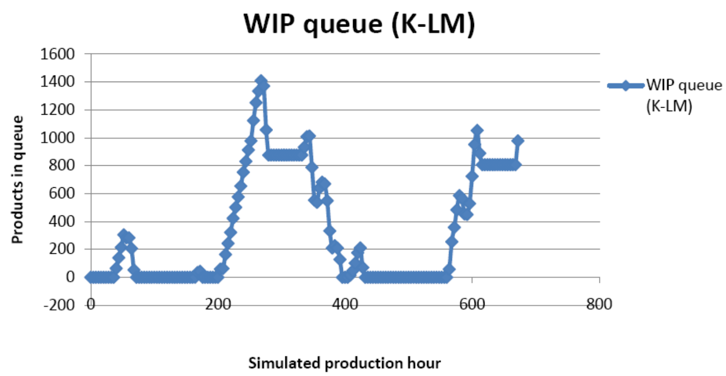


Figure 4.2.10. WIP queue before process K.

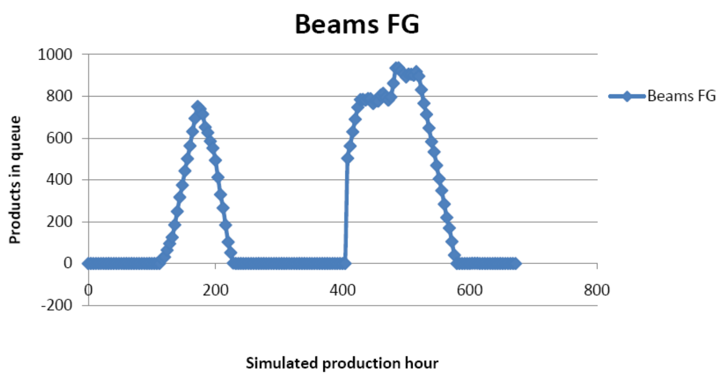
Similar to the *X storage* in the beam flow, this is only a buffer queue sending all products to process K.



This queue sorts products going to the last process (L for most articles), before leaving for *Finished goods storage*. Note that the strange behavior is probably because of the shift pattern for process M.

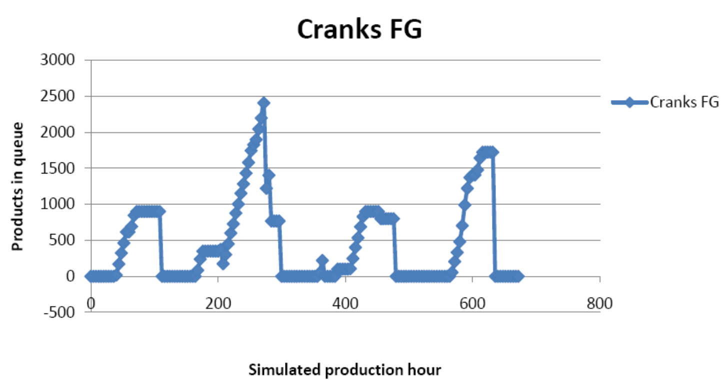
Figure 4.2.11. WIP queue between process K and processes L and M.

Moving on to the *Finished goods* storage, where products that have spent less than 72 hours in the production flow from the *X storage* is held to wait until they have reached the 72 hour mark. If they have spent more than 72 hours in the flow, they are directly sent out of the system (to the customer). This means that the plots of the *FG*'s (*Finished goods storages*) can provide information on how smooth and rapid the flow after the *X storages* is. Basically, a plot of a good planning outcome would consist of steady, high points.



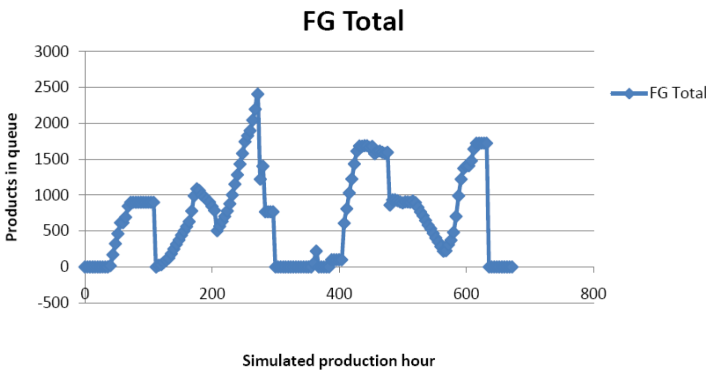
In the *beams FG* products have not been piling up that often, indicating that the flow has been pretty slow long periods of time. Note that some of the zeros can be a result of that no beams actually were produced during that time.

Figure 4.2.12. Level in the finished goods storage for beams.



The flow of cranks seems to have been smoother than the flow of beams, since products more often wait in this storage. An expected result since there are fewer processes in the cranks flow. The variation is however very large.

Figure 4.2.13. Level in the finished goods storage for crankshafts.



A combination of the two plots above supplies information on how the total forging planning performs in the last steps of production. The best forging planning, in a perfect production layout, would give a straight line at a certain level in this plot.

Figure 4.2.14. Plot of the combined levels in both finished goods storages.

4.3 Results from the VSM

The current state map resulting from the VSM process can be seen in Figure 4.3.1. In the bottom of the figure the value added time in seconds and the amount of time a product spends in each buffer can be seen, the lead time is the two added together. The value added time as a portion of the total lead time can then be calculated; in this case the value added time was 0.7% of the total lead time. It should be mentioned that the information flow is even more complicated in reality then what the map shows, but illustrating all the informal information exchanges between the departments and planners is almost impossible and would only serve to make the picture unclear. As mentioned earlier there were complications in production during the course of this project, which meant that the expectation was that there should have been smaller amounts of WIP than normal in production since it was the press, the first process in the chain, which mainly experienced problems.

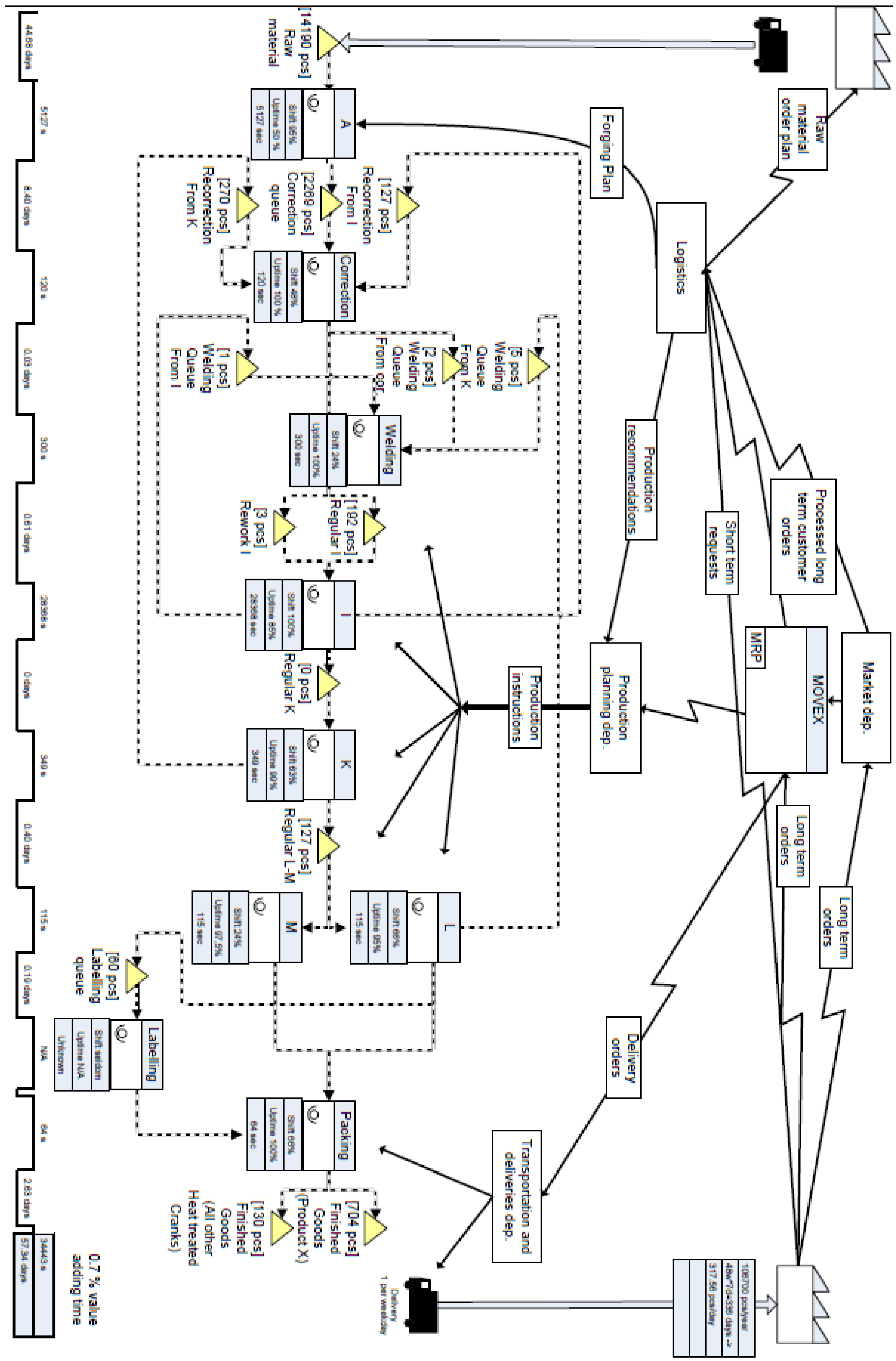


Figure 4.3.1. The value stream mapping.

5 Analysis

5.1 Results analysis

As mentioned in section 4.2, historic state model testing involved doing runs on an original forging plan used in production. It should be mentioned that due to certain circumstances, there was almost no production a couple of weeks prior to when the tests were made, which means that the real system is almost void of WIP when production restarts. This was not the case during the period that the historic state model testing covers; this is instead a representation of the system as it was of late 2010. This means that a warm-up time to fill the system was required during the historic tests but not during the planned model testing. Thus, the historic state model will be better suited when trying to identify possible bottlenecks in the system because of the presence of WIP in the system.

5.1.1 Historic state model results analysis

By looking at the calculated *Utilization during uptime* for the resources respectively it should be possible to draw conclusions of which one is the most stressed. The six most stressed resources, according to that index, are ranked in Table 5.1.1.

Table 5.1.1. Comparison between possible bottlenecks

Resource	Average util.	Util. during uptime	Average number of products in preceding WIP queue
H(C)	0.19	1.35	154,35
A	0.56	1.12	N/A
C	0.16	1.10	548,5
I	0.84	1.00	1572,28
B	0.86	0.94	1325,07
D	0.75	0.86	N/A

However, it is not certain that that the highest ranked resource is the bottleneck in reality. This is namely highly dependent on how the programming is performed and what assumptions were made during the model conceptualization phase. In this case study, process H is built of a procedure containing three shared resources; H(A), H(B) and H(C). The loads, or products, are in this procedure sent to the process queue with minimum amount of loads. This means that H(C) which is a resource with an entirely different shift pattern from the other two (day-shift instead of continuous shift) will get products sent to its queue without being active, thus creating stress on the machine when it is actually producing. In comparison, the fact that H(A) and H(B) is not even close to being ranked as bottlenecks and that the WIP level before these resources is fairly low (154, 35 pieces) indicates that this is not the bottleneck.

The second place in the ranking is occupied by the forging press. This is the first process and it is controlling the inflow of products. Therefore it does not have any WIP queue in front of it and when the last product of a batch is pressed a new batch is immediately ordered, without lead time, to the forging press. This means that it is never starved. When this project started, this resource was considered to be the bottleneck and these values confirm that assumption. An interesting note is that over four weeks the press has got a *Utilization during uptime* over 1, which points out the significance of system dynamics. Basically the press has been performing 12 % better than the nominal mean, and must therefore counterbalance this in the future.

When it comes to process C, a process only occasionally used, it is possible to note that this resource is more undependable than the others in its planning and shift pattern. In reality it can be changed dynamically to fit the forging planning and it might not be a bottleneck in the ordinary sense. However, it is very important to show the effect the planning has on the performance of the process, not least when it comes to the additional lead time for the products passing through this process. According to the simulation output, products in average spend more than a week in queue before passing through the process.

Processes I and B are both heat treatments and both highly stressed at occasions. The project group wants to emphasize the fact that these are the areas where the most assumptions were made, and those assumptions might have been influential when the simulation was run. For instance, the two heat treatments cannot start on a batch before at least 50 products of the batch have arrived in the queue, which is similar to the default principle in reality. However, at times in reality, operators override the control principles and run smaller batches, making the flow even more complex. There is also a rework flow in process I, which is not included in the model, slowing the process down to a large extent. The combined knowledge makes the project group draw the conclusion that the two most common heat treatments (processes B and I) might act as bottlenecks parts of time if the planning is inadequate.

Consequently, the forging planning must be seen as one of the most significant factors when it comes to reducing risks of different bottlenecks restraining the system dynamically. This is an important notion to bear in mind before analyzing the *Planning model* outputs and focus must be put on leveling the flow around the above mentioned processes.

5.1.2 **Planning model results analysis**

The first forging planned tested in the planned model testing was one devised to be used once the production could restart, originally this plan was made for a system that actually had some WIP before the plan was to be implemented. Since this was not the case the plan was revised, the original plan is referred to as version 1 and the revised plan is version 5. Versions 2 through 4 of the plan use version 1 as a base but with batch sizes reduced to 75% and in the case of version 3 and 4 with the batches in a different sequence. As mentioned in the Lean theory chapter, a reduction in batch size should lead to a more leveled production with lower amounts of WIP. The effects of this can be seen in for instance Figure 5.1.1, where it can be seen that the average level of the queue is clearly lower. The peak value is also lower, at about 3000 instead of 3500 and the time the machine starves from a lack of products has been reduced. The starving at the end of the run is because with the smaller batch sizes the numbers of products have been reduced, and thus the forging plan will run out of units before the simulation ends. There is however one big issue with reducing batch sizes, the number of tool changeovers are limited, a factor which is not considered in the simulation. So a batch size reduction might lead to a number of setups that actually is impossible. Another issue in this case is that the new versions produce 25% less products, since the batches are only reduced and not also increased in number. Since customer demand exceeds the new number by far, it is not realistic to implement such a batch size reduction.

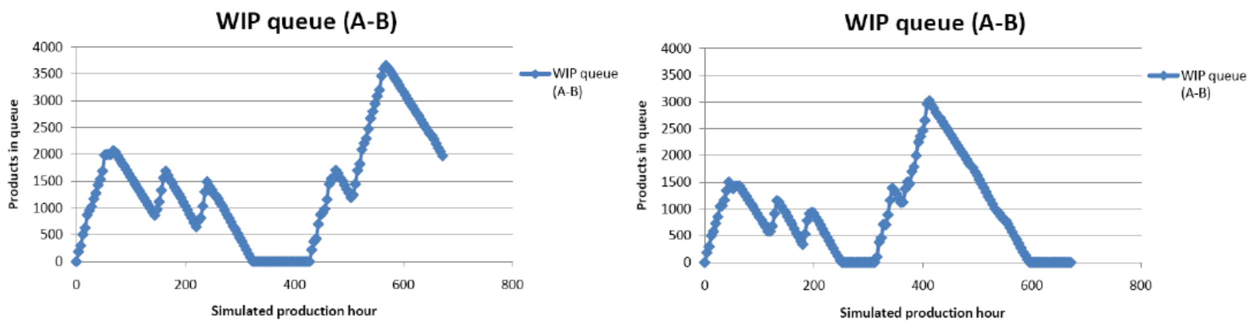


Figure 5.1.1. The WIP queue between the press and the beam heat treatment, version 1 (left) and 2 (right).

When trying to improve upon the new forging plan (version 5), the number of produced units was not reduced, but instead some batches were split into smaller ones and the sequence of batches was altered. A correct sequencing is also a way to create a leveled production as mentioned in 2.2.5. As can be seen in Figure 5.1.2 a better sequencing creates a more even level of WIP in the queues from the press to each of the heat treatments. The total number of WIP is lower as well, and the time when the heat treatments are starved is less because a correct sequencing between cranks and beams means more of a mix between the two from the press. When comparing sequencing with purely reduced batches, one can conclude that just reducing the batch sizes will lead to a plot with the same shape but with lower values. Sequencing production has a better effect since the WIP is better leveled while still reducing the total WIP.

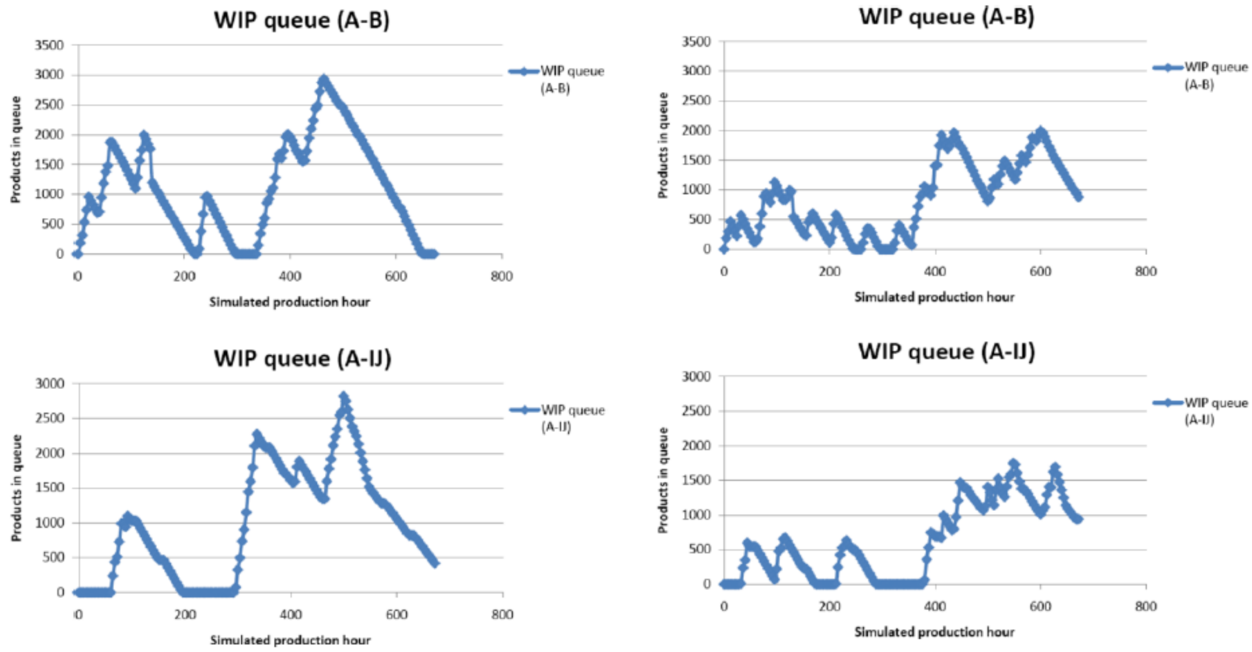


Figure 5.1.2. WIP queues from the press to the respective heat treatments, version 5 (left) and version 9 (right).

Using the experiences gained from testing the different production plans, a forging plan for an entire year was created together with the Lean coordinator at the case company. Things that also needed to be considered when creating the final forging plan were reaching the case company's output target of 417600 products per year; the forging plan of course had to fulfill that target. To be able to reach the targeted quantity the amount of setups had to be limited to a maximum of nine each week and the average batch size has to be just below 970 products, see Table 5.1.2. *Needed production time per week* has to be below 168 (the number of hours in a week) in order to be a feasible solution.

Table 5.1.2. Calculations of possible batch sizes and setups.

8700 per week, 60 % uptime

Average batch size (pcs)	870	970	1090	1250	1450.0	1740
Number of needed batches	10.0000	8.9691	7.9817	6.9600	6.0000	5.0000
Setups	10.0	9.0	8.0	7.0	6.0	5.0
Needed production time per week (hr)	168.9722	167.4583	165.2963	163.7824	160.9722	158.9722
Without setups	148.9722	149.4583	149.2963	149.7824	148.9722	148.9722

Calculations were performed for a different amount of production weeks per year (46 and 48 weeks) and three different uptime levels (55%, 57% and 60%). It can be concluded that the current uptime of the press is insufficient to reach the targeted quantity, which in fact is not strange since the case company predicted a higher uptime level than what has been achieved.

The following figure and table illustrate what a typical forging plan can look like, over one week and four weeks. The plans consider the need for setups and maintenance, the fourth batch every week will be a special one that might be split into smaller batches or tests units can be produced in that slot.

Table 5.1.3. Typical forging schedule for one week

Schedule:		**Batch size (pcs)**	**Assigned time (hr)**
	Batch 1	600	9.722222
	Setup		2
	Batch 2	1200	19.44444
	Setup		2
	Batch 3	1000	16.2037
	Setup		2
Special batch	Batch 4	900	14.58333
	Setup & maintenance		10
	Batch 5	1200	19.44444
	Setup		2
	Batch 6	1000	16.2037
	Setup		2
	Batch 7	600	9.722222
	Setup		2
	Batch 8	1200	19.44444
	Setup		2
	Batch 9	1000	16.2037
	Setup		2
	Total	8700	166.9722

Table 5.1.4. The gameplan (forging plan) as input data to the simulation

Batch number	Article number	Flow code	Batch size	Simulation based Article number (1-61)	Note
1	Article type 5	ABDEG	600	45	
2	Article type 2	AIKM	1200	35	
3	Article type 3	ABDE	1000	15	Special batch afterwards
4	Article type 1	AKL	1200	24	Maintenance afterwards
5	Article type 2	AIKL	1000	26	
6	Article type 4	ABDFGH	600	7	
7	Article type 6	ADFG	1200	38	
8	Article type 3	ABDE	1000	15	
9	Article type 1	AKL	600	10	
10	Article type 2	AIKM	1200	35	
11	Article type 4	ABDFGH	1000	7	Special batch afterwards
12	Article type 1	AKL	1200	24	Maintenance afterwards
13	Article type 6	ADFG	1000	38	
14	Article type 7	ABCDE	600	43	
15	Article type 2	AIKM	1200	35	
16	Article type 3	ABDE	1000	15	
17	Article type 1	AKL	600	10	
18	Article type 6	ADFG	1200	38	
19	Article type 2	AIKL	1000	26	Special batch afterwards
20	Article type 1	AKL	1200	24	Maintenance afterwards
21	Article type 4	ABDFGH	1000	7	
22	Article type 5	ABDEG	600	45	
23	Article type 2	AIKM	1200	35	
24	Article type 6	ADFG	1000	38	
25	Article type 7	ABCDE	600	2	
26	Article type 1	AKL	1200	24	
27	Article type 2	AIKL	1000	26	Special batch afterwards
28	Article type 1	AKL	1200	24	Maintenance afterwards
29	Article type 3	ABDE	1000	15	
30	Article type 1	AKL	600	10	
31	Article type 6	ADFG	1200	38	
32	Article type 2	AIKL	1000	26	

Figure 5.1.3 finally illustrates the WIP queues for the final forging plan, as can be seen the WIP through beam heat treatment (B) is at constant low levels while the crank flow increases slightly more. There is however no real peaks and none of the machines are starving for a noticeable amount of time. Note that the simulated forging plan does not include the special batches and might thus be even more leveled if a fitting article is produced in those slots.

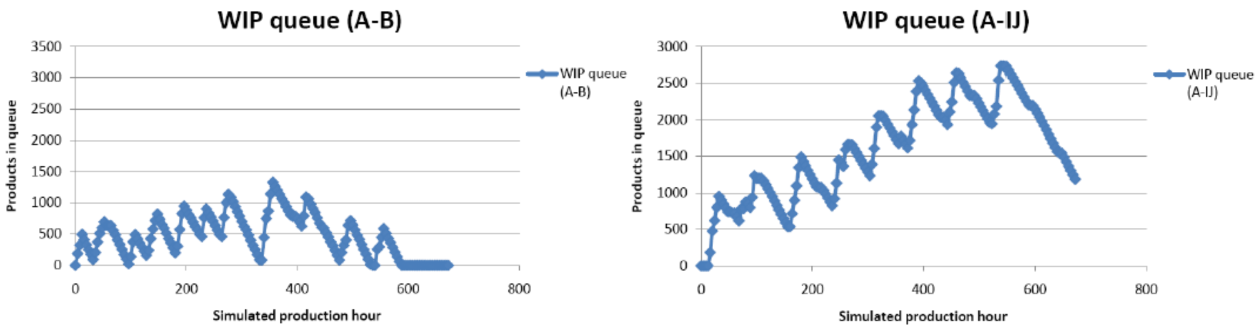


Figure 5.1.3. WIP queues from the press to the respective heat treatments, final forging plan (version 12)

5.1.3 VSM results analysis

A value adding time of 0.7% of the total lead time is not exceptionally low since value added times in low single digit percentages are not uncommon. However, the heat treatment has a cycle of time of about 14 hours, with such processes in the production chain one would expect the value added time to be a bigger amount of the total lead time. The daily demand of products was based on average daily customer orders from data received from the case company, however there is currently a backlog which means that it is possible to ship more products than what is the daily order average. This would mean that the average total lead time should be lower which in turn would increase the value added time as a share of total lead time. The large amount of raw material is probably an effect of the complications with the press and the raw material being ordered according to a pre set plan which means that raw material will build up in storage. In a normal state, there is likely to be less raw material but instead more WIP so the share of value added time would not increase if that was the case.

Something to note in the VSM are the many return flows, where faulty products are sent back to be reworked. This indicates that there are quality issues with the processes as well as the material, as mentioned in section 2.2.4 high quality and low scrap rates are required to create a reliable flow.

As mentioned, in a normal state there should be higher amounts of WIP and lower amounts of raw material. However currently there are almost 3000 products worth of WIP even at these expected low levels, and this for only one of four product groups. A target of 15-20000 units of WIP during normal production is then quite ambitious with the WIP most likely increasing when the press performs better.

5.2 Evaluation of methodologies

An important part of this study is to evaluate different benefits and shortcomings of the applied methods. This can be done in various ways and using different approaches, many of which are complex and hard to grasp. In this project the simplest, most straight-forward comparison possible is used for the quantitative evaluation; taking numbers from both methodologies and putting them side by side. For the qualitative comparison, on the other hand, the thoughts of the group members are just put up for contemplation.

5.2.1 Quantitative comparison of results

The first observation one needs to do when comparing the VSM and the declared simulation output is that the amount of queues between the two is not the same. This is simply a result of the simplifications needed to complete the simulation study. As mentioned before, the different rework and correction processes in the map are not included in the model, since it would be too time-consuming in contrast to the value it would create. About the packing process, it is included in the process time of processes L and M in the model, and does not have an external queue preceding it. The queues and the amount of products they contained in the VSM and the average value from the *Historic state* simulation are given below.

Table 5.2.1. Comparison of number of pieces in queue between the two methods

Queue	VSM (pcs)	Historic state (pcs)	Difference (compared to VSM value)
A2IJ*	2461	1572.28	36.11%
X storage cranks**	0	8640.09	N/A
K2LM***	187	245.08	-31.06%

* Includes regular correction queue (which all heat treated cranks pass)

** Consists of all types of crankshafts (not only heat treated) in DES model

*** Consists of all types of crankshafts (not only heat treated) in DES model, includes labeling queue from VSM

As seen in the Table 5.2.1, the VSM and the simulation model give similar values in terms of amount of products in queue, the big difference being the *X storage*. The simple explanation to this is that when the VSM was executed the forging press had performed miserably for some time. It was plainly not able to supply the wanted amount of products and the level of the in-production storage was therefore minimized. Note that the total amount of products in the flow (excluding X storage) was 31.3 % off (2648 pieces compared to 1817 pieces).

Table 5.2.2. Comparison of time spent in queue between the two methods

Queue	VSM (days)	Historic state (days)	Difference (compared to VSM value)
A2IJ*	9.04	4.76	47.32 %
K2LM**	0.59	0.46	21.59 %

* Includes correction, welding and regular queues

** Consists of all types of crankshafts (not only heat treated) in DES model, includes labeling queue from VSM

The reasons to that the values of the *X storage* is not presented in the Table 5.2.2 is that there was no products in the storage in the VSM and that in the simulation model products could be forged for a very long time before they were ordered from the storage, as a result of some differences in the two lists controlling the system, see section 4.1. Values would therefore have been misleading. One of the most important observations from Table 5.2.2 is that the different rework queues add a lot to the total lead time, and more importantly, they are often located around the identified bottleneck, process I.

Furthermore, the VSM has a few more possible points of comparison that could not be extracted from the simulation model. For instance, no data about *Raw material storage* could be collected since that is outside of the model's boundaries. Also, there is little value in comparing the *Finished goods storage* between the two, because in the simulation model a generalization implying that products that has spent less than 72 hours in the flow after *X storage* is the only ones staying in the storage. This might be too unrealistic and should only be viewed as a measurement of how rapid the flow is.

The group consider the above given values to be expected, still the fact that only averages from the simulation has been used here cannot be emphasized enough.

5.2.2 Qualitative comparison of methodologies

This section will provide the project group's thoughts on the different methods. It has been shown that the two methods give two diverse, yet valid, representations of reality and the differences has been quantitatively established. However, the most important notion of the methodologies must be the actual usage of them. Essentially, the question is; what can be achieved using VSM and DES respectively and to what effort?

There is of course a sea of difference between the two methods, and so a smaller number of the most important differences are analyzed in this section. First off, the static nature of a VSM makes it virtually impossible to be sure of which process is the bottleneck, or at least that it is the only bottleneck. Something contrasting DES diametrically, in which it is possible to use lists like those in section 5.1.1 to evaluate possible constraints.

Next, the methodologies vary a lot in required education and skill as well as in tools needed; VSM being a straight-forward, easy understandable pen-and-paper method and simulation requiring training in both model construction and analysis. Simulation also often requires expensive software and a lot more time to perform, both adding costs.

Another difference lies within the assumptions involved; a simulation of complete reality is impossible and generalizations and simplifications is needed, while a VSM is created to map all flows – production flows and information flows. In this project, the information flow has been extremely generalized compared to reality and even if the VSM does not improve the flow itself it can at least give a valid picture of it.

What has been most obvious to the group members during the project is that a VSM is, compared to a simulation study, much easier to present comprehendible. Something that has been essential in the *Planning model testing* phase, where a VSM inspired approach could be used to rapidly present the results of the test for the expert group, minimizing the waste of time.

Moreover, the project group feels that it is more difficult to get valid data out of a future state map in the VSM approach than it generally is to make changes in the simulation model and perform tests. On the other hand, the group member had the expertise before starting the project.

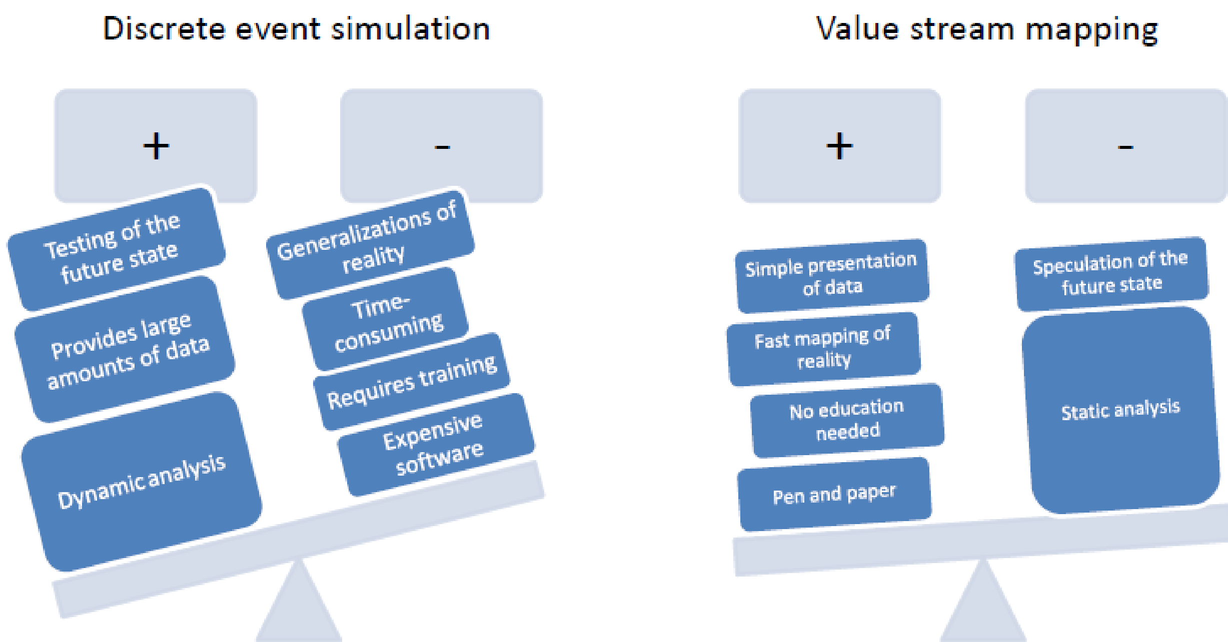


Figure 5.2.1. Comparison of VSM and DES properties

Figure 5.2.1 does only compare the actual performing of the two methods as such. Another very important part of the methods is the implementation phase, which is not included in this analysis. Therefore it is essential to emphasize on the fact that creating and implementing the future state plan of a VSM requires great knowledge of the processes and also education in production systems, thus reducing the positive brick *No education needed* on the VSM scale a bit.

5.3 Finding new ways of working – The new methodology

Finding the above mentioned problems and shortcomings of the two applied methods inspired the group members to create a new method. However, the time given, the expertise and combined knowledge of the group have made it impossible to create more than a framework for a methodology. Besides, a framework is more general and can be applied to more areas than just manufacturing.

In the last section, different wanted and unwanted properties were discussed and in the perfect world all of the wanted properties could be combined into one super-tool. This is however not achievable since some of them are contradictory. For instance, a tool that can reenact and make use of system dynamics needs great amounts of cleaned and controlled input data. To know which data to feed the model and where to insert it requires training. Nevertheless, there are some properties that can be combined into a methodology more efficient than either one of VSM or DES. The project group believes that this project has given the knowledge to construct such a methodology.

Originally, the intention was to use data from the VSM as input to the DES model, but that thought had to be discarded due to dissimilarities between the two methods. The dissimilarities can be advantageous as well however, since the flows of information are not really identified when creating a DES model, but mapped when doing a VSM, using both methods will give a more complete picture of reality. However, due to the nature of simulation in general and AutoMod especially, the information flow recorded in a VSM can hardly be used for input to the simulation. This is because the simulation is a simplification of reality, and the information flow is most of the time, such as in our case, extremely complex and thus is not well suited to be simulated. Instead generalizations of the information flow have to be done when creating a DES model.

Initially, the group realized that the biggest problem with DES was that it needed so much training. Yet, this is not something that the new methodology will take into consideration since a dynamic tool is what it is intended to create. Next, a large problem with the simulation output is that it is very hard to grasp. The project therefore suggests that data is presented just like it is in VSM, with a map with processes and queues. If the DES model is set to print the current level of each queue to an Excel-file at times, say every hour, a template plotting queue levels can easily be created. Printed plots can be taped to the presentation map and the result would be a value stream map with plotted graphs showing queue levels instead of snapshots.

By utilizing this approach, a company or organization could get the advantage of being able to play with future state plans, not far from when companies pay consultants a lot of money to play “the Lean game”. The difference now is that they do it in their own factory instead of one built of Lego. The negative side being that the first model creation phase is time-consuming, requires training, a software and, thus, some money.

This methodology was tested during the *Planning model testing* at the case company with great success. In one single afternoon the group members, together with the expert group, were able to test more than 10 different forging plans and see the output from them.

To better understand the methodology, it is illustrated in Figure 5.3.2, each step marked by a number which are described concisely below:

1. The first step of the process is creating the VSM current state map, which is done by the entire project group. This step serves as a kick-off for the project and helps all members attain needed knowledge about the system.

2. After gathering knowledge about the system; product flows, cycle times etc. that the VSM provides, the group discusses what issues need to be addressed and creates a fitting problem formulation for the programming group to conceptualize.
3. In this step the conceptual model is created, the programming group is responsible for making sure that the conceptual model is correct, since they are aware of the limits of the DES software as well as what kind of input is possible. The rest of the project group must still take part in this step, especially those knowledgeable about the production system to ensure that the logic of the conceptual model is correct.
4. The programming group translates the conceptual model to a computerized version, the involvement of the rest of the project group depends on the goals of the project. If educating the group members in DES is a part of the project, this step must be a lot more pedagogical than if the programming group simply can create the model on their own.
5. In the validation stage, those in the project group with extensive knowledge of the production system can once again take part, especially in the face validation step if such a step is included.
6. Finally, the computerized model is run and results are obtained, key results are buffer levels and machine utilization.
7. Here the values obtained in step 6 are used to create a new current state map; plots of the varying levels of queues and machine utilization are used instead of the static values obtained in step 1.
8. The map is then evaluated, for instance it should be possible to identify bottlenecks, both temporary and permanent. Another measure that can be taken, like the one we did in this project, is changing the production plan to better level the production levels. Knowledge gained from the creation of the first current state map is still available, and recommendations based on that can still be made of course.
9. The suggested improvements are then implemented into a map of the future state.
10. The future state map is computerized…
11. …and then the model is executed. The loop is then closed and we return to step 7 where a new map is created based on the results from the simulation. The loop is then repeated until the group feels satisfied and decisions of what changes should be made has been done. Since running a DES model often give more output than can be summarized in a VSM, for instance it is possible to test the effects of specific changes in the production system. It is also possible to pause and investigate the cause at a time when the system performs badly. Input from running the DES model can then be directly input into the improvement plan.
12. Finally an improvement plan to reach the future state is created and submitted.

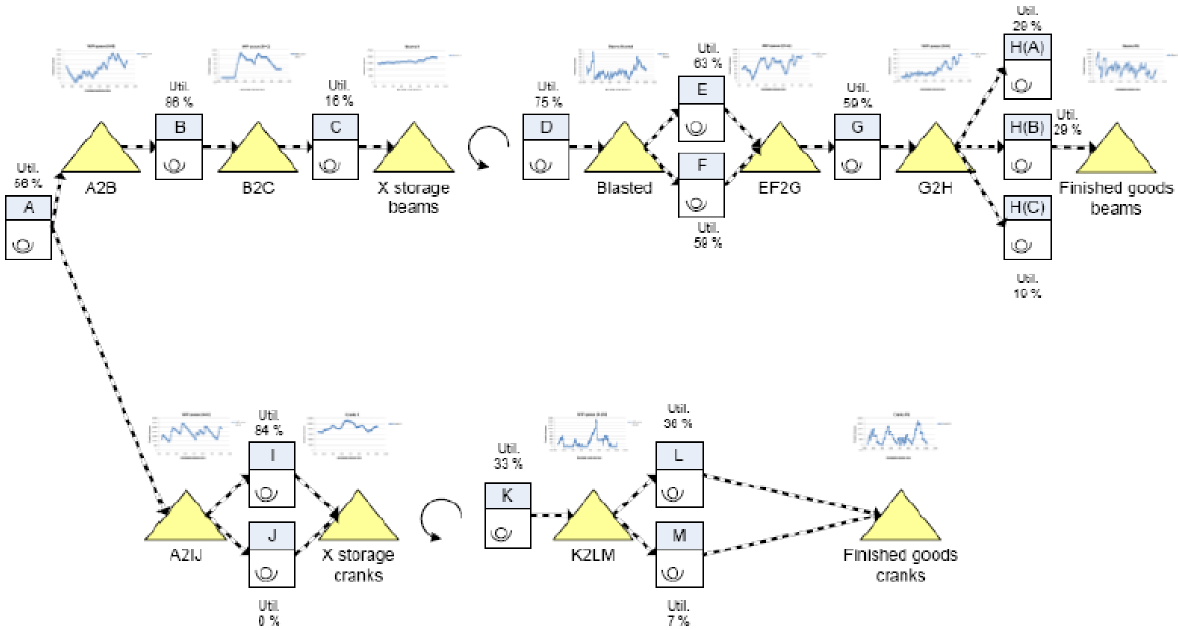


Figure 5.3.1. Value stream mapping inspired representation of DES output with plotted graphs.

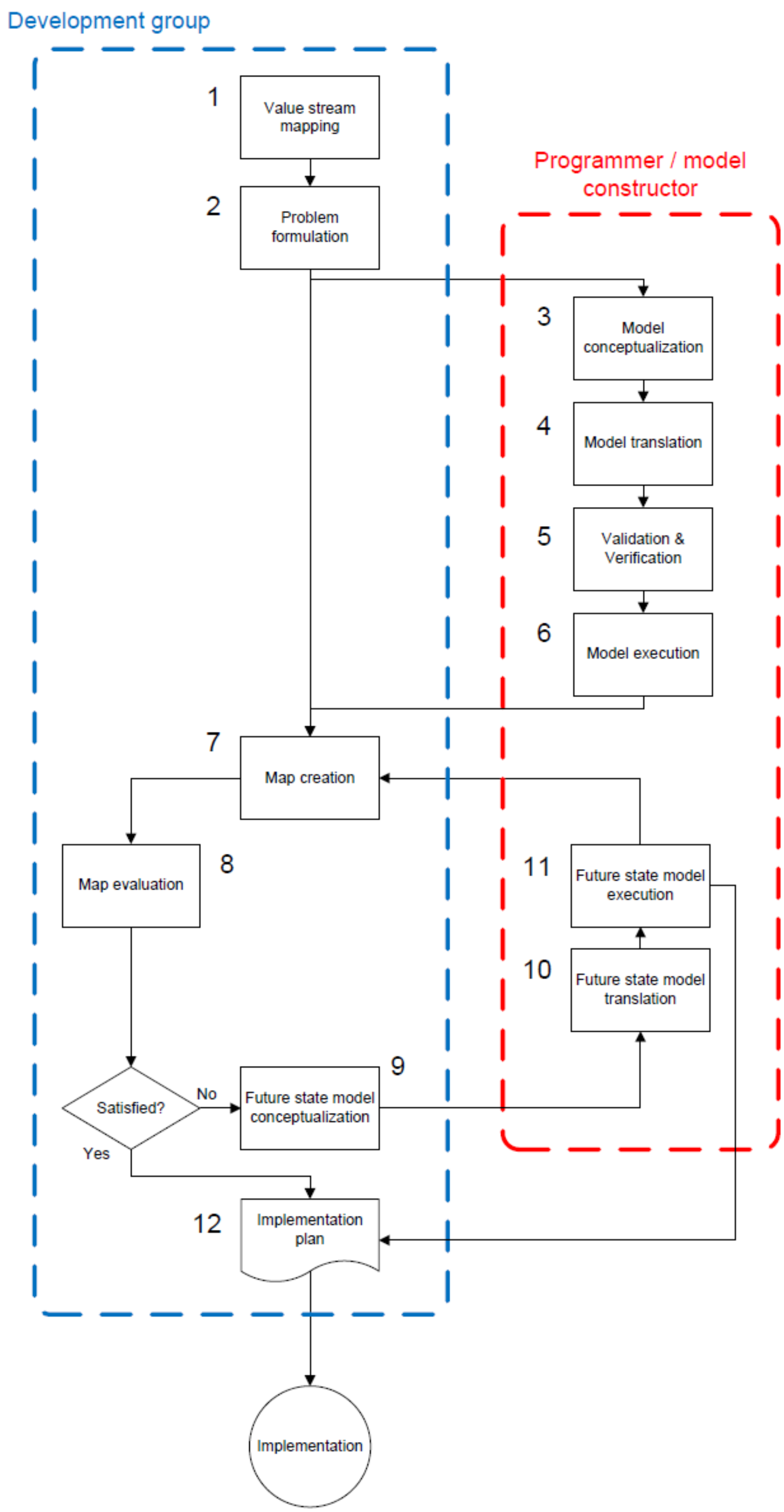


Figure 5.3.2. Flow chart of the proposed methodology.

6 Discussion

The first question formulated was geared towards solving the issues of WIP in production and if possible identify bottlenecks. The suspicion of the Lean manager and the Lean coordinator was that it was the press that was the major bottleneck of the system, something that we agree with after studying the results from the simulation. The biggest reason for this is of course that the press spends a lot of time broken down; if the availability of the press could be increased the output of the system would also increase. Since the press is the bottleneck there will be no large amounts of WIP accumulated in a certain buffer inside the system since the press is the first process in the production chain. As long as the order plans for raw material consider the downtimes of the press the level of raw material stored will be kept at a reasonable level. After the press the processes that are possible bottlenecks are the heat treatments (B and I). When considering the crank heat treatment this is especially interesting since the simulation does not consider the large amounts of re-work that has to be performed on heat treated cranks. In fact, the simulation does not consider the correction and welding operations at all, and according to the VSM these two operations receive and process quite a lot of re-work from the heat treatment as well as subsequent processes. The lack of a logging system for the operations in the crank flow might skew the simulation results, but one should consider the possibility of the real system being worse than the simulation itself, which would make the need for improvements in this area even more important.

A reduction in batch sizes would also reduce WIP according to the simulation results, but with the current demands on setups and output it is impossible to just reduce batch sizes to get these results. This confirms the need for short setup times to reach a flexible production system that is stressed in Lean theory. By trying to level the schedule by sequencing the batches produced, the simulation showed clear reductions in WIP and less starved machinery between the press and the heat treatments, this is a clear indication of that leveling the production schedule has positive effects on the WIP levels. Intuitively, one could associate production leveling with a reduction in batch sizes as well, and we agree that the possibility of batch size reduction would make the sequencing of batches easier. However, the high output target makes a batch size reduction impossible without a reduction in setup time in the press. If a setup time reduction was to be achieved, there is still the issue of forging tools being available, however additional capacity in that regard is already installed but unused.

The high output target is set because the case company believes that there is currently such a high level of demand for their products that they can sell basically everything they produce, provided that they manufacture the correct products. This is proven to an extent by the presence of a backlog and the VSM showed that at least very few articles of heat treated cranks were stuck in storage and unsellable. These factors will of course reduce some of the risks of overproduction presently; however it is unlikely that this kind of demand will last for a sustained period of time since demand seems to be dependent on economic cycles, during the economic crisis demand was extremely low. Such high demand together with the other issues of quite long setup times, rework and some processes being unreliable makes a just-in-time production system unsuitable for the case company. According to Lean theory a JIT system is dependent on short setup times, reliable processes and low scrap rates (see section 2.2.4) and the system is designed to tie production directly to customer demand, but since the demand is so high currently linking demand to production with *kanbans* for instance is very difficult. A high customer demand is however not a reason to be satisfied with the current situation, if re-work rates and processes could be improved the production system would be better prepared for an inevitable drop in demand. Such improvements would of course better the current situation too, with decreased lead times and reduced WIP as a result.

Something that always must be discussed in a project like this is the accuracy of the results. Main weaknesses of any simulation project are the generalizations and assumptions when creating the model. We have assumed that there will never be lack of raw material for the press which is not entirely true. This should not be an issue in the current situation since it is different forging plans for the near future that have been simulated and the raw material stock should be at a higher level than normally because of the recent subpar performance. When the model starts the system is empty, which is not exact either, since there is always some WIP in the system, but these low levels should not have a large effect on output and throughput time. And as mentioned, the availability of forging tools has not been considered; this should not have any effect at all though because of the low number of setups that is possible. Not including the welding and correction processes in the crank flow is an issue however, a substantial number of units pass through the correction process and it is only manned during two shifts each day. It is very much possible that including these two processes in the simulation would have affected the output somewhat.

Then there are the things that cannot be simulated, for instance snap decisions made on what to produce and decisions on how to split an original batch in a new process. Customers wanting to change their orders on short notice are something that cannot be simulated either and this does happen frequently to our case company. The biggest issue regarding simulation is the lack of logging system for stops and other downtimes. For all processes except basically the press, downtime data used in the simulation has been based on interviews and not stop logs. Inaccurate stop data will affect the dynamics of the system and thus affect the output. To what extent is hard to determine, but the assumption has to be that the people responsible for the processes are aware of the process performance and thus there will not be any major inaccuracies.

Issues like these are however a part of every simulation project and in no way exceptional, in total we believe that the accuracy of the simulation model is sufficient and that there is no reason to doubt the results. Actually a lot of time has been allotted to create a model that was more advanced than usual. For instance it contained fourteen different product flows; it is not unusual to make even larger generalizations, reducing the number of articles in the simulation to three or four.

The weaknesses of the VSM are the same as been covered earlier in the report, i.e. VSM being static and just a snapshot, but it should also be noted that although the information flow is mapped in a VSM, it is still hard to grasp the complexity of such a flow. The arrows are mainly indicating directions of information, but mapping for instance a three-way meeting in a comprehensible way is difficult.

The second question formulated was how to use VSM and DES together when carrying out an effort to reduce WIP in a manufacturing company. The new method we have developed is what we think is the answer to this problem. There might be some issues with this new method though. A project group using the method might be somewhat divided between those knowledgeable about VSM and the creators of the DES model, it is important that the entire group is involved through all steps of the project. Presenting DES results in a VSM can also be lead to a misinterpretation that a DES model does not have more to offer than a VSM, which is not true, this must be kept in mind to misuse the DES tool in such a project.

7 Conclusions

The two main question formulations are repeated below to see what possible conclusions can be drawn from them respectively:

- What are the levels of WIP and how much do the dynamics of the system affect these levels?

Determining certain levels of WIP and how the dynamics of a system affect them exactly turned out to be an ambitious question. Conclusions can instead be made on how to attempt to reduce WIP levels and how the forging planning works with regards to customer orders. When this study started, there were issues with high levels of WIP, but along the project's time the performance of the forging press caused the WIP to drop below the wanted levels. Even initially, before the poor press performance, the case company had a backlog of deliveries, which makes the group draw the conclusion that the planning for the forging press is crucial for keeping up with customer demand and maintain low levels of WIP. Leveling the planning and then identifying the best alternative by running a number of plans through a simulation model should lead to a more leveled production and a lower amount of WIP. A straightforward, but difficult, way to reduce WIP is to improve the processes and re-work rates, for instance by using the VSM we can conclude that to reduce the amount of WIP in the crank flow, resources should be directed towards improving the quality of the processes as well as the material, an improvement in quality would lead to a reduction in re-work which in turn would lead to a reduction of the WIP levels in the crank flow as well as a reduction in lead time.

- How can a combination of a dynamic DES model and a VSM help a manufacturing company reach desired levels of WIP?

There are a few important advantages of VSM that a simulation generated method never will be able to compare to; for instance the fact that a mapping of an organization finds the information flow between processes. In that sense, they are two entirely different methods and can therefore not be combined in that phase. However, the group can conclude that a VSM can be of valuable assistance when creating the conceptual model for a simulation project, even though that approach was not applied in this project.

This project supplies an example of how output of DES can successfully be shown and interpreted using a layout similar to the well-known layout of a VSM. It has been of great importance and support when evaluating different planning principles since it is generally more comprehensive than the unformatted output of AutoMod. Basically it can contain extensive amounts of data, with dynamics included, and still enable people to rapidly grasp the data.

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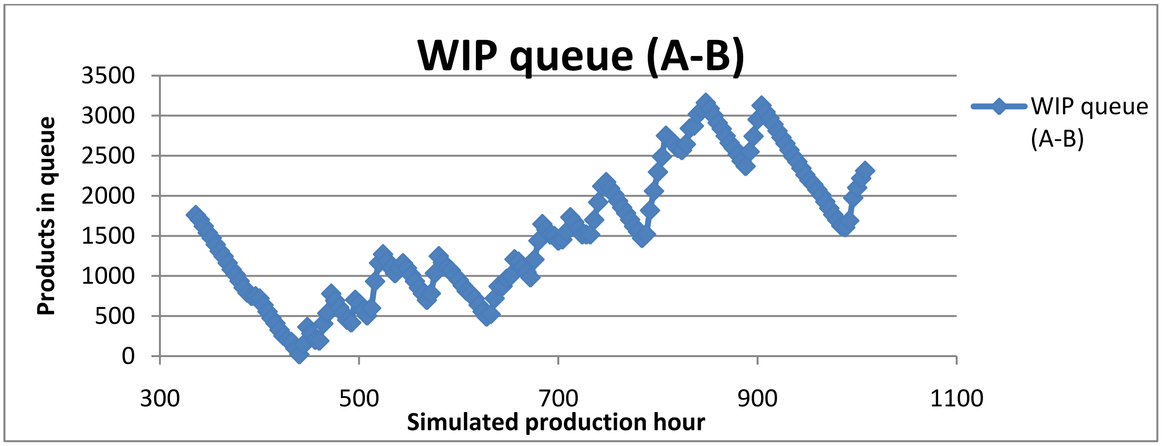
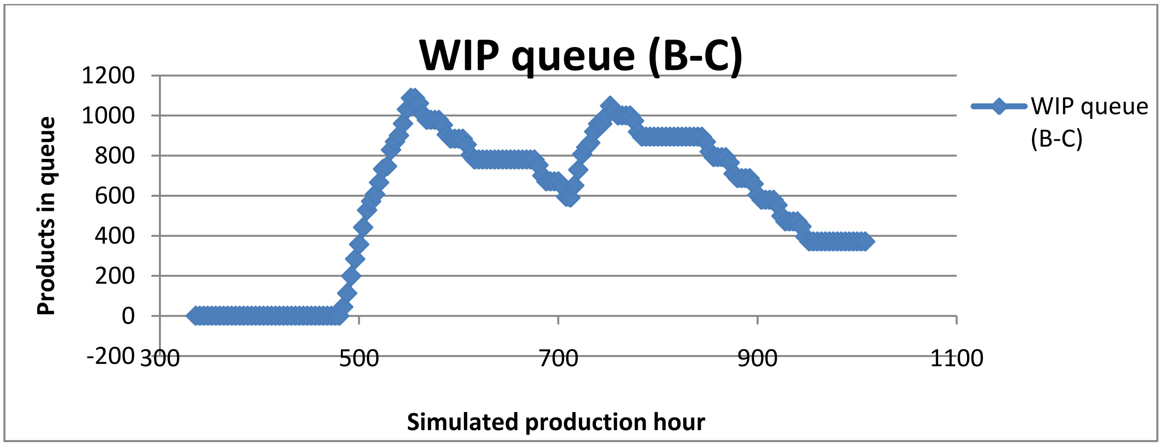
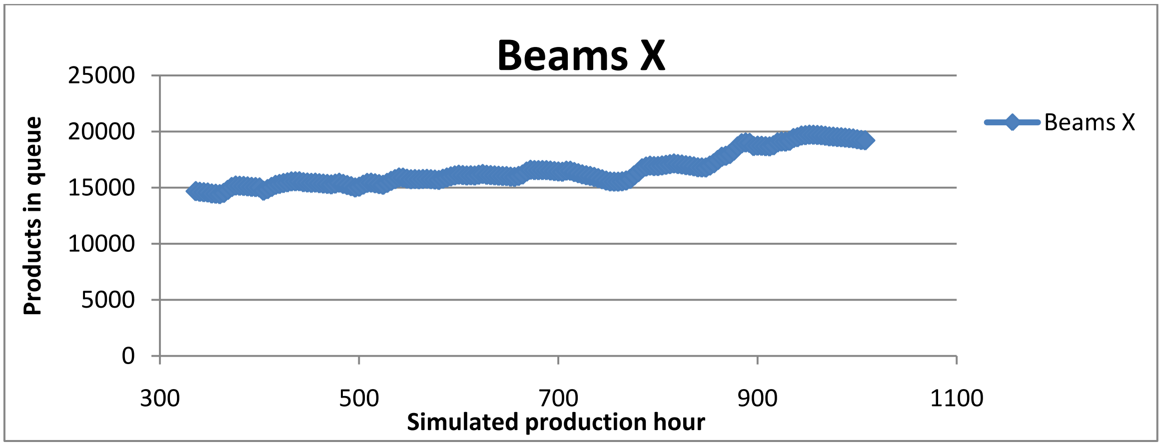
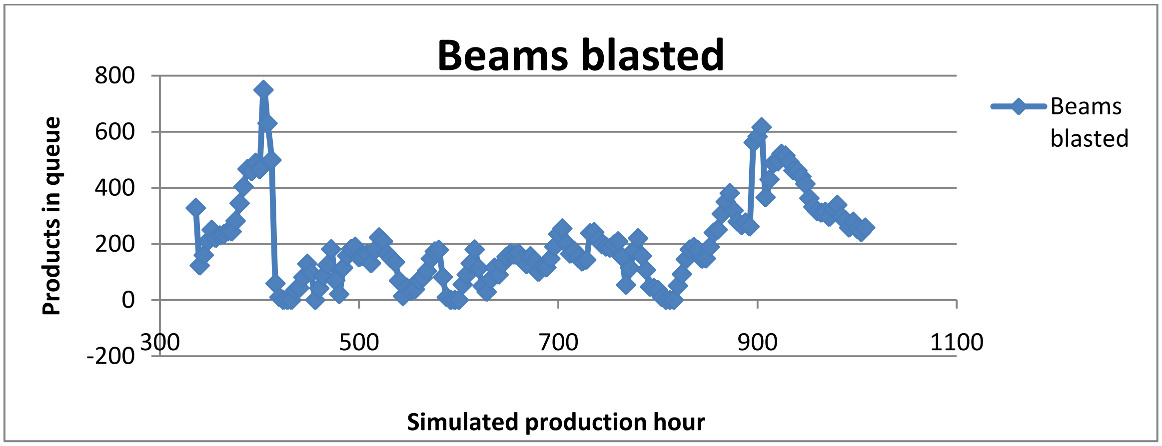
I. Appendix A

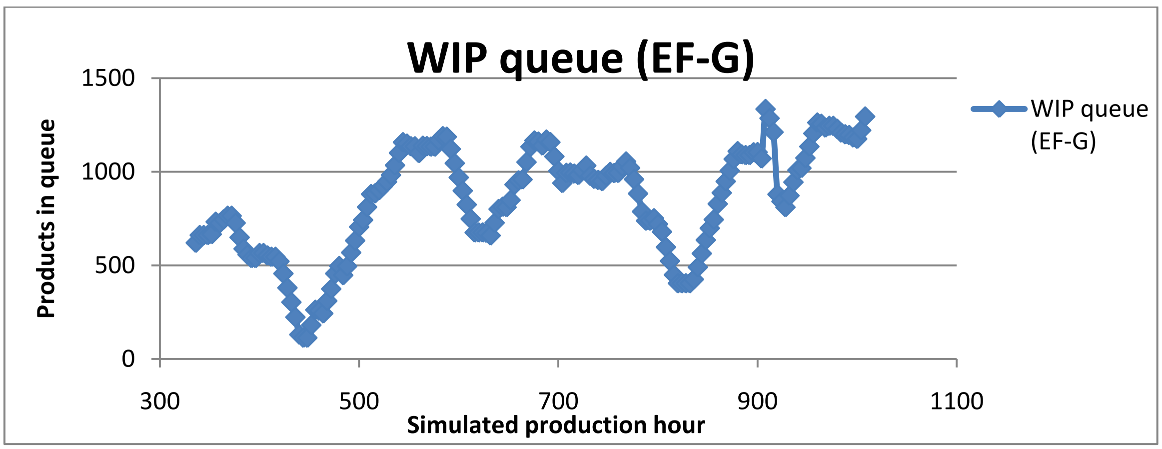
Plots from the *Historic state model testing*. Queues during four weeks of production simulation, after two weeks of warm-up time.

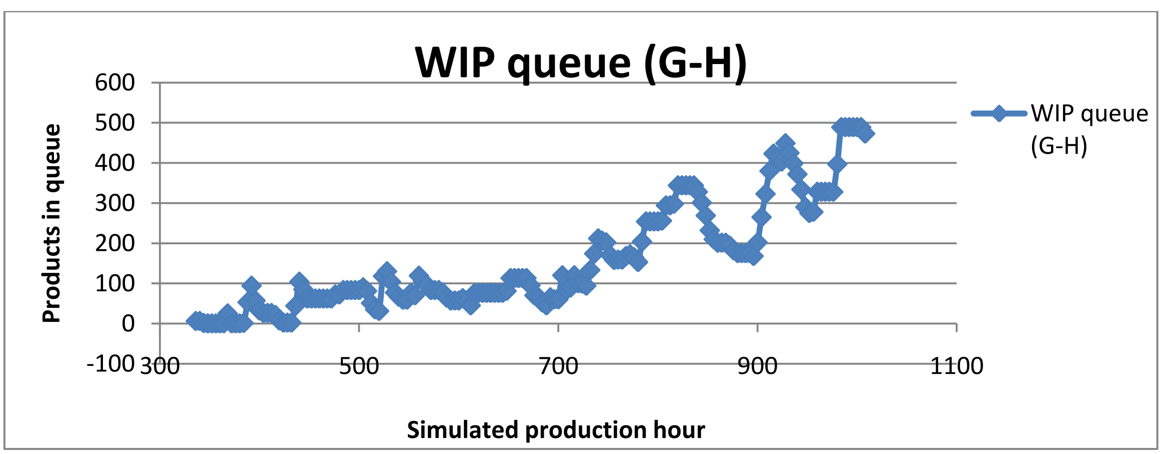


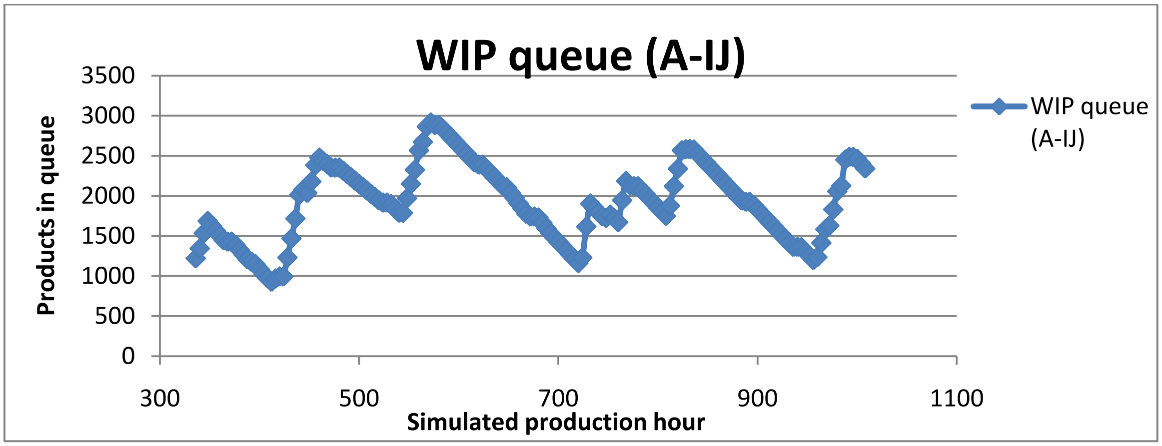


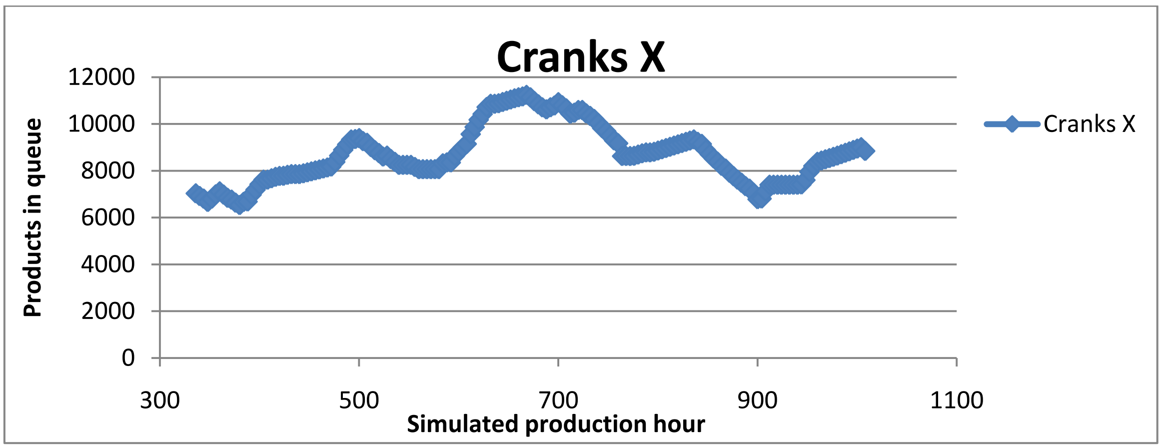


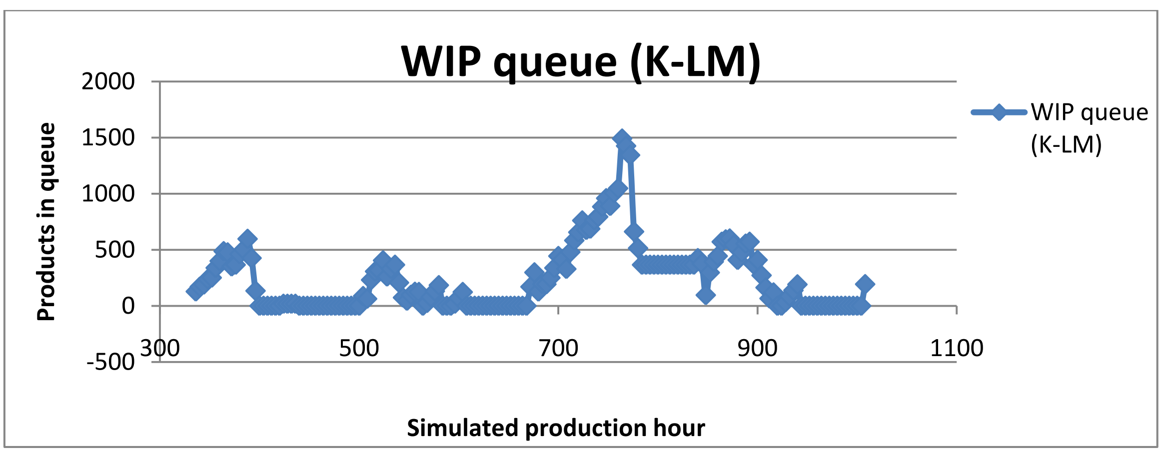

Beams blasted
Products in queue
800
600
400
200
0
-200
300
500
700
900
1100
Simulated production hour
Beams blasted

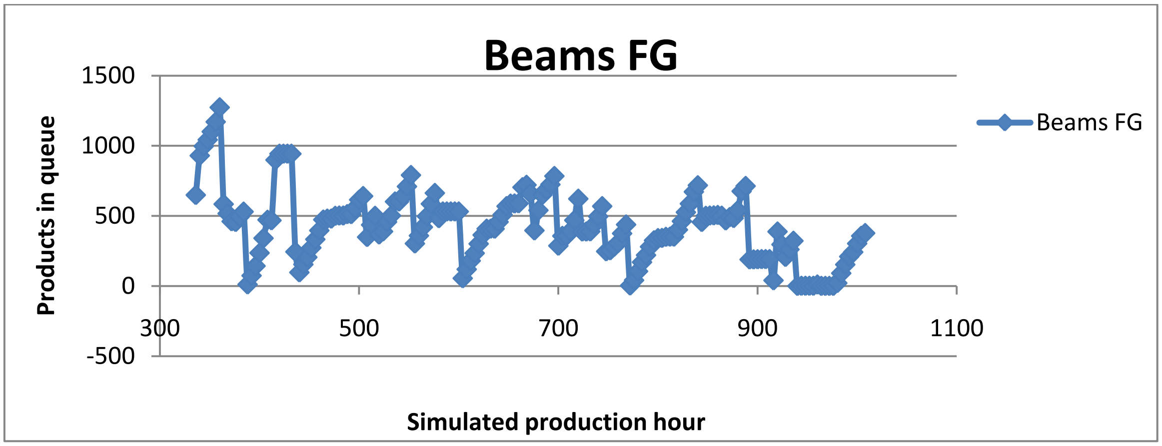

WIP queue (EF-G)
Products in queue
1500
1000
500
0
300
500
700
900
1100
Simulated production hour
WIP queue (EF-G)

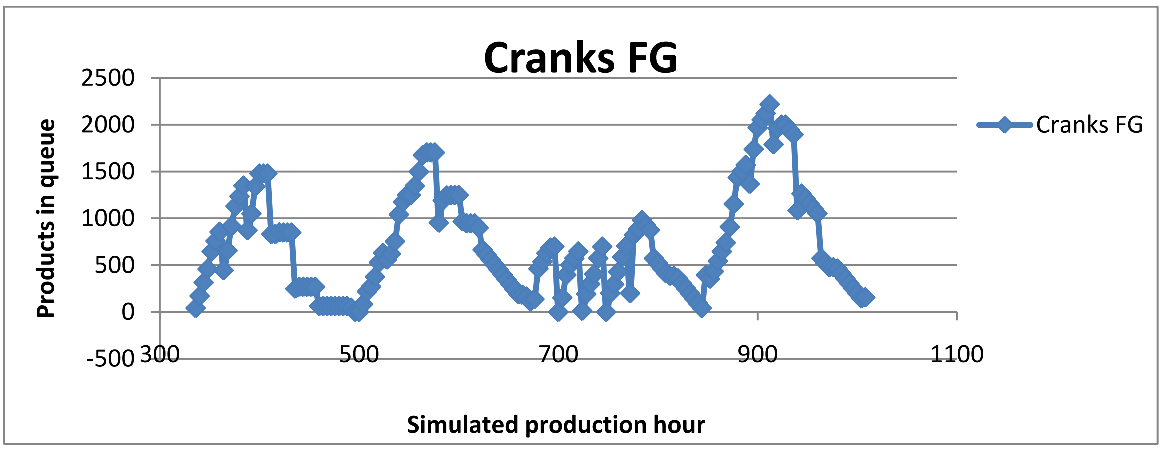

WIP queue (G-H)
Products in queue
600
500
400
300
200
100
0
-100
300
500
700
900
1100
Simulated production hour
WIP queue (G-H)

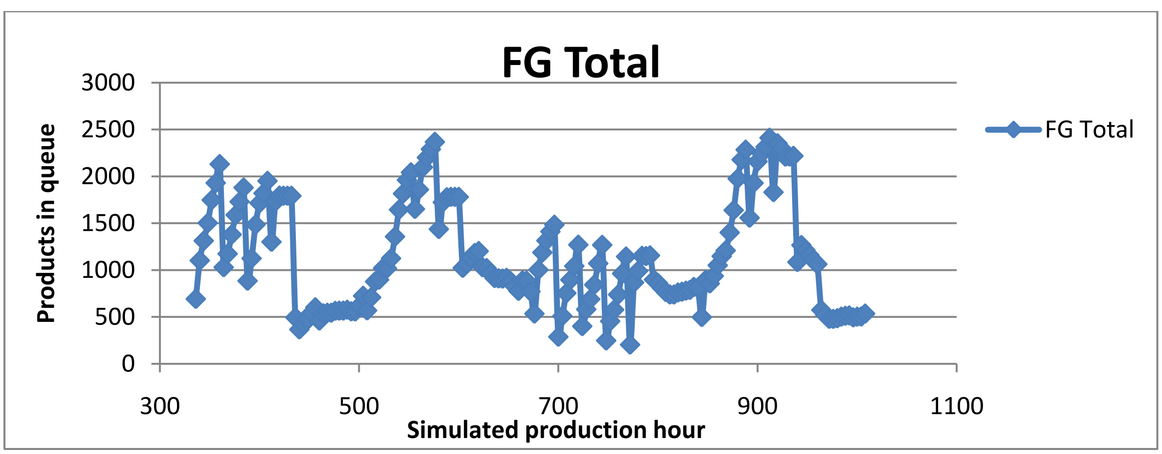

WIP queue (A-IJ)
Products in queue
3500
3000
2500
2000
1500
1000
500
0
300
500
700
900
1100
Simulated production hour
WIP queue (A-IJ)


Cranks X
Products in queue
12000
10000
8000
6000
4000
2000
0
300
500
700
900
1100
Simulated production hour
Cranks X


WIP queue (K-LM)
Products in queue
2000
1500
1000
500
0
-500
300
500
700
900
1100
Simulated production hour
WIP queue (K-LM)


Beams FG
Products in queue
1500
1000
500
0
-500
300
500
700
900
1100
Simulated production hour
Beams FG

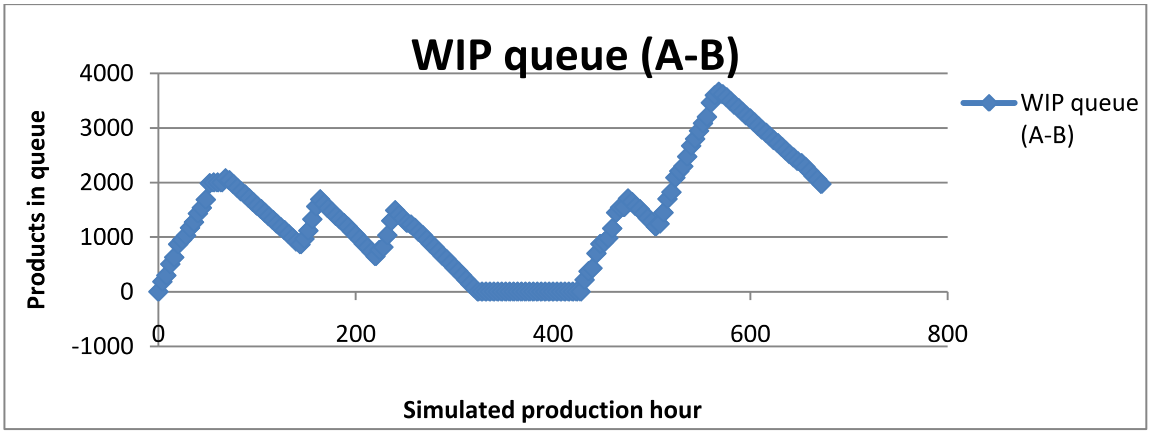

Cranks FG
Products in queue
2500
2000
1500
1000
500
0
-500
300
500
700
900
1100
Simulated production hour
Cranks FG

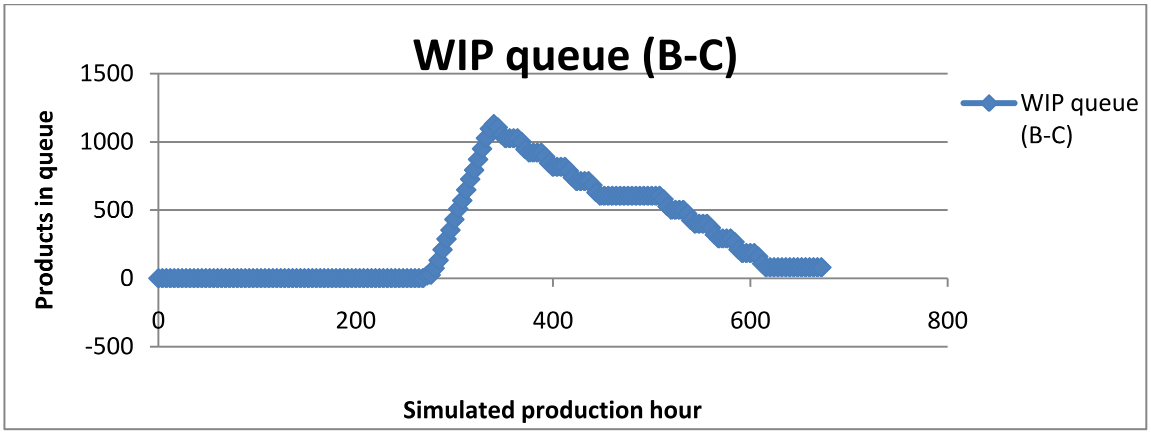

FG Total
Products in queue
3000
2500
2000
1500
1000
500
0
300
500
700
900
1100
Simulated production hour
FG Total

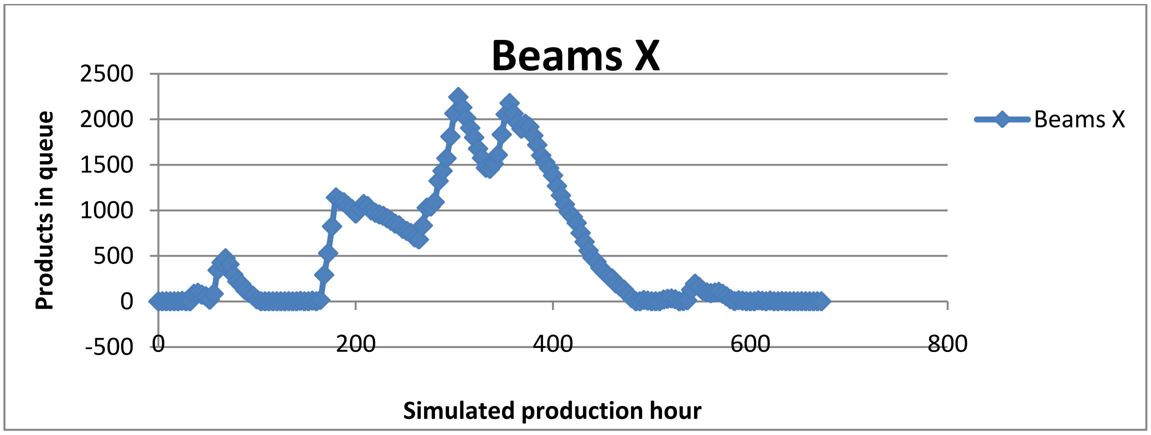
II. Appendix B

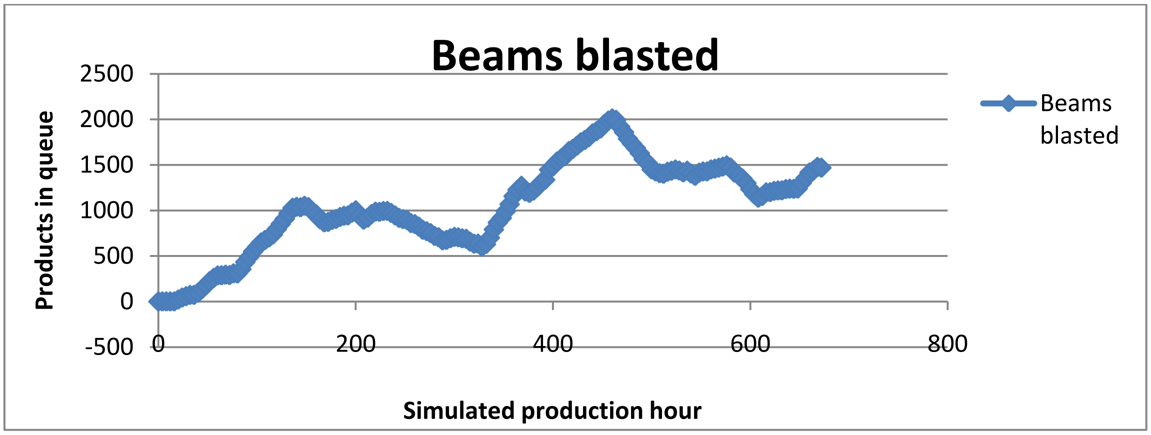
Plots from the *Planning model testing*. Queues during four weeks of production simulation.

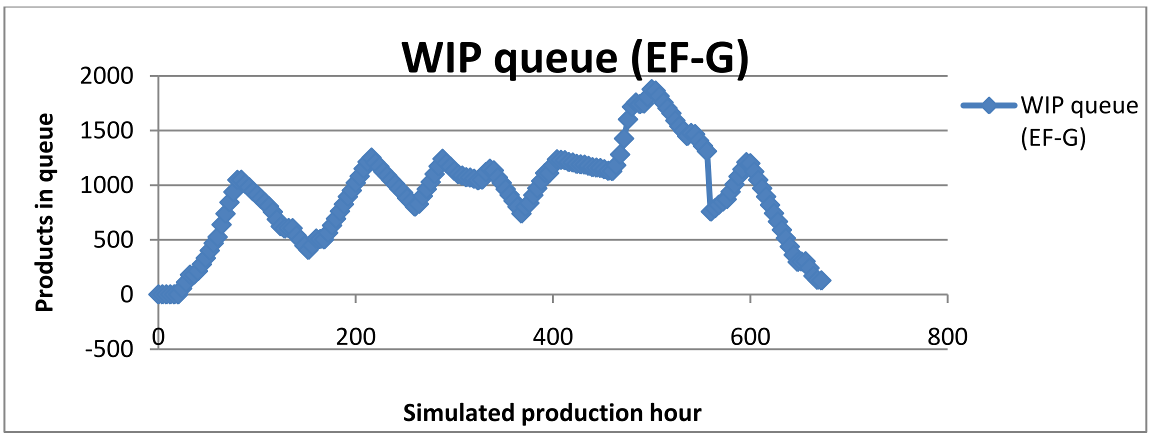
Version 1

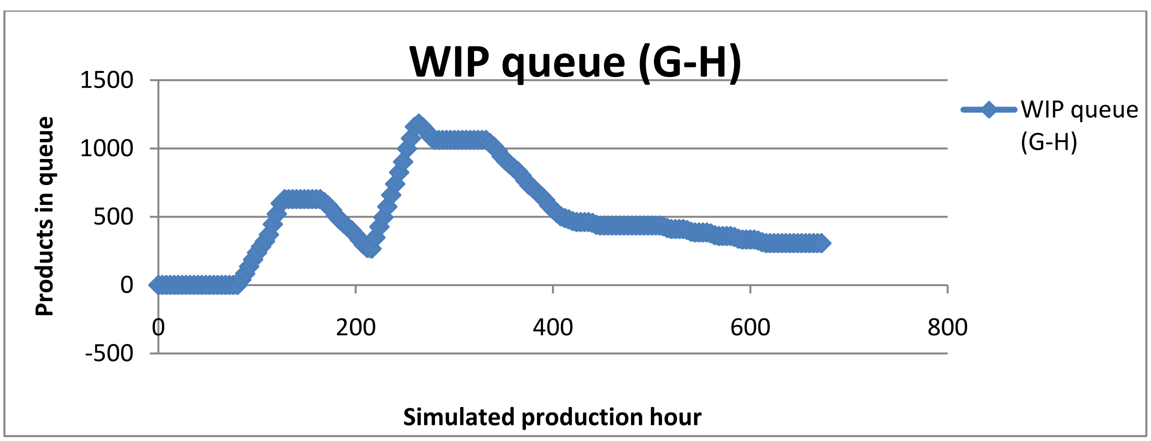


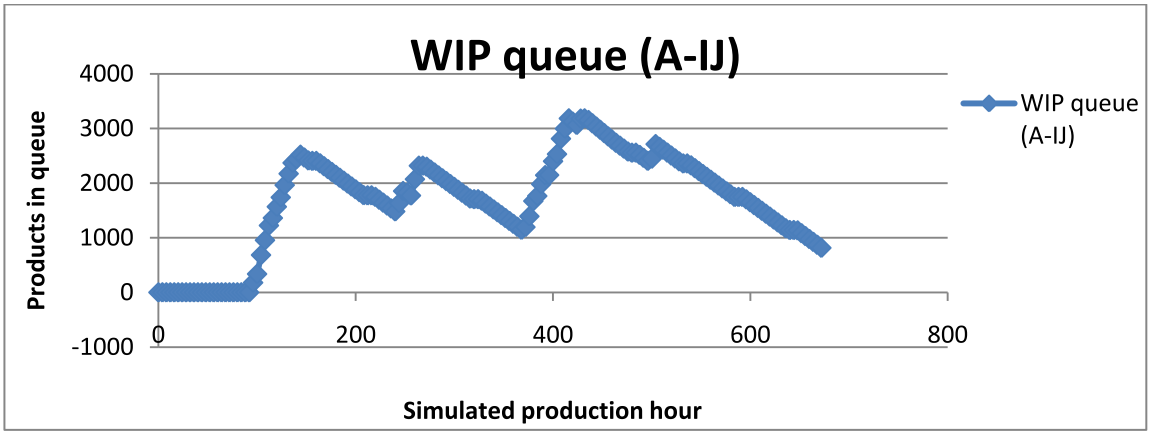


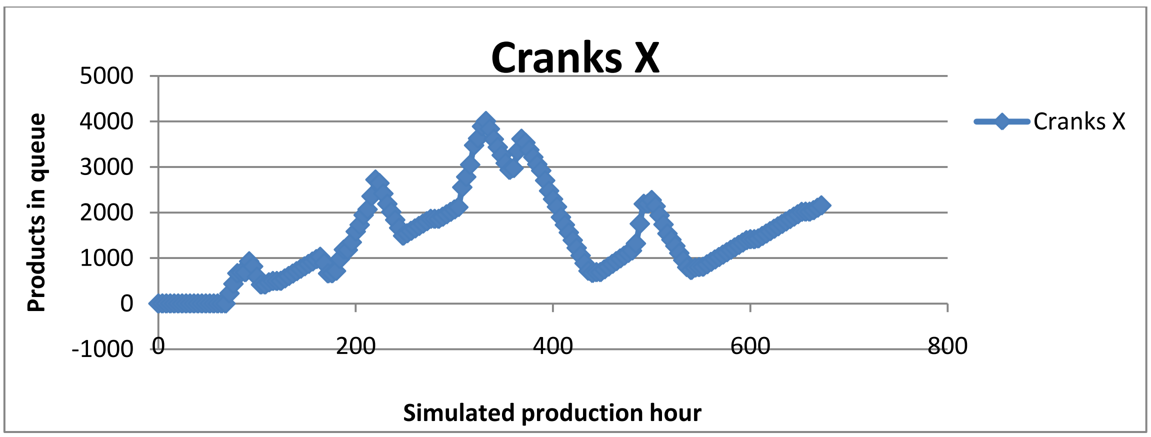


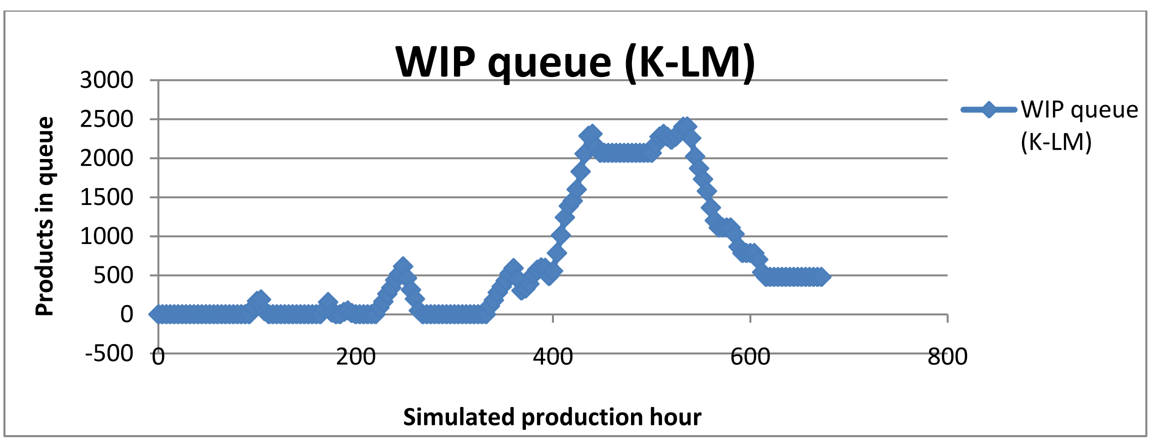

Beams blasted
Products in queue
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
Beams blasted

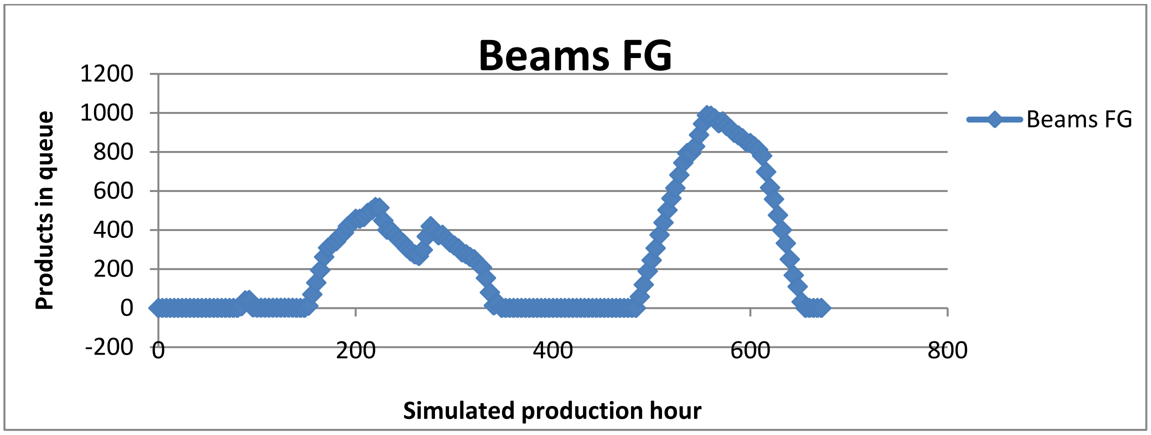

WIP queue (EF-G)
Products in queue
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (EF-G)


WIP queue (G-H)
Products in queue
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (G-H)

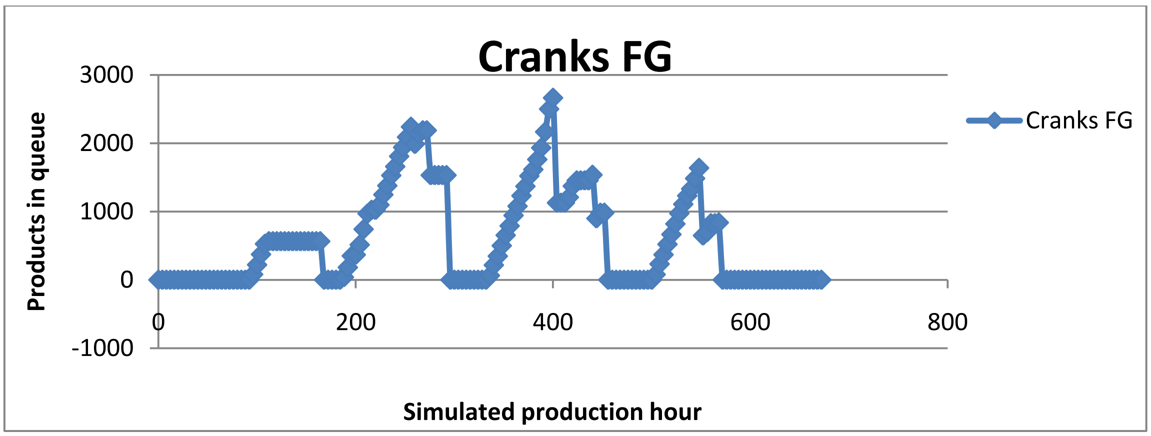

WIP queue (A-IJ)
Products in queue
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Simulated production hour
WIP queue (A-IJ)


Cranks X
Products in queue
5000
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Simulated production hour
Cranks X

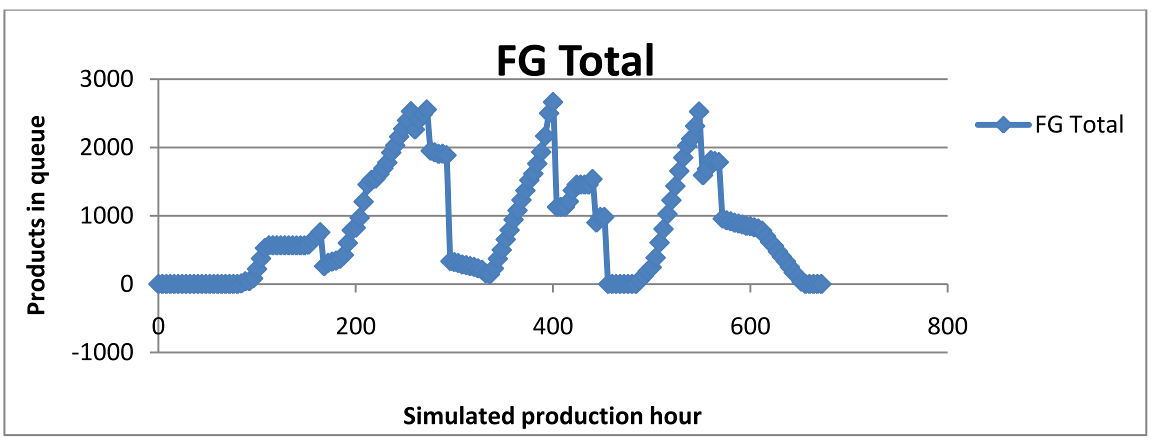

WIP queue (K-LM)
Products in queue
3000
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (K-LM)



Beams FG
1200
1000
800
600
400
200
0
-200
0
200
400
600
800
Products in queue
Simulated production hour
Beams FG

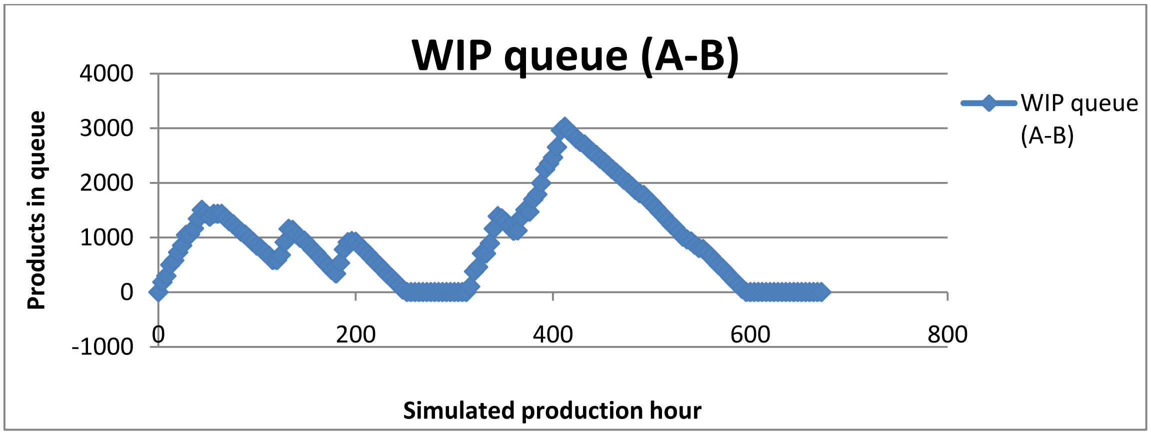


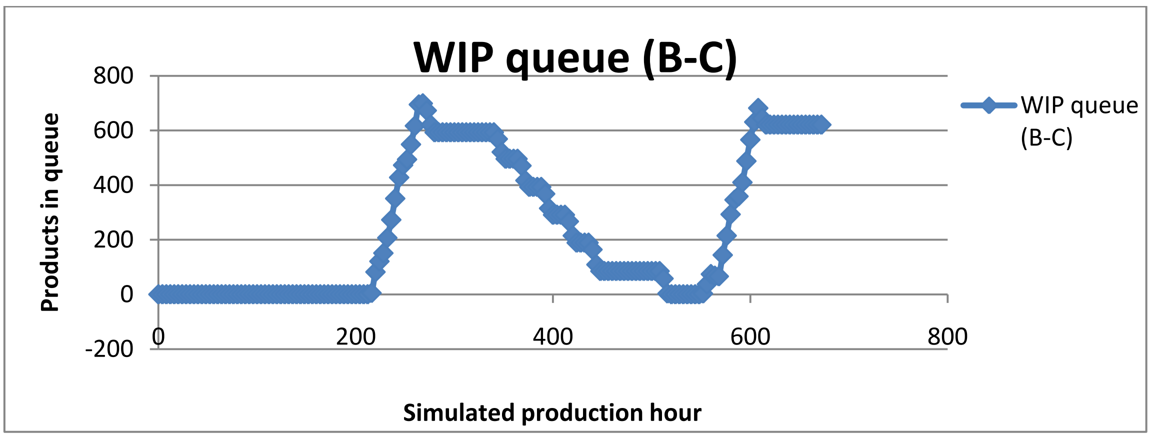
Cranks FG
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
Cranks FG

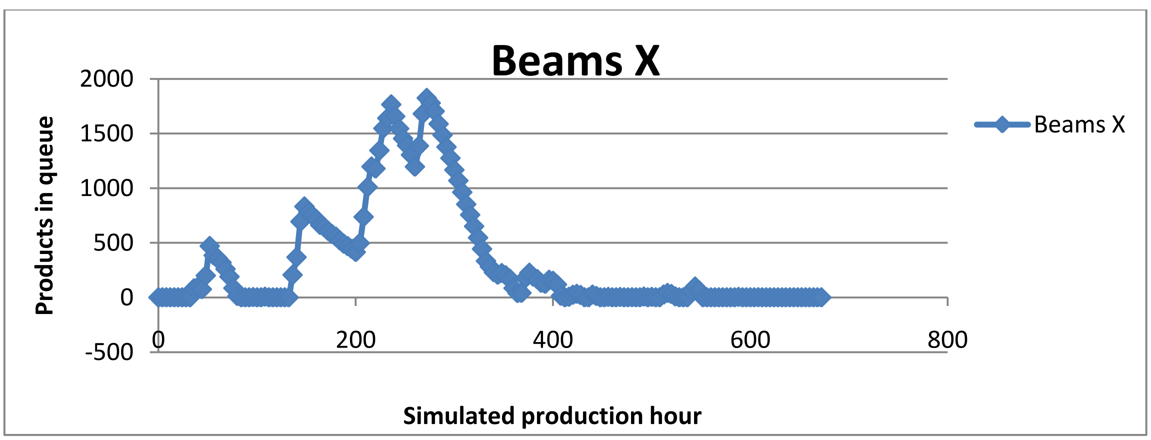


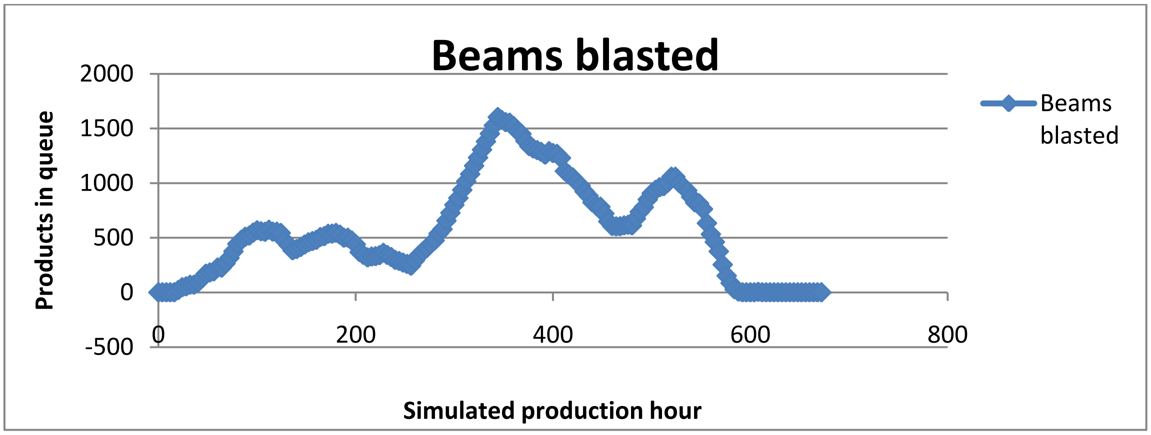
FG Total
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
FG Total

Version 2

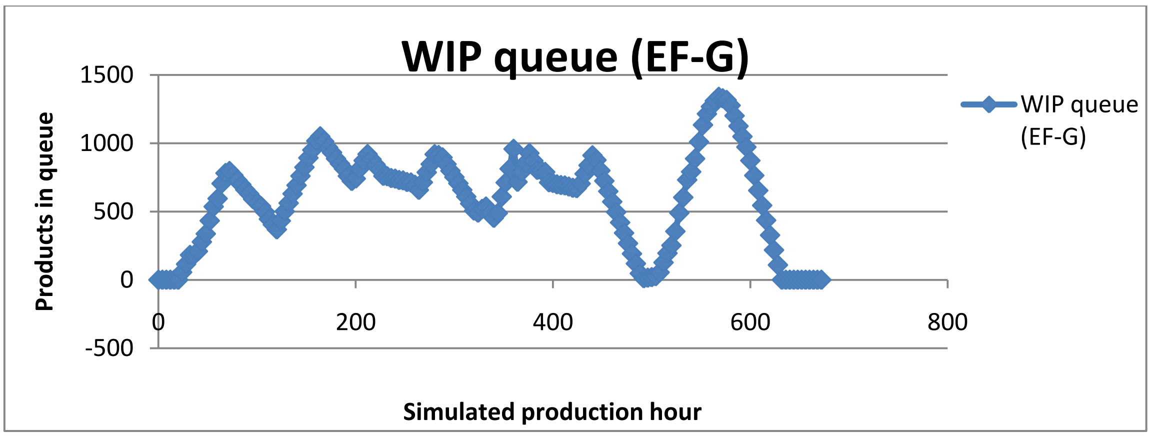

WIP queue (A-B)
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (A-B)


WIP queue (B-C)
800
600
400
200
0
-200
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (B-C)

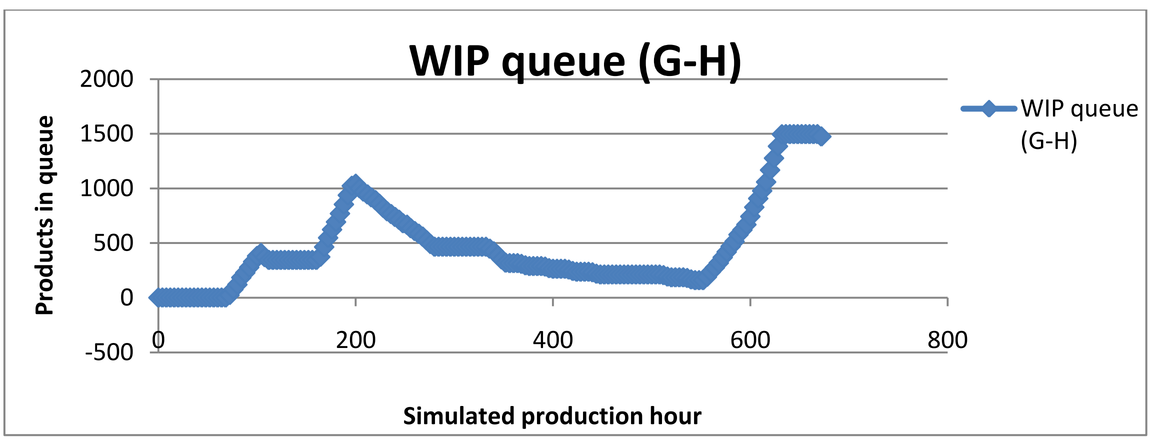

Beams X
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Beams X



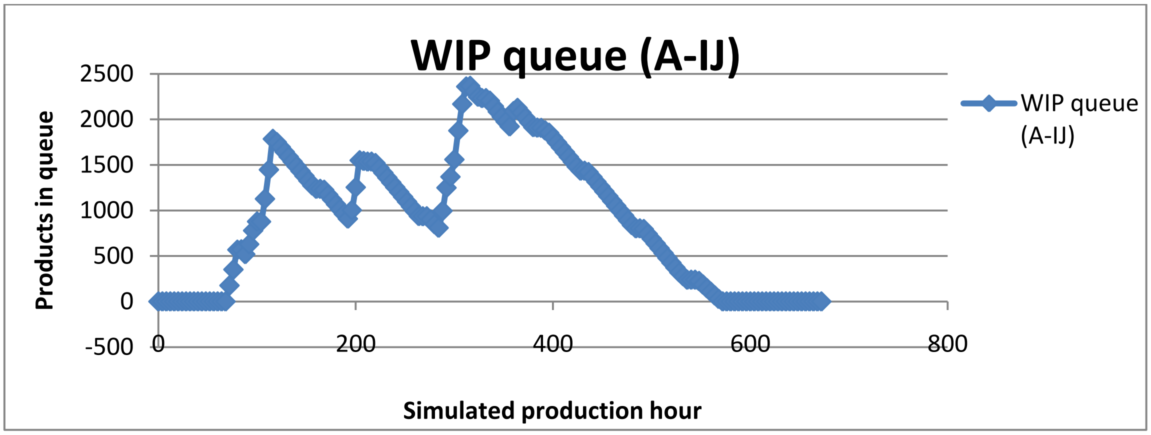
Beams blasted
Products in queue
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
Beams blasted

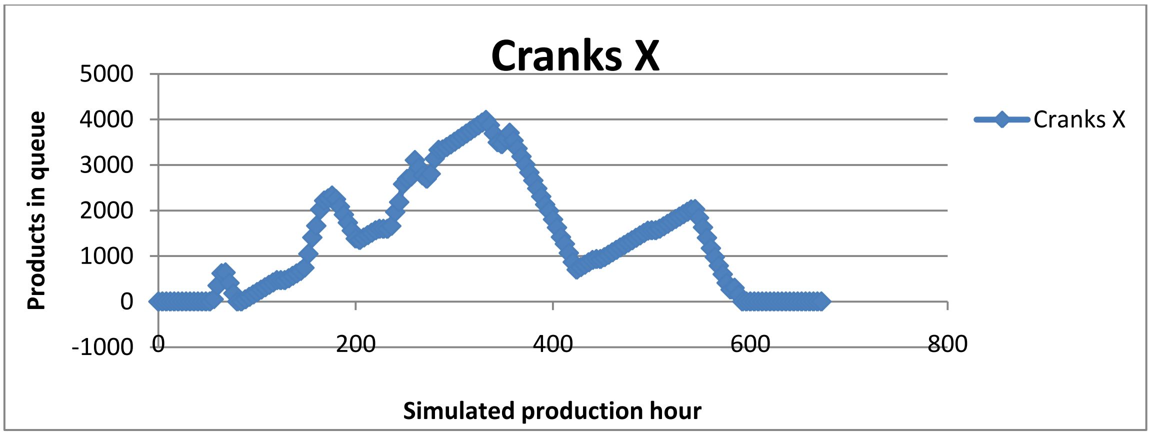


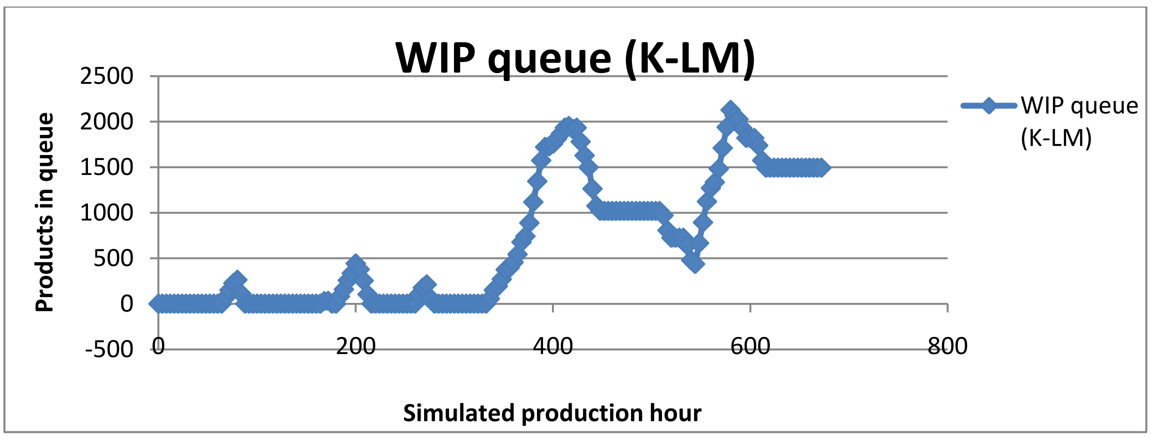
WIP queue (EF-G)
Products in queue
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (EF-G)

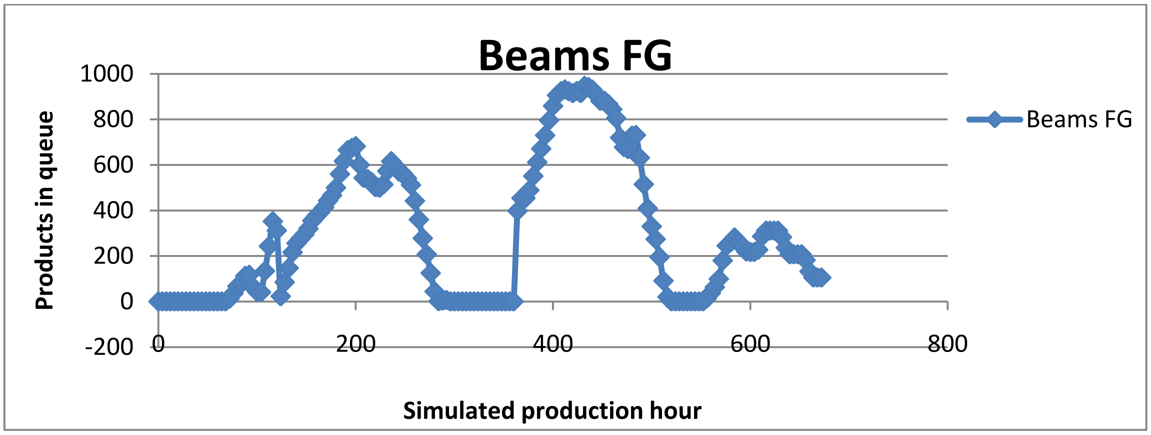


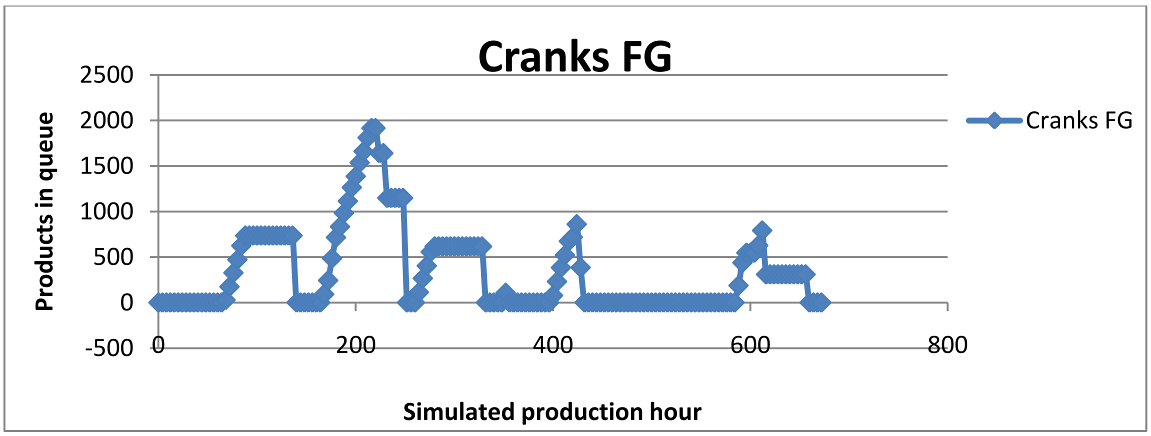
WIP queue (G-H)
Products in queue
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (G-H)

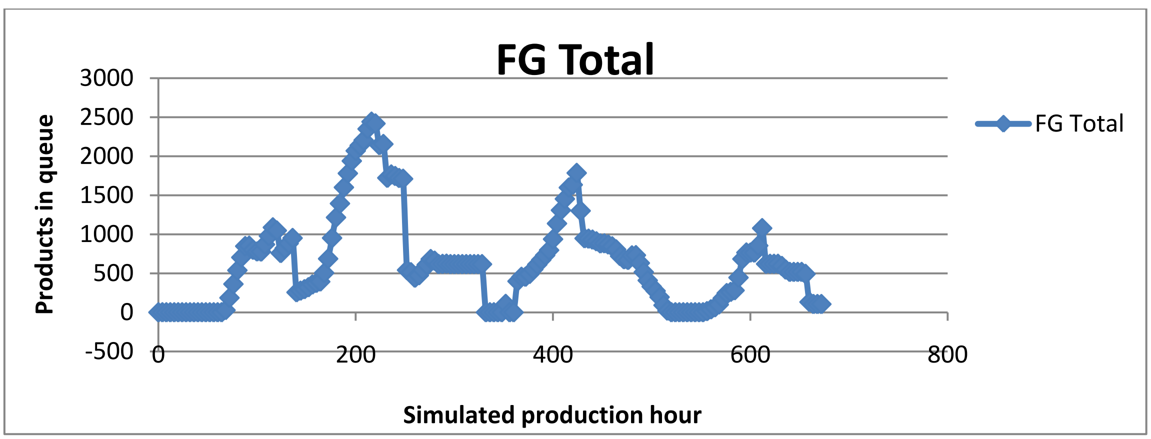

WIP queue (A-IJ)
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (A-IJ)


Cranks X
5000
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
Cranks X

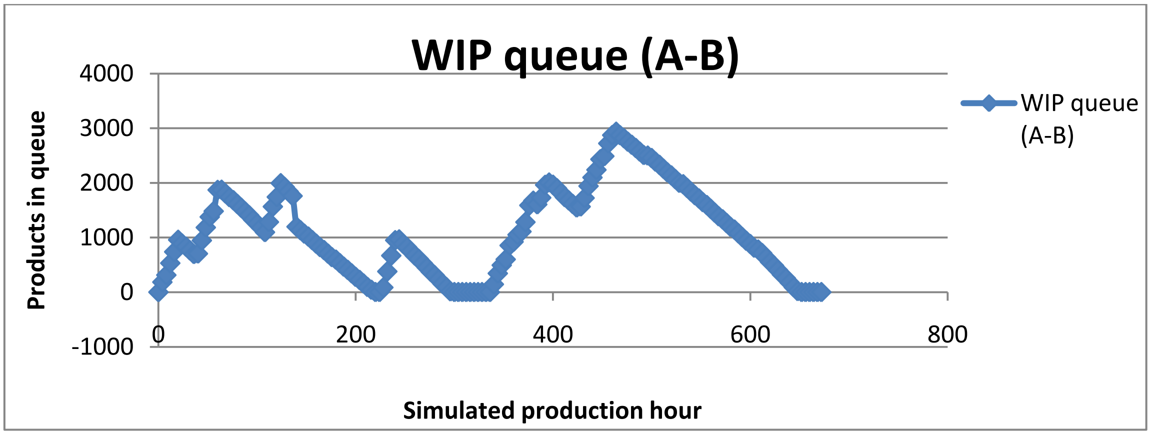

WIP queue (K-LM)
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (K-LM)

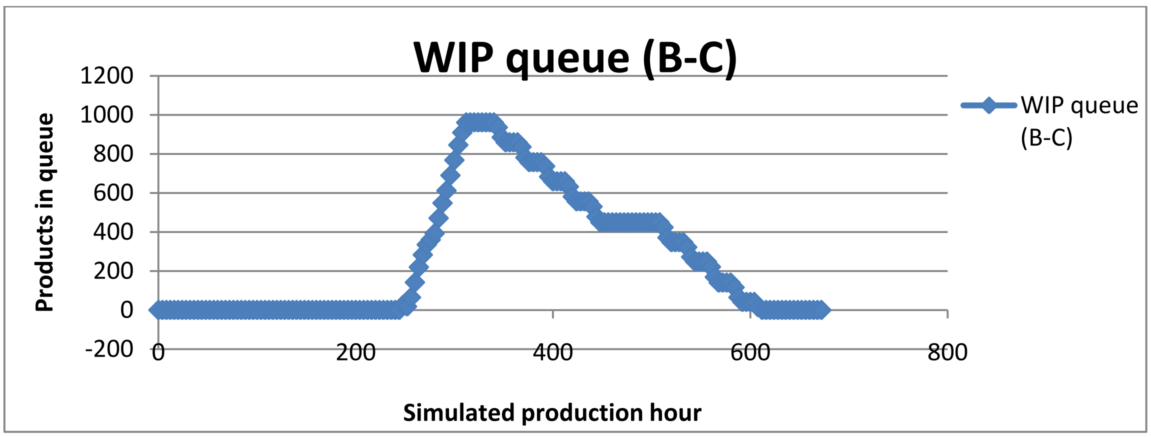

Beams FG
Products in queue
1000
800
600
400
200
0
-200
0
200
400
600
800
Simulated production hour
Beams FG

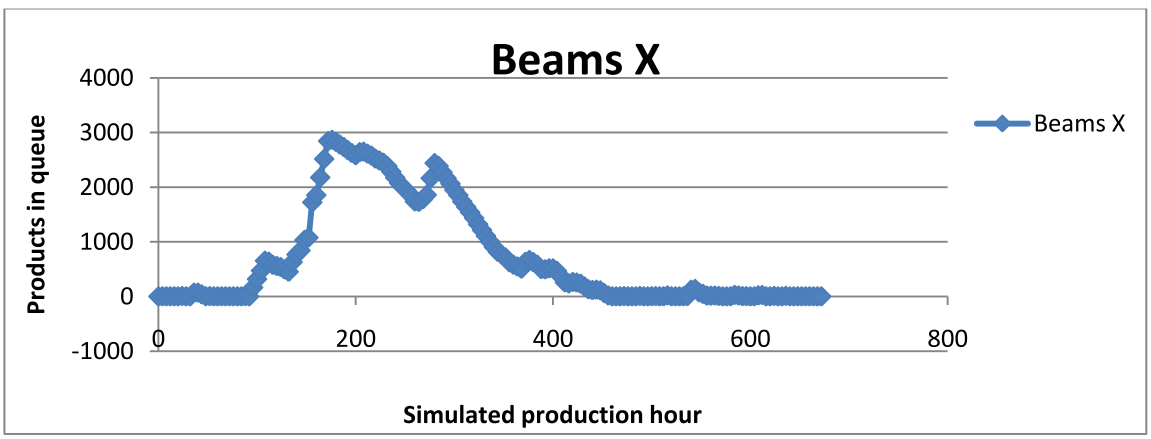

Cranks FG
Products in queue
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
Cranks FG

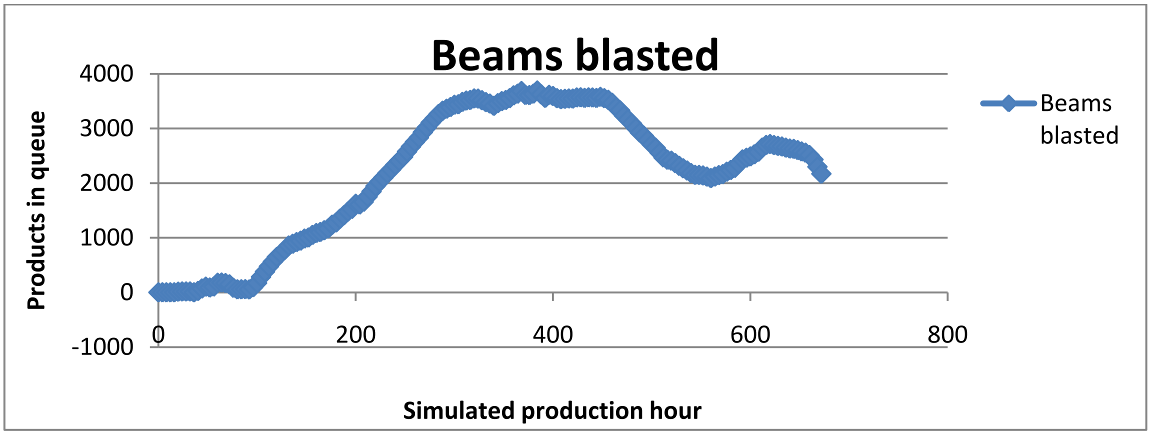

FG Total
Products in queue
3000
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
FG Total

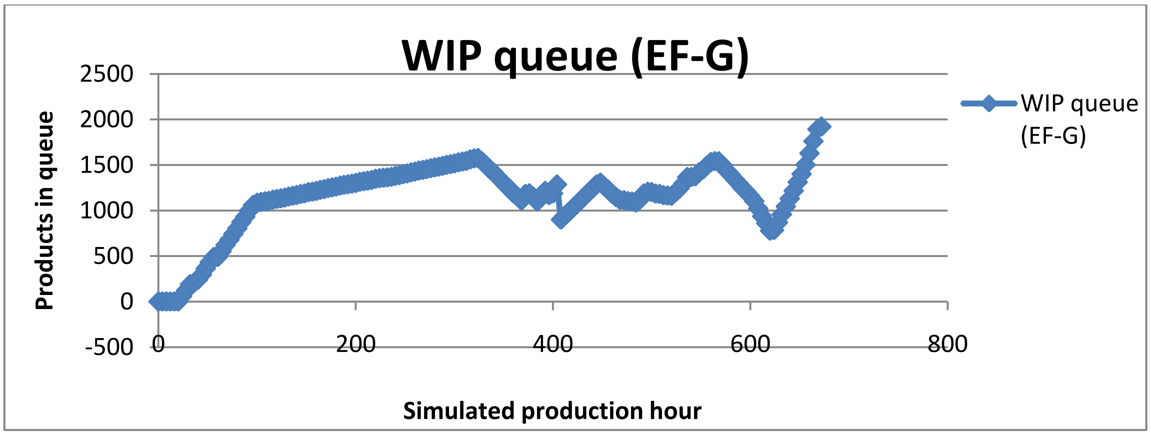
Version 5

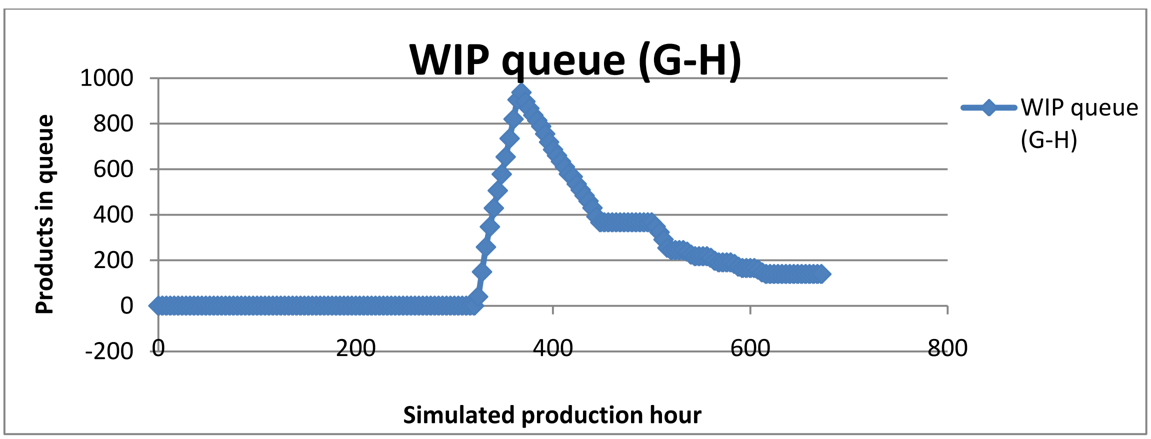

WIP queue (A-B)
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (A-B)

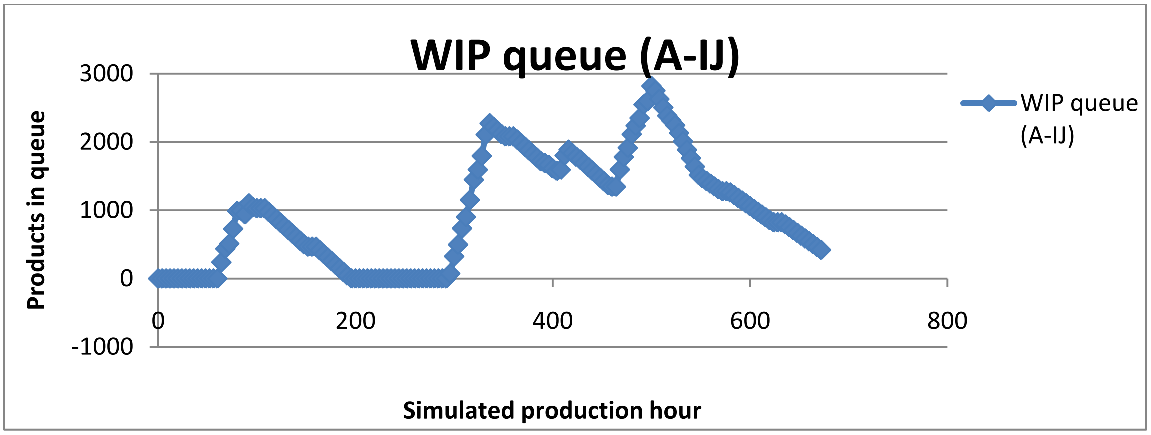

WIP queue (B-C)
1200
1000
800
600
400
200
0
-200
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (B-C)

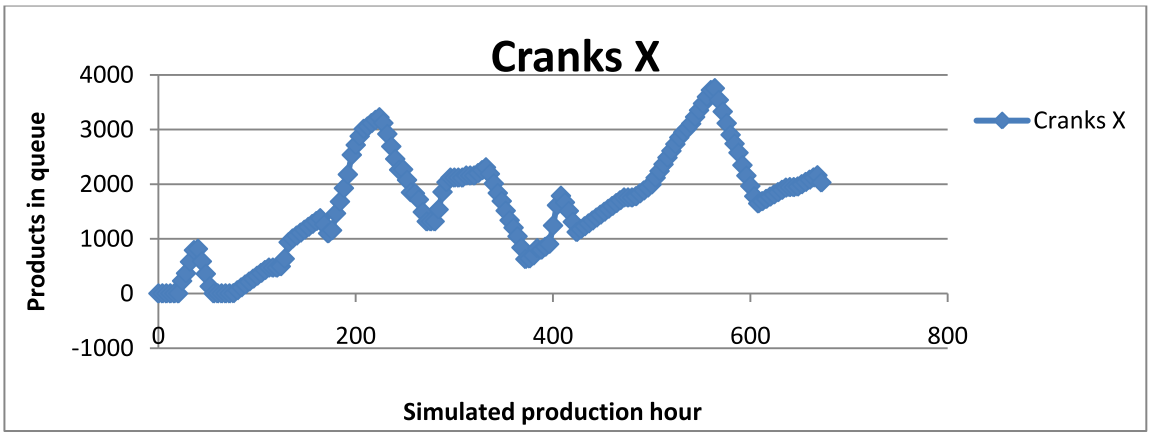

Beams X
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
Beams X

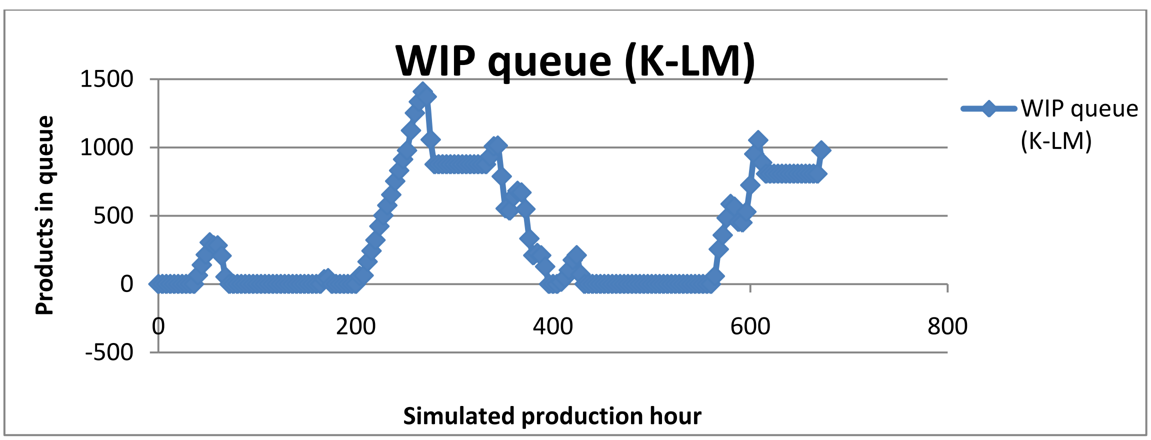

Beams blasted
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
Beams blasted

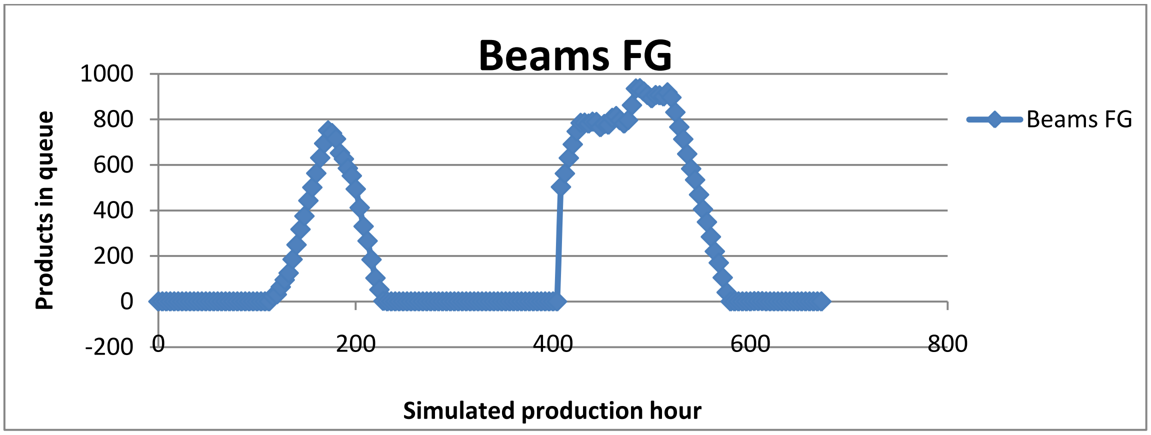

WIP queue (EF-G)
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (EF-G)

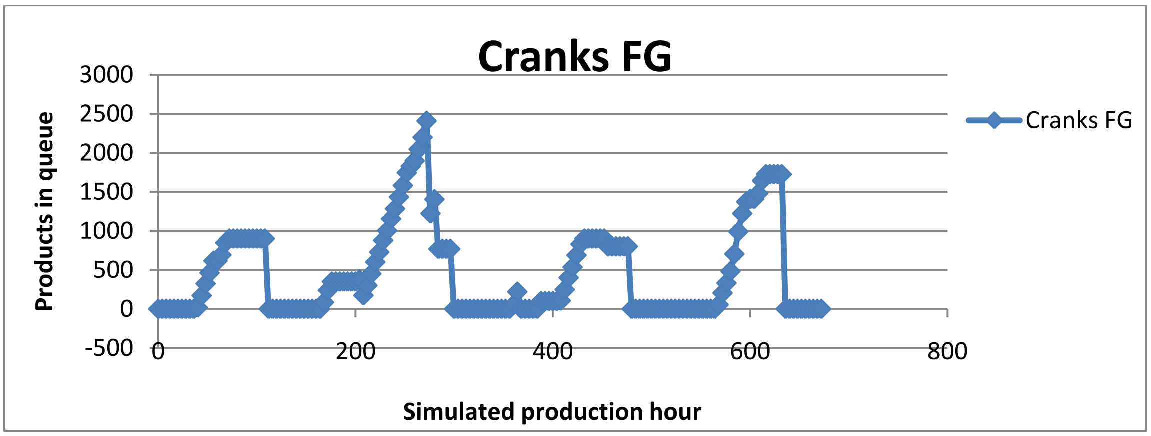

WIP queue (G-H)
1000
800
600
400
200
0
-200
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (G-H)

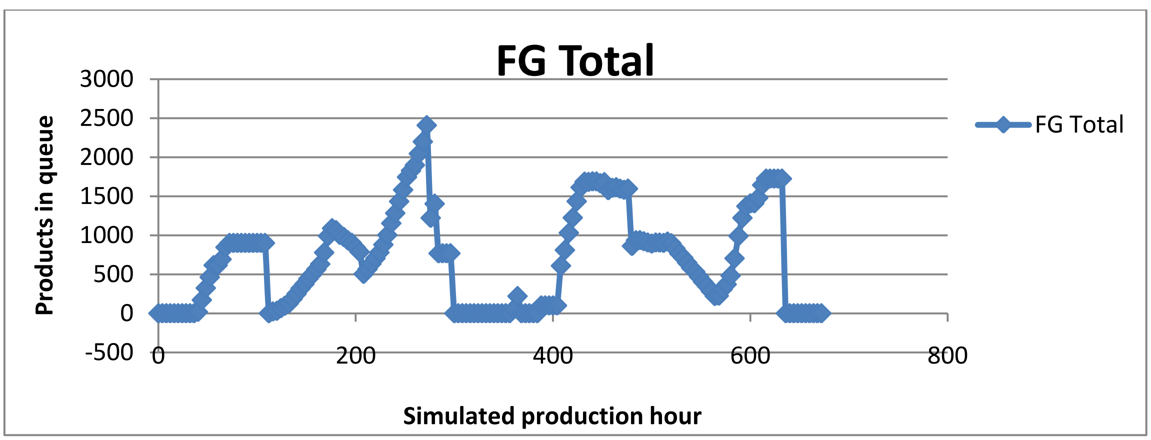

WIP queue (A-IJ)
Products in queue
3000
2000
1000
0
-1000
0
200
400
600
800
Simulated production hour
WIP queue (A-IJ)


Cranks X
Products in queue
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Simulated production hour
Cranks X

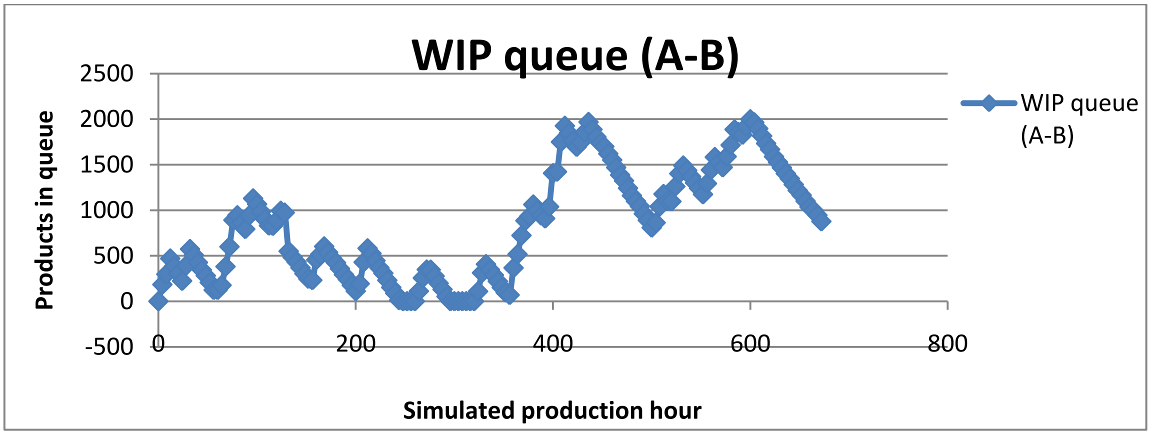

WIP queue (K-LM)
Products in queue
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (K-LM)

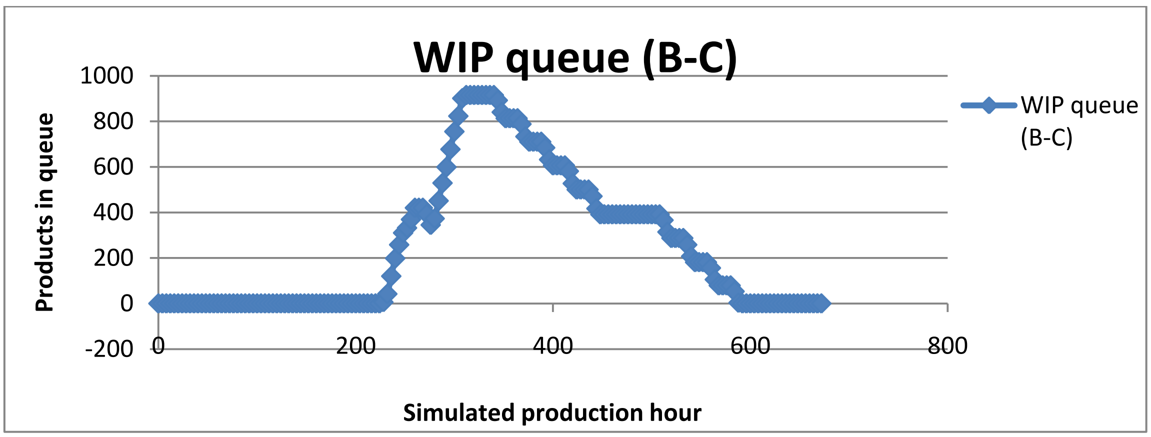

Beams FG
1000
800
600
400
200
0
-200
0
200
400
600
800
Products in queue
Simulated production hour
Beams FG

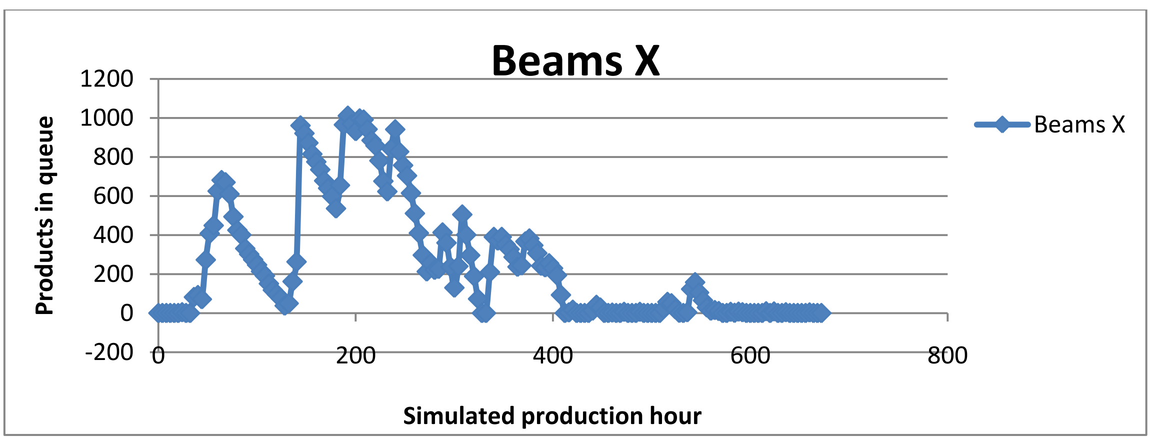

Cranks FG
3000
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Cranks FG

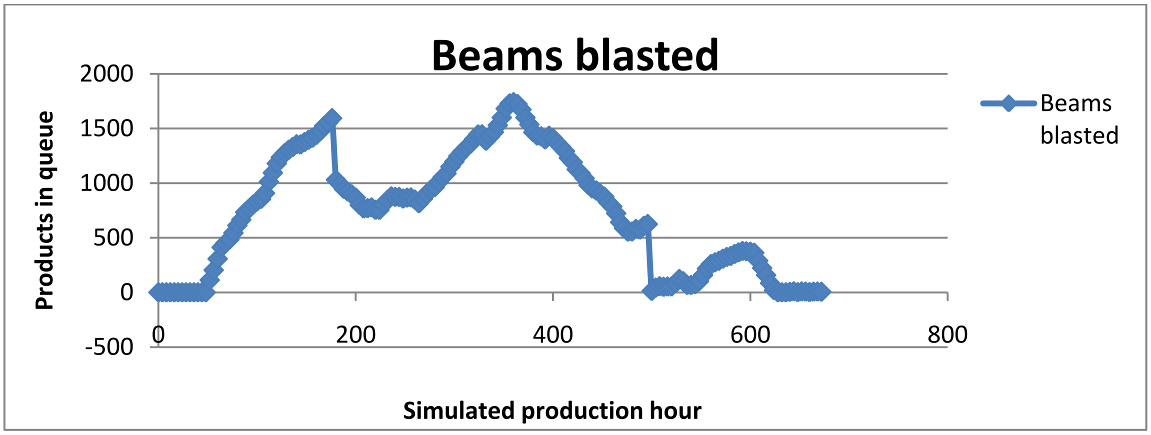

FG Total
3000
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
FG Total

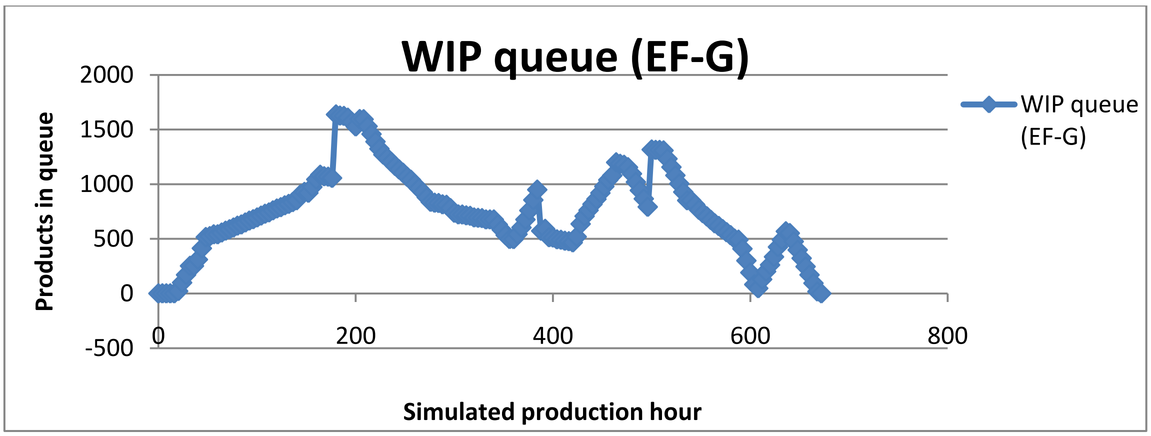
Version 9

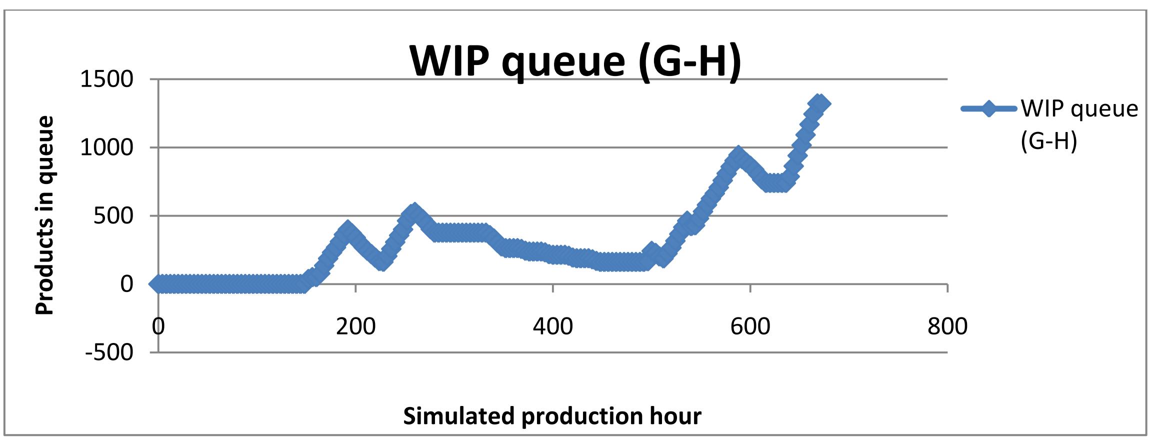

WIP queue (A-B)
Products in queue
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
WIP queue (A-B)

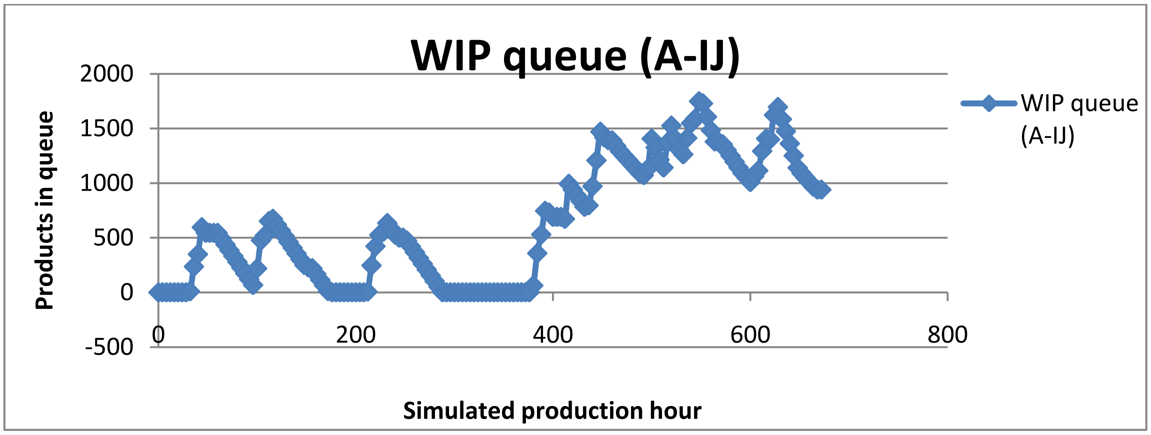

WIP queue (B-C)
Products in queue
1000
800
600
400
200
0
-200
0
200
400
600
800
Simulated production hour
WIP queue (B-C)

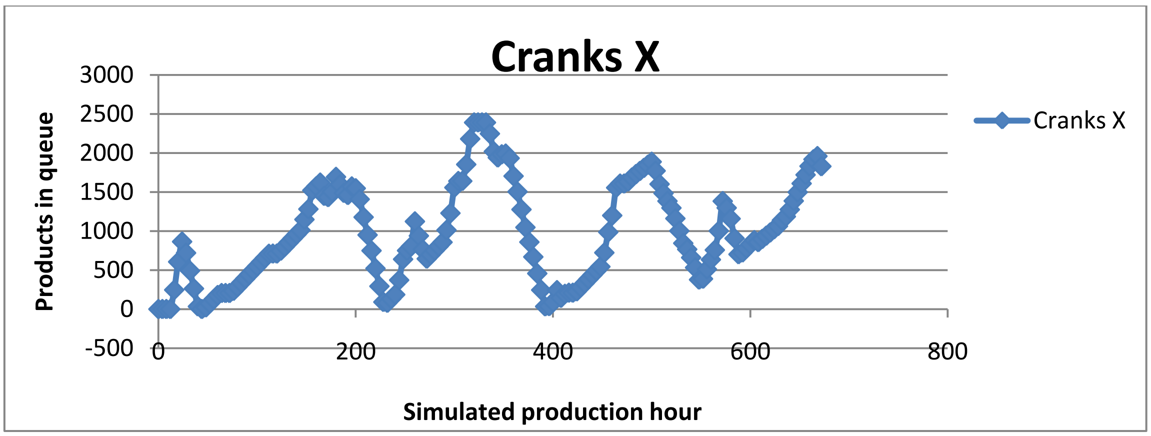

Beams X
Products in queue
1200
1000
800
600
400
200
0
-200
0
200
400
600
800
Simulated production hour
Beams X

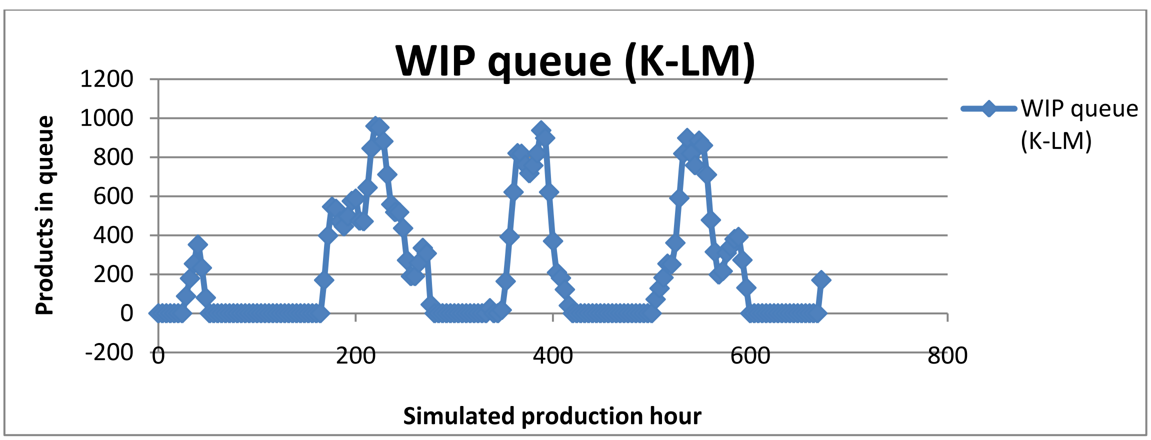

Beams blasted
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Beams blasted

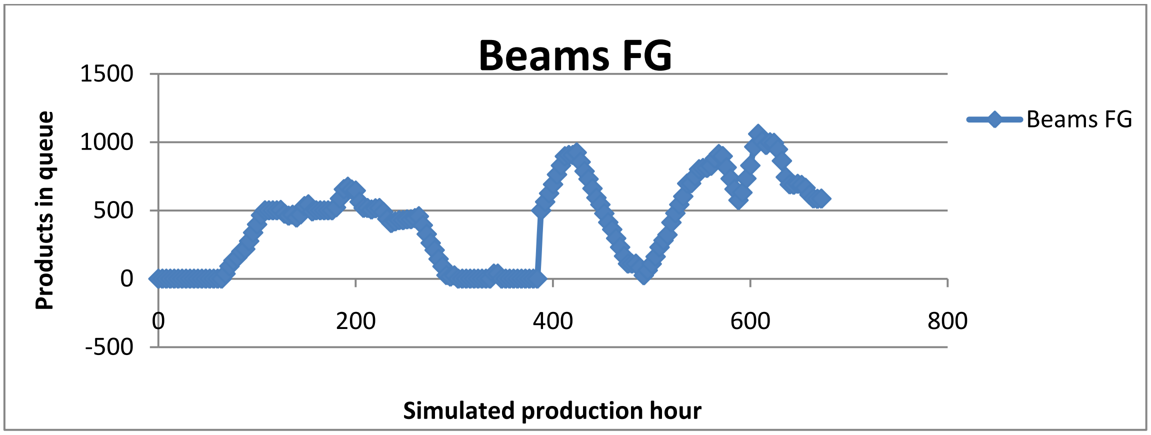

WIP queue (EF-G)
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (EF-G)

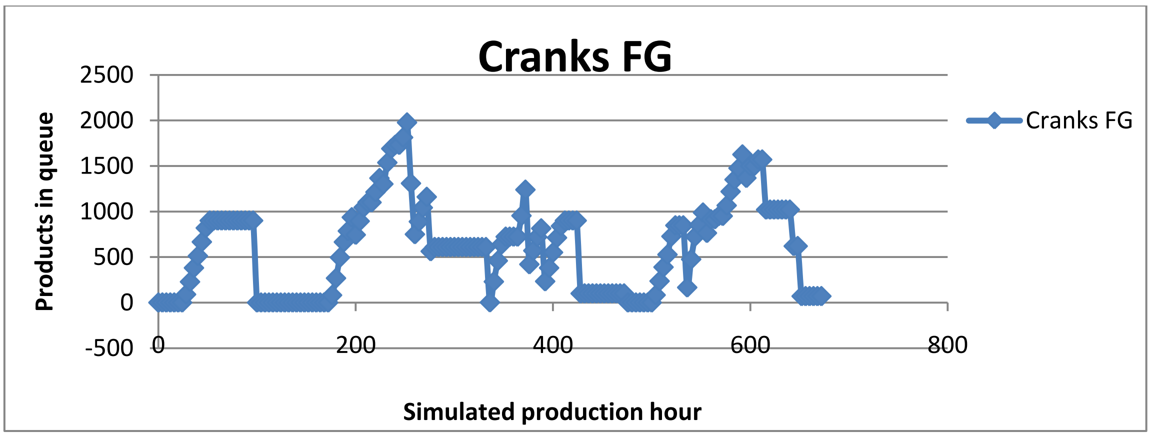

WIP queue (G-H)
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (G-H)

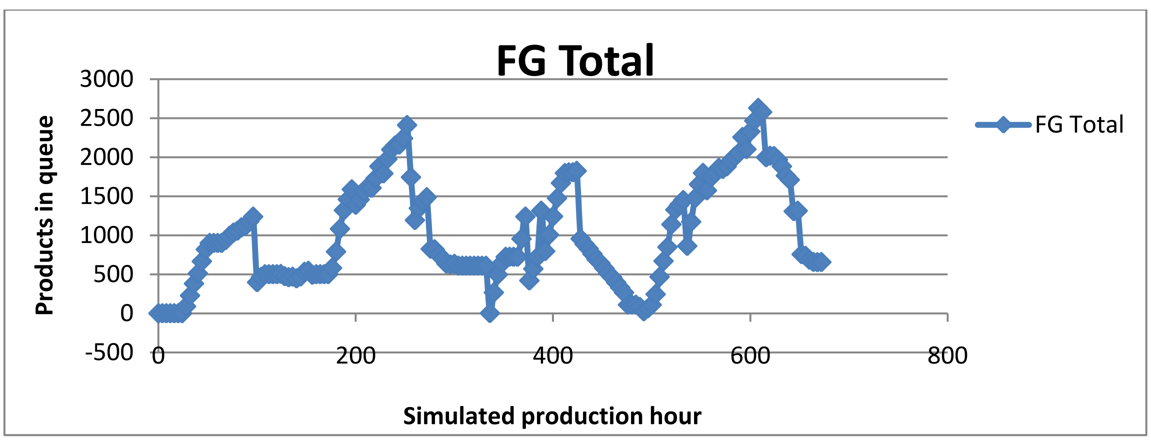

WIP queue (A-IJ)
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (A-IJ)


Cranks X
3000
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Cranks X

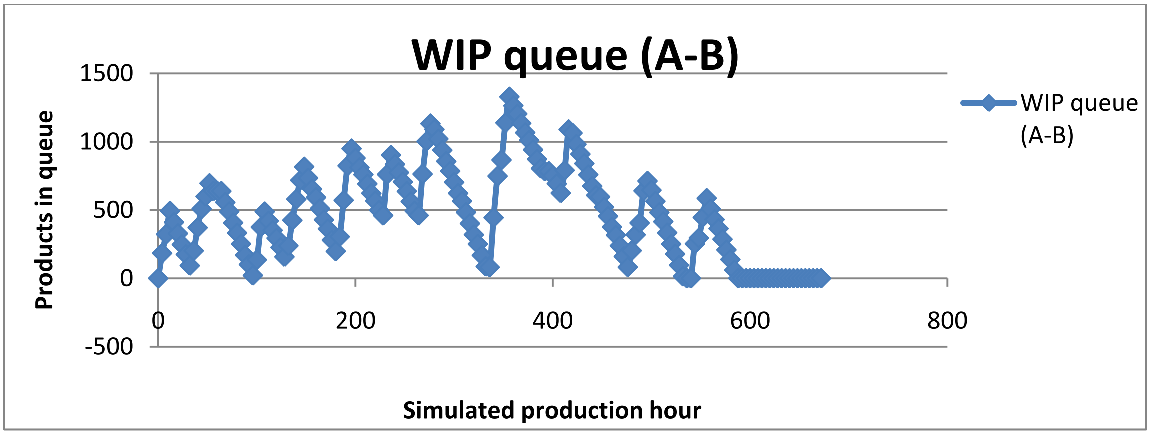

WIP queue (K-LM)
1200
1000
800
600
400
200
0
-200
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (K-LM)

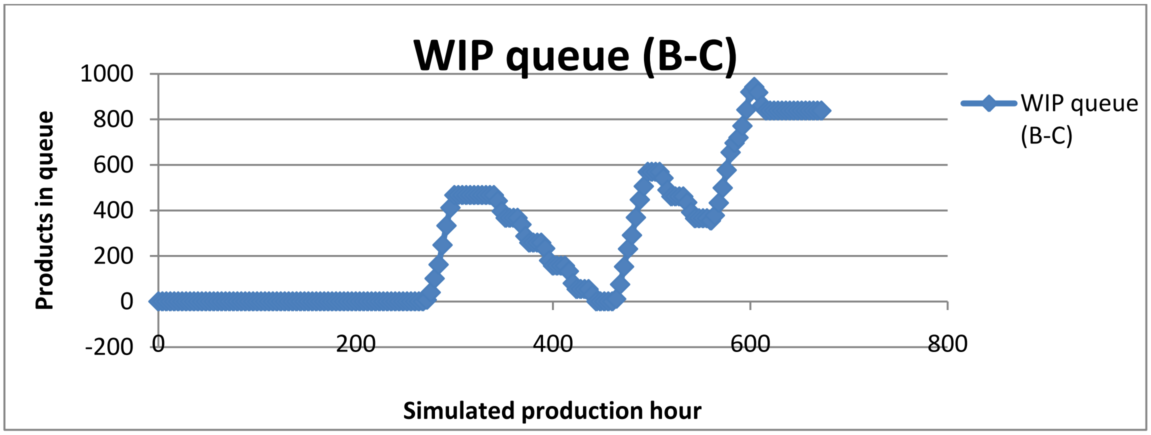

Beams FG
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Beams FG

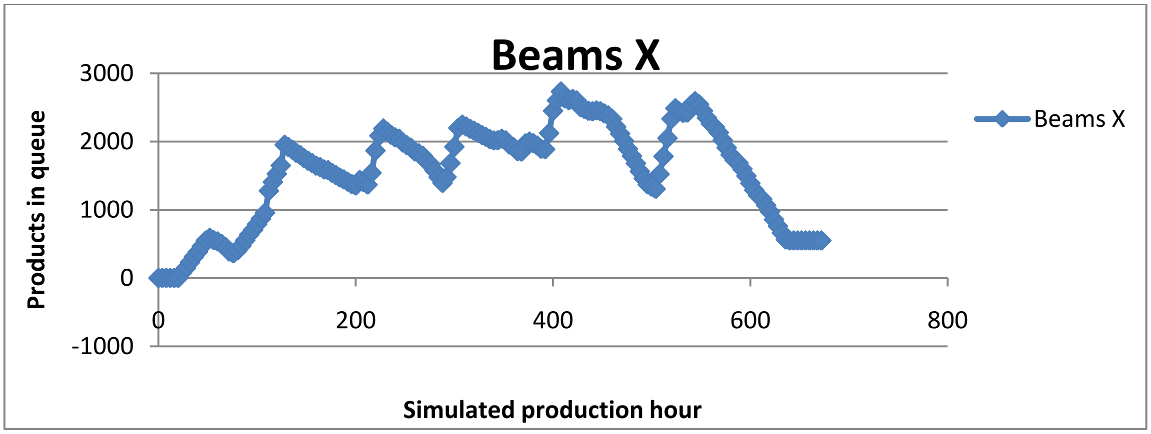

Cranks FG
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Cranks FG

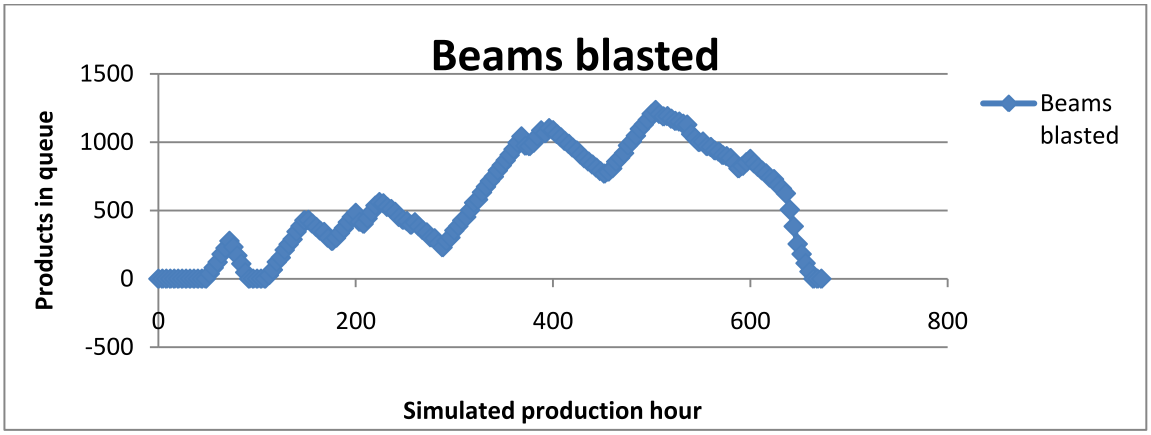

FG Total
3000
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
FG Total

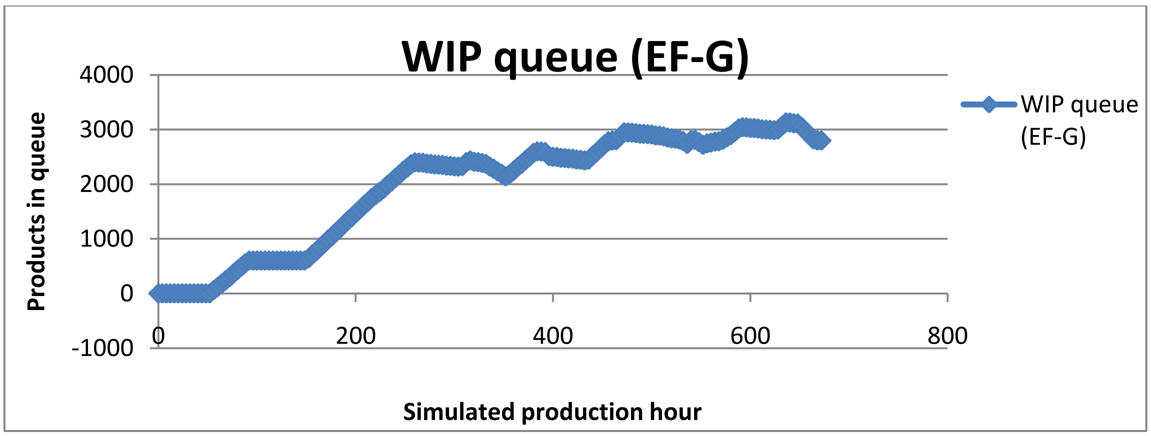
Version 12 – The gameplan

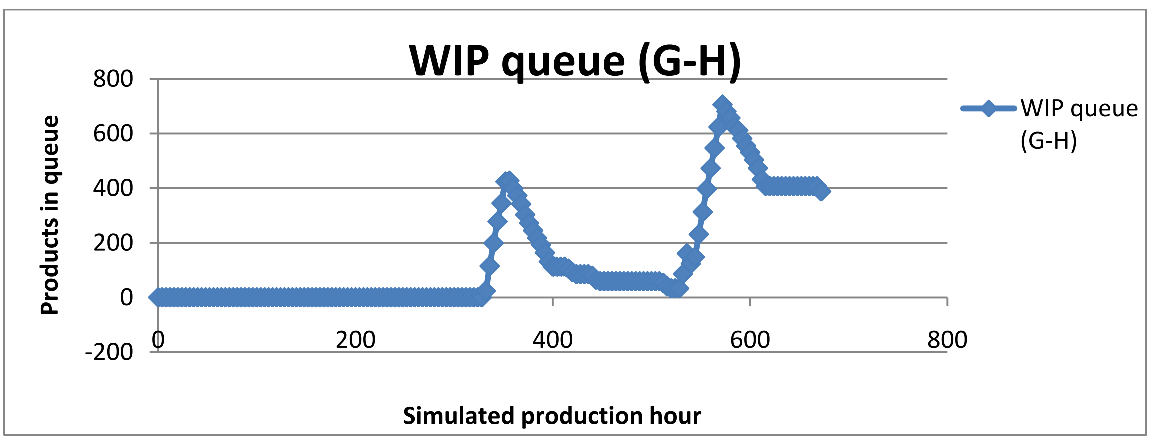


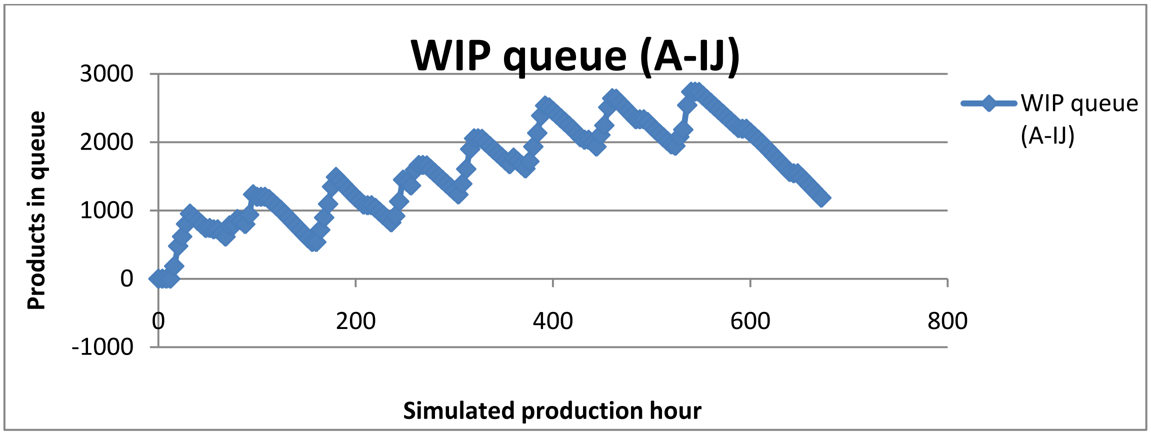


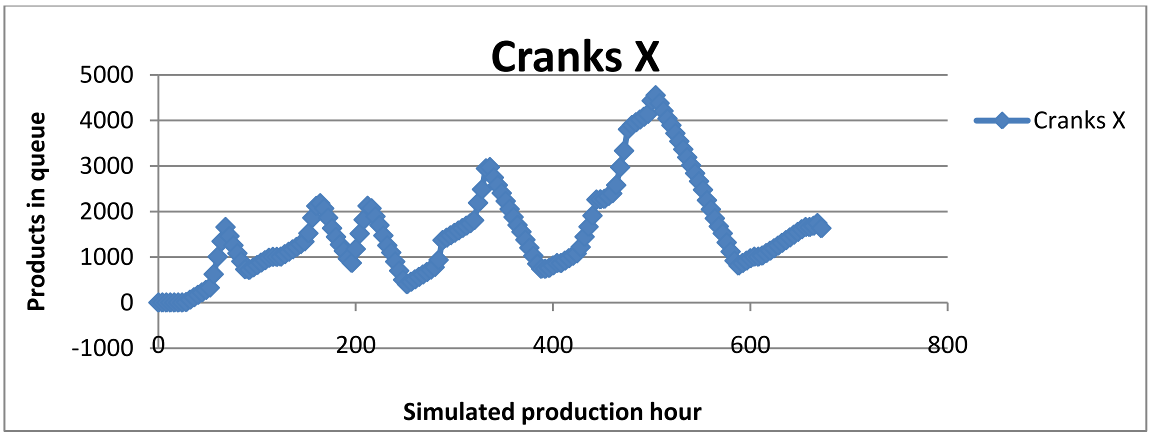


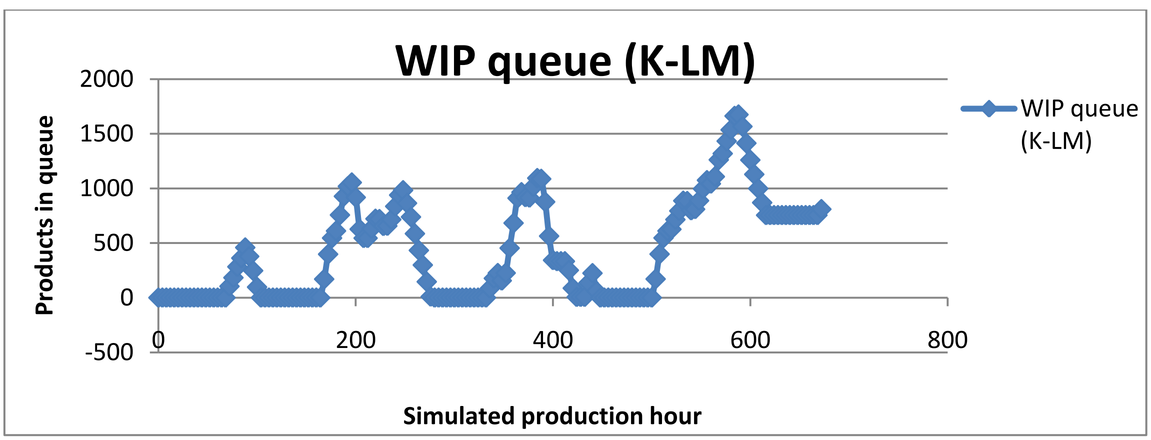

Beams blasted
Products in queue
1500
1000
500
0
-500
0
200
400
600
800
Simulated production hour
Beams blasted

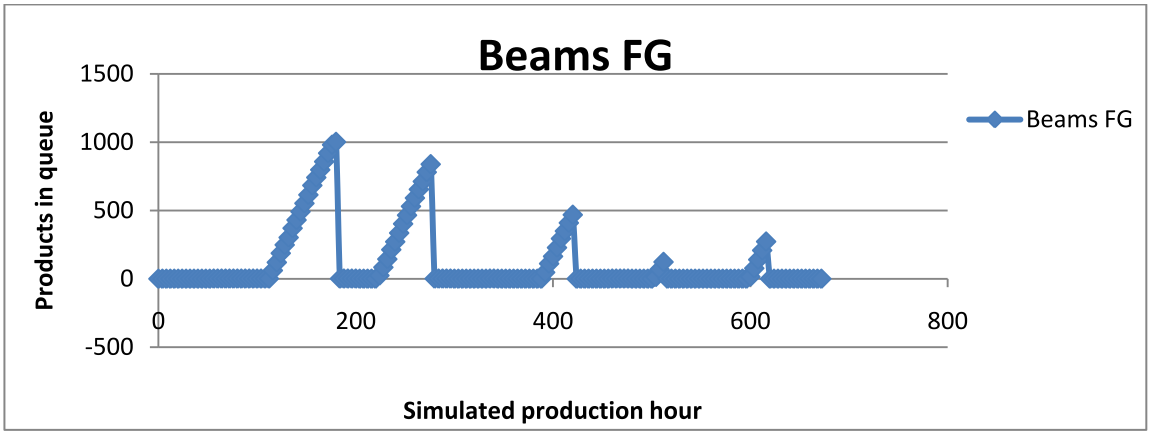

WIP queue (EF-G)
Products in queue
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Simulated production hour
WIP queue (EF-G)

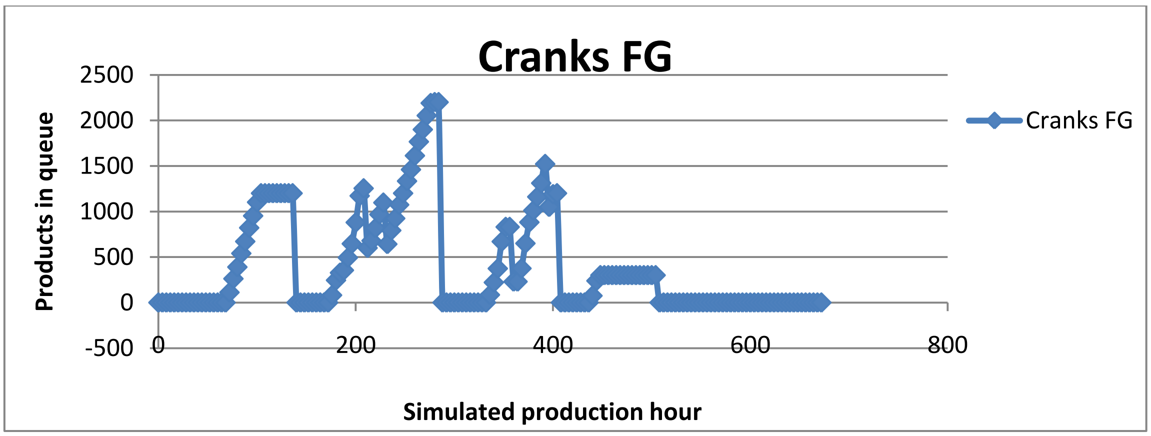

WIP queue (G-H)
Products in queue
800
600
400
200
0
-200
0
200
400
600
800
Simulated production hour
WIP queue (G-H)

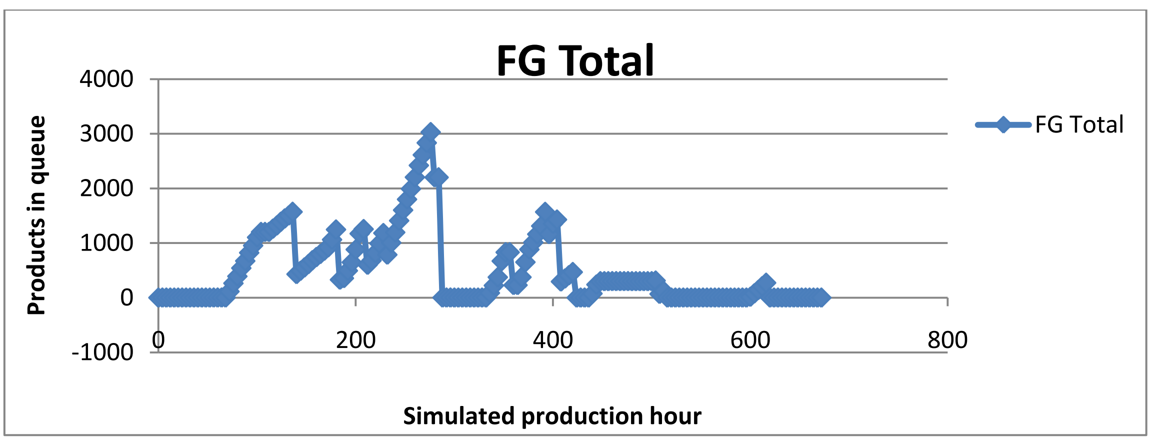

WIP queue (A-IJ)
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (A-IJ)


Cranks X
5000
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
Cranks X


WIP queue (K-LM)
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
WIP queue (K-LM)


Beams FG
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Beams FG


Cranks FG
2500
2000
1500
1000
500
0
-500
0
200
400
600
800
Products in queue
Simulated production hour
Cranks FG


FG Total
4000
3000
2000
1000
0
-1000
0
200
400
600
800
Products in queue
Simulated production hour
FG Total