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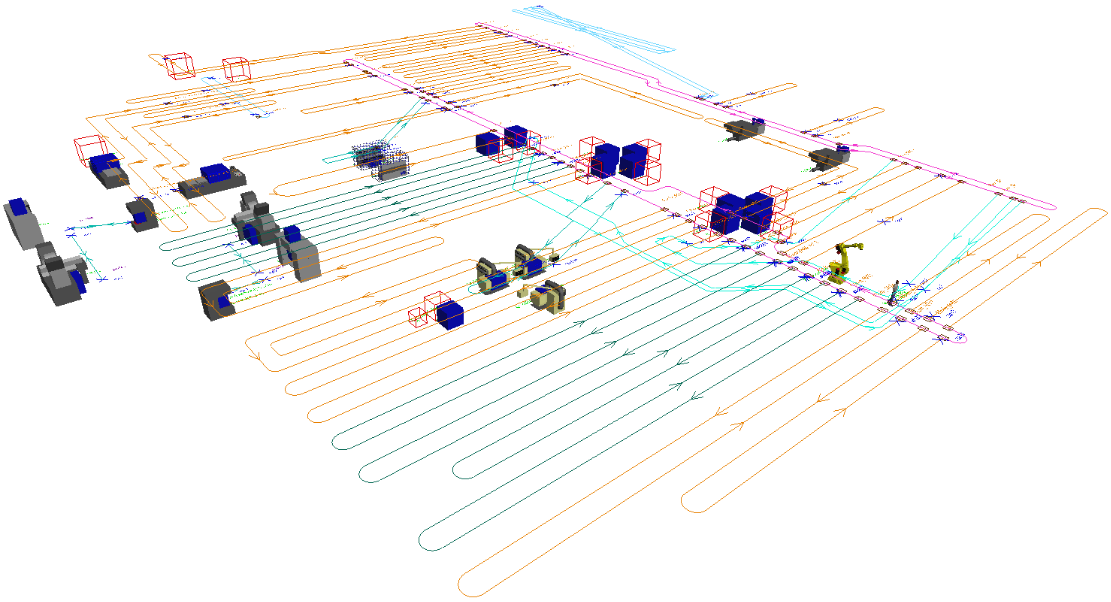

Simulation of Instrument Panels Production Process

Modelling a Digital Twin of the Production System and Improving the System Through DES

Master's thesis in Production Engineering

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Gothenburg, Sweden 2019

MASTER'S THESIS 2019

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Cover: Instrument panel production system model constructed in AutoMod showing the machines, operators and the conveyor system.

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Abstract

International Automotive Components (IAC) has always kept up with the advanced technologies and now aspires to simulate the production system expecting ways to improve it. A production system is very complicated due to several governing factors and planning improvement in the production is a meticulous process. With simulation, the engineers and the managers get a better picture of how a change in the production is going to affect the system. The purpose of this thesis is to help the company improve its production with the help of simulation and answer some of the "what if" questions pondered by the management. The thesis work is confined to company-specific objectives and delivers the results and reasons from the simulation. This thesis develops a Discrete Event Simulation (DES) model for production-related investigations and deriving conclusions to the ideas. The DES model is a digital twin of the factory, built using AutoMod following Jerry Bank's methodology. AutoStat is used to simulate a scenario for several iterations considering many events within the system.

Results of this study are analyzed and provided in terms of the throughput time of the products and the utilization of resources. Detecting bottlenecks and suggesting improvements has been an important activity. A general remark from the thesis is that any change in the production facility is escalated and easily comprehended using a DES tool and simulation is therefore viewed to be a very useful tool to improve a production facility.

Keywords: AutoMod, Bottlenecks, Digital Twin, DES, Jerry Banks methodology, Simulation.

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Abhishek Shetty and Gagan Kumar, Gothenburg, August 2019

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Introduction

This chapter will introduce the project background, followed by the purpose and objectives of the thesis, concluded with scope and delimitations.

1.1 Background

With the advancement in technology and the gaining popularity of Internet of Things (IoT), the digital twin of a physical system is now a matter of contention in every major production plant. The ever increasing demand to streamline a production system and achieve high productivity is one of the reasons why many companies turn to the simulation of their production system. This thesis deals with one such aspiring company IAC and in improving its production process using simulation.

Today, one of the leading Instrument Panel (IP) manufacturer - IAC Group AB in Gothenburg has a very complex production system in terms of the process flows, product variants, buffers and various call-off processes. The Manufacturing Execution System (MES) manages the necessary buffering driven by various tool changes, product consumption, machine status and a call-off process in the various process steps to be flexible enough in terms of surrounding processes, material availability and controlled flow patterns. Some flows are directly controlled as “First In First Out (FIFO) flow” while some are dynamic in nature meaning a sorting happens within a buffer and IP’s are called off in a particular sequence, which makes the system more complex.

Eton system provides the material handling solution to IAC with an overhead conveyor system. All the IP’s are picked up by the hooks from a pickup point, carried into an overhead buffer and retrieved at a drop-down point when necessary, after which the empty hooks move to a designated location. Each of this physical phenomenon is translated into a digital model in AutoMod. However, with as many as 48 IP variants and a daily based customer demand, it is a challenge that IAC faces everyday in meeting the fluctuating requirements with very less scope for errors. IAC currently faces a rigorous challenge of meeting every day customer demand in producing the 48 variants of IP’s. Arriving at better buffer capacity condition, utilizing the available resources more effectively thereby increasing productivity is what IAC seeks to ponder upon.

1.2 Purpose

The purpose of the thesis is to improve the production system of IAC by making the instrument panel production process more efficient through simulation. Improvement in the system in terms of buffer capacity, resource utilization, sequential flow of parts and streamlined production will be the target points. It also serves to identify the extent to which DES can be used in solving real industry problems and to learn how efficient and reliable the solutions are.

1.3 Objectives

The thesis is planned and the simulation model is designed and executed to achieve the following three objectives:

1. **To estimate the optimum number of hooks required in the conveyor system.**
   In order to achieve a particular production output, identify the minimum and the maximum number of hooks/product carriers in the conveyors required to run a particular production plan.

2. **To study the effects of changing the foaming machine combination.**
   Out of the ten available foaming machines, currently, six of them are used to produce V526 IP variants while four of them produce V54X IP variants. To study what if the combination is 7:3 instead of 6:4 in terms of throughput time and machine utilization.

3. **To study the effects of an additional Flaming Robot.**
   The idea is to invest in a new flaming machine, which is currently a bottleneck machine. To study how good this idea is in terms of throughput time and machine utilization.

1.4 Scope

The focus of the thesis is to build an accurate DES model resembling the real production plant and use this model to improve the production system of IAC. The results from the simulation will aid in decision making at IAC and support in converting the ideas into reality.

1.5 Delimitation

The simulation is conducted to produce a fixed production output, that is 709 IP's, representing a particular day's production at IAC. Therefore, it is the throughput time and machine utilization that will be the improvement parameters. The thesis will be executed with a particular production plan by the authors to run the model that may not exactly match reality. However, the model is flexible to accommodate new production plan. The frequency of tool changes in machines will vary compared to reality. The output of the simulation is concerned only for one particular day's production and all the conclusions made are subjected to the particular production plan for the particular day. This thesis is limited to build and identify the best improvements in the simulation model that can be implemented in the real production system of IAC. This thesis does not include any cost analysis for the improvements done in the production system and the simulation concerning only the instrument panel will be executed. The thesis work is limited only to identifying the bottleneck machines and not improving the bottleneck machine/ eliminating the bottleneck.

2
Theory

In the following section, the theory behind the thesis work concerning manufacturing system, simulation and bottleneck identification are explained from the literature study done.

2.1 Discrete Event Simulation

Simulation always deals with a complex problem that cannot be solved using simple mathematical models because the problems are dynamic and there are elements of uncertainty. Based on the kind of the problem that the simulation is supposed to support, simulation can be divided into managerial/strategic or technical. The technical simulation includes mostly plant operational problems arising from engineering area and can be supported by technical simulation as a part of a digital factory. Simulation to solve the technical problem can further be classified into process-oriented and machine-oriented. Process-oriented is a complete production process simulation aimed to support or improve a specific process in terms of Key Performance Indicators (KPI), Overall Equipment Effectiveness (OEE), cycle time, etc. Figure 2.1 shows some of the reasons to do process simulation. Machine oriented simulation, on the other hand, is concerned with individual machines, resources or cells. One could explore the limits of the resources thereby ensuring process stability (Lachenmaier, J.F. et al., 2017).

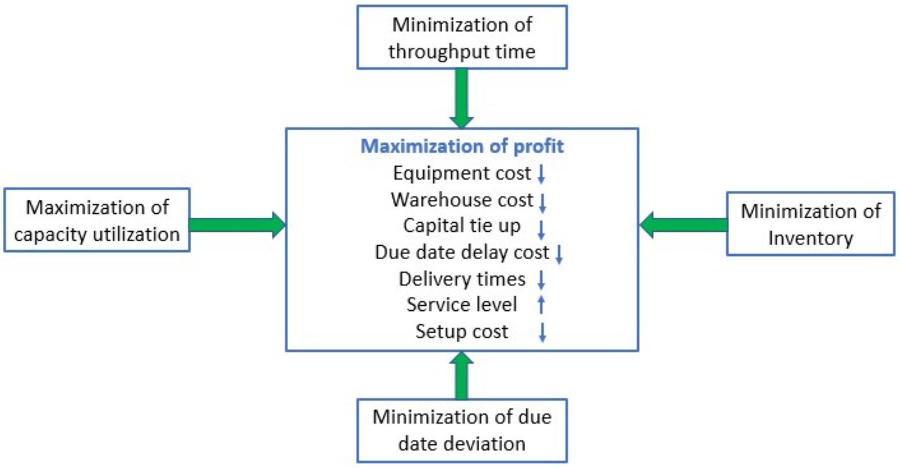


Figure 2.1: Goals of process simulation (Lachenmaier, J.F. et al., 2017)

In the food processing logistics and distribution system (Sun, X., 2014), a convenience food sorting system has been modeled in the automod simulation software. The large number of variants in the production system needs a sorting system to deal with customer demands for a specific product. From the paper Sun (2014), it's seen that IAC is focused on similar sorting simulation model in sorting the variants of instrument panels.

Why Simulation?
Advantages:

- Experimentation without disturbing the real production system.
- Visual and pedagogical.
- Considers the system dynamics.
- Quick analysis.
- Exploring possibilities, constraints, improvements.
- Making wise decisions, investments and specifying requirements.
- Combines problem identification and finding solutions.

Disadvantages:

- Model building requires special training.
- Time consuming: trade off between time/cost and possible profits.
- Difficult to interpret simulation results.
- Gives a precise impression despite possible problems.
- Human decisions are difficult to model. (Banks, J., 2004)

2.2 Digital Twins

A digital twin is a real time connected, digital simulation model of an actual product, process, social infrastructure or system of the same (ÅF-Digital Twins Level, (2019). Simply put, it is a digital copy of a physical system.

Sameer Kalwani in the article "The Evolution of Digital Twins for Asset Operators" classifies the digital twin maturity into six stages based on the data processing, as seen in figure 2.2. Concerning the thesis, stage 2 and stage 3 maturity is of interests. Stage 2 is an operational twin or a simulation twin like the AutoMod model built. It is built with historical data with primitive data integrity. A more mature twin model allows flexibility, high fidelity and real time data integrity supporting general purpose analysis (Kalwani, S., 2019).

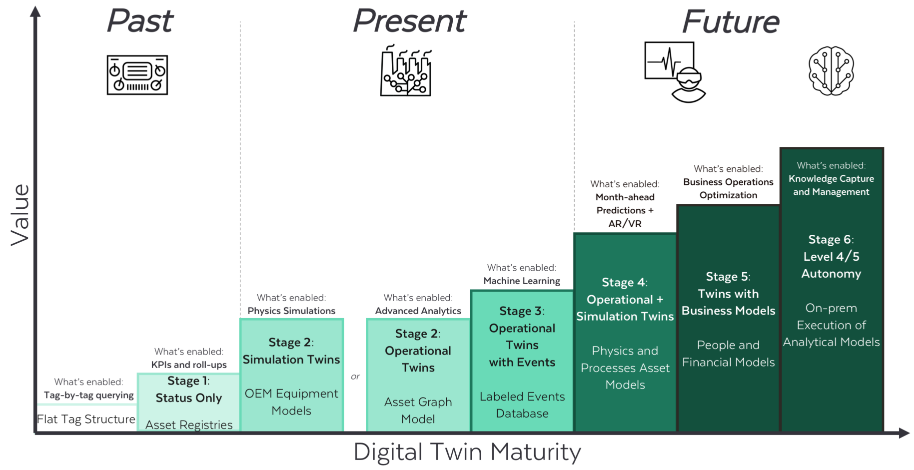


Figure 2.2: Digital twin maturity (Kalwani, S., 2019)

More specific to the manufacturing industries are the six levels of digital twins described by ÅF as seen in figure 2.3. The base of this hierarchy is a digital model of an asset, unconnected to a real entity. It is used under assumed conditions to design and simulate how the object responds to different scenarios. The level 1 twin is smarter as it is connected to the real entity in real time. These kinds of digital models describes the actual process and presents the results to the user in a value-based way. The level 2 digital twin aids in entity diagnosis. A smarter level 3 digital twin can forecast and calculate the states of resources, such as reduced functions, downtime, etc. From this outcome, optimal use of the object can be achieved which minimizes the costs and maximizes the return of any necessary investments. With built-in AI, level 4 digital twins are very intelligent. The digital twin learns from its experiences and proposes actions, for example on the performance enhancement of machines. The highest level of digital twins takes its own decisions and handles the object itself. Machine operators and other employees are of lesser/no service here (ÅF-Digital Twins Level, 2019).

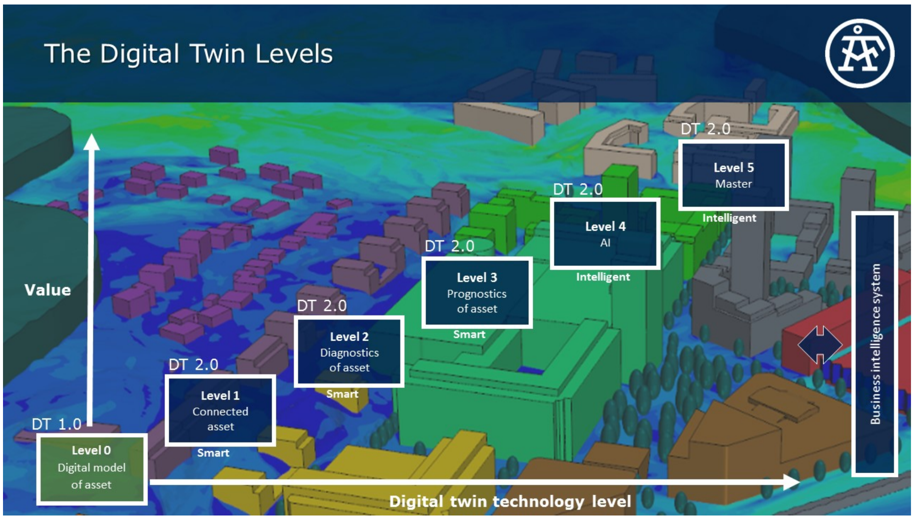


Figure 2.3: Digital twins levels by ÅF (ÅF-Digital Twins Level, 2019)

It is clear from the above two excerpts that the current model built for the thesis purpose is a very basic digital twin, which could be the first step for IAC towards smarter manufacturing industries.

2.3 Flexible Manufacturing System

Simulation is a well-proven method to design and analyze a Flexible Manufacturing System (FMS) (Chen Z. & Jiang C., 2011) and IAC happens to have a FMS. Automated Storage and Retrieval System (AS/RS) provided by Eton to IAC is required to be accurately captured and modelled in the simulation. Many random factors such as machine failures, sorting, rework and scrap makes the system even more complicated. This FMS is a typical discrete event system and simulation is a suitable method to analyze FMS. The work by Chen and Jiang (2011) have used AutoMod to model the pallet flow that uses Radio-frequency identification (RFID) which in turn is integrated with the MES. This work affirmed the option of using AutoMod for this thesis. The case is very similar to IAC production system where each IP has a RFID tag in it and its movement is tracked which allows the MES to suggest the machines what kind of variant to produce next. A FMS with high throughput will have large in process data stored in MES and appropriate measures were taken in advance to acquire all required data before the model building phase was started.

The work "Hybrid simulation-based optimization of discrete parts manufacturing to increase energy efficiency and productivity" (Sobottkaab, T., et al., 2018) considered simulating the actual production line for rolls in an industrial bakery plant. The plant in this study has a lot of similarities with IAC. Though the simulation by itself is not much related to the thesis scope, the process followed here is a matter of interest. The plant consisted of different machines, conveyors and storage systems. Different material flow variants were having different process parameters like processing times on machines under different scenarios. The base model of the plant was depicted first with the help of a conceptual model. The production run and analysis were tested for three seasons in 2016. Although the simulation has been conducted for three seasons, the presentation of results focused on one-day scenarios to reduce the time taken on simulation evaluations. Likewise, this thesis is based on a similar kind of production plant with various process parameters and product variants under different scenarios. The base model of the existing plant is built first using the conceptual model. This base model was then altered to suit the different objectives. The case study focused on developing a novel planning tool that increases the general performance of the production system and makes it an integral part of the MES. This idea is developed in drafting a production plan for IAC which also is an integral part of the simulation model. Therefore, the developed simulation model for IAC includes a provision for the production planning and this planning largely affects the system output. Since the production planning feature is integrated into the simulation model and plays quite a crucial role in the execution, it was duly noted during the model building phase (refer chapter 3.1) to make the feature as user-friendly as possible and easily editable for future uses or alterations.

2.4 Bottleneck Identification

The idea behind implementing simulation is to visualize the considerable improvements in the industry in identifying the bottlenecks in the production line. Identifying the constraints also known as bottlenecks in the production systems is of prime importance for a plant to operate at full potential. These constraints limit the throughput of the system and there are standard methods for identifying the bottleneck machines.

There are three conventional bottleneck detection methods: utilization, the waiting time and the shifting bottleneck, (Roser, C., et al., 2003). The shifting bottleneck machine method is considered to be the best and most accurate method of bottleneck detection. For any simulation scenario, the utilization method of bottleneck machine identification was believed to be suitable from the study by Ericson, A., (2017). Utilization simply means the amount of time a resource is being used. In other words, a machine is said to be utilized when it is not idle. It is generally expressed as a percentage of the time. A machine with the highest utilization is most likely to be a bottleneck machine. Simulation and utilization method of bottleneck detection are interlinked since it is easy to get the machine utilization figures, average queue sizes and machine failures through simulation. The study also mentions the downside of using the simulation for bottleneck identification that a model is never a true copy of a factory and wrong assumptions or misinterpretations can misguide anyone. Also, the factory today may not be the same tomorrow since the production system keeps updating and hence investing time in simulation model may not be worthy.

2.5 Literature Review - Simulation in Production

Literature review formed a strong base to conduct the thesis. Concepts of production system, data collection and simulation was understood by reading well established articles, journals and books. Literature study was conducted to understand and establish the need for simulation, the type of simulation model to be used and ways to improve a production system.

Simulation of production systems or factories is in general used for the analysis and improvement of the production activity and to support product development and production management. The main principle of simulation is the emulation of an existing or planned system and its behavior over time by using an approach (Schönemann, M., 2017). The simulation of Instrument Panels at IAC production system is relatively complex which has quite similar challenges analyzed in the book "Multiscale Simulation Approach for Battery Production Systems" by Schönemann, M. Battery systems consist of different components which relate to different production stages each of which has specific requirements in production (Schönemann, M., 2017). Likewise, IAC production system has a greater number of product variants that causes the production system to have different components that are essential in production processes. There are four main simulation approaches that can be used to model the desired system behavior (as cited in Schönemann, M., 2017). They are discrete event, dynamic systems, agent based and system dynamics.

From the same book “Multiscale Simulation Approach for Battery Production Systems”, lots of findings are compared with the simulation in this thesis and suitable solutions are being implemented to overcome the challenges. A very important challenge in building a model is collecting the required details or data of models. The digital twin approach aims at combining a real-world system with a virtual duplicate (Schönemann, M., 2017). Very detailed models contain many objects and cause effort in development and maintenance. Very simplified models bear the risk of being too coarse and not sufficiently accurate for the given planning task (Schönemann, M., 2017). Other challenges are related to the clear definition of the simulation study objectives, the participation of all involved stakeholder, and availability of required know-how and skills, selecting of a suitable simulation tool, as well as sufficient validation (Schönemann, M., 2017).

Just like the battery production has different production stages, Instrument panels at IAC undergoes many different production processes. Cell production is characterized by sequential process chains with specialized processes. In addition, cell production makes great demands on the environmental ambient conditions such as temperatures, humidity, and cleanness which requires specific building equipment (Schönemann, M., 2017). Likewise, IAC has demands on the environmental ambient conditions for foaming process especially when it rains. The moisture content will result in producing the defective product in the foaming process. In this thesis, the environment condition will not be considered and is independent of the simulation results. The simulation of Instrument panel in particular shall consider the utilization of machines, machine breakdowns, the lead and cycle times of jobs, the output of finished product units per time, quality rework and scrap rates. Furthermore, the simulation must consider the influences of product variants on processes and the material flow (Schönemann, M., 2017). Specifically, at IAC it is a must to consider the product variants as it is in huge number and it has so much influence on the simulation study in order to determine the output and utilization of the production systems.

3

Methodology

This chapter is about the various methods used in building the simulation model and also in executing the project. It describes the different phases in the thesis that were planned and delivered.

3.1 DES Method

The digital twin of the complex IAC production system is built based on Jerry Banks model which is a standard method that guides a model builder to accomplish the project. This scientific method aids to design a system with uncertainties resulting in the creation of a very accurate digital twin. Following flowchart shows the standard steps to be followed in a simulation study.

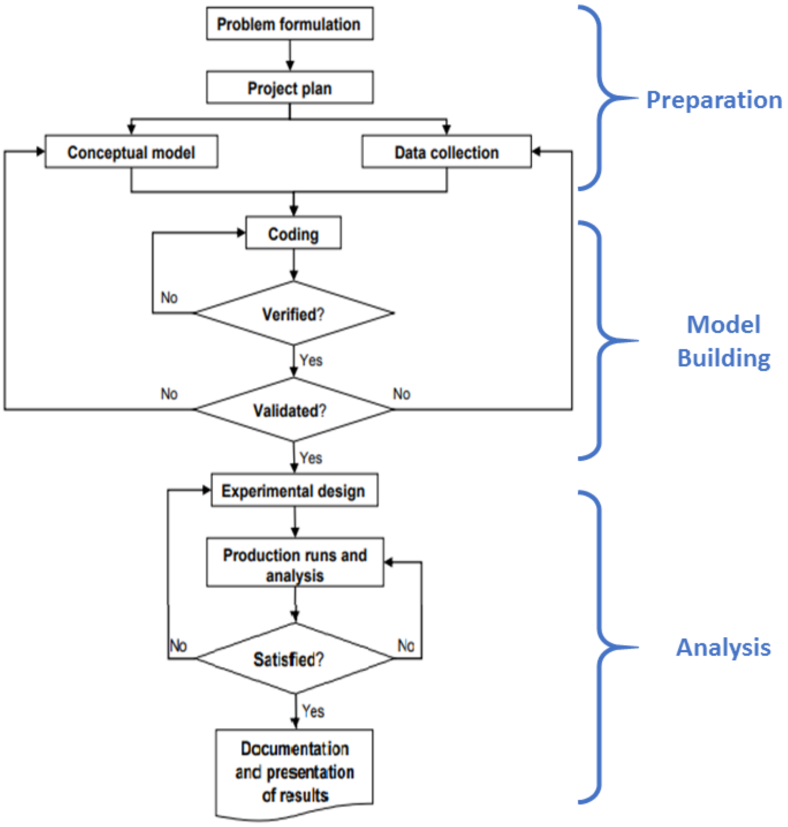


Figure 3.1: Jerry Banks model - steps in simulation.

1. Problem formulation.
Defined problem statements were handed over by IAC in the beginning. However, the problems were reframed to suite the academics interest and the available time.

2. Setting objectives and overall project plan.
Once the problem was defined, project plan particular to the simulation was drafted. The defined objectives created various scenarios that required to be analyzed while building the model. An overall project time plan was prepared, followed and tracked by a set of milestones that are achieved eventually to reach the target.

3. Model conceptualization.
With the defined plant layout of IAC, a conceptual model was prepared that represents the plant operations as a flowchart (Refer Appendix A). A conceptual model is a series of mathematical and logical relationships between the model entities (Banks, J., 2004). Parameters like cycle times, MTTR and MTTF, time for tool changes, set-up times, scrap rates, production schedules, working hours, etc are collected and presented in the conceptual model.

4. Data collection.
Conceptual model building and data collection were done in parallel involving several interviews. To build the conceptual model a list of data requirements was submitted. It was essential to have all the data in the right format that are fed into the conceptual model. The data obtained had to be filtered, sorted and refined to the requirement. For example, the data of machine breakdowns was delivered as the number of times that a machine had broken-down and total downtime in a month. This is something that must be in MTTF/MTTR value to be used in the model. Therefore, this data was refined as required for the simulation.

5. Coding.
Refering to the conceptual model, the base model is coded in AutoMod so that the model imitates the real production system. Power and free system was used to model the interactions between the conveyor system, machines and loads. Path mover system was used to model the interactions between the operators and the machines. This operational model was built, verified and validated to check if it behaves as expected.

6. Verified?
It is highly advisable to begin the verification process as a continuing process throughout the model building process (Banks, J., 2004). Hence the code was verified continuously after every update in the model. This helped to cross-check whether the code written for the base model corresponds to the existing system of IAC. According to Jerry Bank, there are several ways to perform verification of the code. The built code was reviewed by both the authors. The AutoMod Debugger was used to verify the codes line by line. It elevates the presence of any errors. Also, complete animation was reviewed to have a better picture of the material flow.

7. Validated?
The verified model was then validated to see how close the model represents the real production system. Since the base model is built for the existing system, the sensitivity of the model is analyzed by changing the model input to get the desired output. The count of IP's produced in a day and the time and sequence in which they were produced at IAC and the respective similarities in the simulation model provided credibility to the model built. Even the animation of the base model was used for validation.

8. Experimental design.
The operational model has got different entities that can be varied during the experimentation stage. In the experiment, the length of the simulation run was set to a total output of 709 IP's which indeed was the production output of IAC for a particular day. At least 20 iterations were run in AutoStat for each experiment. Vary single factor analysis and Single scenario analysis were performed. The AutoStat is used in the experimentation to find the combinations of factors such as minimum and maximum hooks, a combination of processing machines, etc.

- Experiment Objective 1:
Run the simulation model with no scrap and no machine failure, resembling an ideal production condition. This will yield the minimum number of hooks required. Run the simulation model with higher scrap and higher machine failure resembling a bad production condition. This will yield the maximum number of hooks required, since the IP's now require a longer duration of time to reach the end of the line.

- Experiment Objective 2:
Change the foaming machine combination from 6:4 to 7:3. Change the material flow to the foaming machines as well. Compare the throughput time of each IP and the machine utilization.

- Experiment Objective 3:
Create a new flaming robot. Introduce another station for the robot and a dedicated conveyor line to it. Keep everything else the same and run the simulation. Compare the throughput time of each IP and the machine utilization. Use utilization method of bottleneck detection to identify the new bottleneck machine.

9. Production runs and analysis.
Based on the scenarios coded in the base model, production runs are used to estimate measures of performance that are being simulated (Banks, J., 2004). AutoStat has got the option to vary single to multiple factors in the programming code. The results are further analyzed and compared carefully.

10. Satisfied?
If the obtained results are deviated and dissatisfied, more production runs are needed, and the scenarios need to be altered accordingly before the next production runs begin.

11. Documentation and presentation of results.
From the beginning of model building until its completion, simulation analyst would have gone through the same code so many times to modify or correct it. It is necessary to document the model so that it can be helpful for the analysts or the other stakeholders to understand how the model operates when being run. Proper code indentation helps readers to understand the structure and the logic of the program (Banks, J., 2004). It is likely to have a successful implementation of the simulation results when the client is involved throughout the simulation study (model building).

3.2 Model Building

To begin with the model building phase, it was ensured that sufficient data has been collected and transformed to the required format if it was not delivered as anticipated by the company. The objectives of the thesis were redefined during the simulation study with the involvement of the supervisors. This was made specially to carry out the simulation study smooth during the complex model building. The base model is then modified to obtain the objective specific models. It is this base model whose results are compared with that of the objective specific models and conclusions are drawn from the comparisons. Since the study of the model behavior at IAC is discrete i.e., specific change in the system state variables at a specific point, DE (Discrete Event) approach has been used. This indicates that the DE approach simulates the dynamic behavior of the production system instead of continuous behavior.

The simulation in this thesis is a complete technical package involving both process-oriented and machine-oriented simulations. While the first two objectives stated in chapter 1.3 are more process-oriented, the third objective is completely focused on flaming robot capacity, thus making it a machine-oriented problem. It is evident that the goals of process simulation for the thesis regarding (Lachenmaier, J.F. et al., 2017) figure is minimizing the throughput time and maximizing the capacity utilization and hence all the results presented in this thesis are in terms of throughput time and resource utilization. Comparing these two parameters from each of the simulation run done in one of the study course project will thereby help in evaluating how the system behaves when a particular input is varied. Choosing the best system setup will accomplish the goals of the process simulation.

Since IAC deals with several variants of the panels depending on the car model, customer needs and other features, sorting the panels and sending them into the right conveyor lines is quite important. While some sorting operations require time and manpower, sorting the parts will ensure integrity and efficient operation of the system (Sun, X., 2014). This will help in deciding the right amount of buffer level and the right amount of product type in each buffer, which also is the main condition to be included in the simulation model. But the paper mentions the usage of only AutoMod which produces less accurate results since AutoMod run is only for one particular case. Therefore, AutoStat will be run in this project for more precise results, thereby considering all the random events like Mean Time To Failure

(MTTF), Mean Time To Repair (MTTR), rework rate and scrap.

The two main features of the base model built for the thesis are flexibility and dynamics. Since the thesis serves a purpose to analyze production for a particular day, it was important to include the production plan for the particular day. It was more important to build the model flexible such that the production plan could be altered easily accommodating other ideas and run instantly to obtain the results. This is done by asking the program to read many external files (.txt files) that is easily editable and comprehensible by anyone. The built model for the thesis needed to be very dynamic in nature. Any production plan is subjected to constant change and this case is no different. Adding dynamism into the model makes it more realistic, depicting some random events that are not controllable/inevitable. There are three random events in the model as below:
Rework station cycle time = normal distribution (15,2) minutes
Reworked part = 15% of total IP's produced
Scrapped part = 2.25% of total IP's produced

The numbers for the random events are derived from a random production week's record. The random events are governed by the software and the software chooses the values from the given range. AutoStat simulates different random events during each iteration. AutoStat runs are made to make sure the results obtained are from these random events where many combinations are considered. Therefore, more the runs done, more accurate is the result obtained. However, running too many iterations is time-consuming. With so much complexity and flexibility in the model, it was taken care to make the base model user-friendly. Both editing the model and extracting the results were made easy.

AutoMod from Applied Materials is a Discrete Event Simulation tool that can model very large and complex manufacturing, distribution, and material handling systems. Engineers and managers can exploit AutoMod for any decision-making process related to production and logistics ("Applied Materials", 2019). The software is designed for detailed analysis of operations and flows. It aids in running a “what-if” scenario in a simulation environment and predicts results ("AutoMod", 2019). AutoMod consists of a build package and a run time package. In the build package, the physical and logical model is built. Various defined systems exist in the software in order to build a physical system. The logic for the system is coded and compiled into an executable program. The executable model is quick and fully interactive where any statistics can be viewed at any instant. The simulation and the animation are run in parallel. (Chen Z. & Jiang C., 2011). AutoMod provides two modules specific to the kind of production system at IAC. The path mover system and the power and free system, both of which are used to build the base model. The path mover system as seen in figure 3.2 is used to build the model linking the machines, the parts and the operators. A power and free system as seen in figure 3.3 allow the user to build the relations between a machine, a conveyor and a part. Both these models are integrated into one base model as a whole.

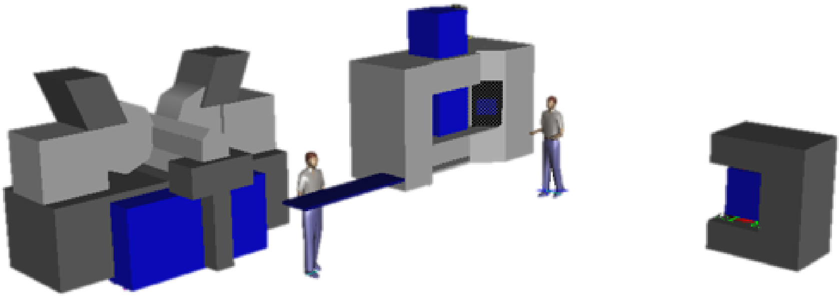


Figure 3.2: Path mover system in AutoMod.

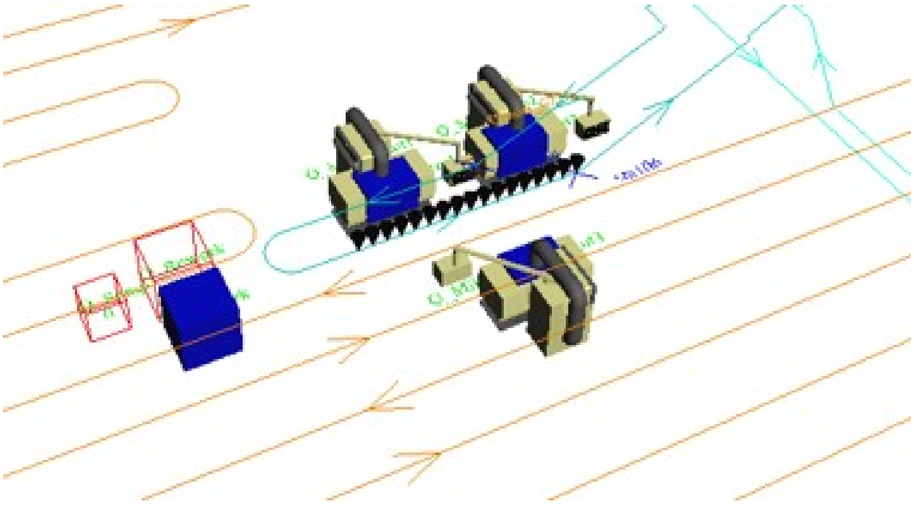


Figure 3.3: Power and free system in AutoMod.

The base model is built to produce 709 IP's using 955 hooks. The hooks are generated at several locations and park at specific locations in the conveyor, as in the factory. A particular production plan is drafted according to the author's knowledge/understanding which of course is editable if required. All AutoStat "Vary single factor analysis" runs are made for 20 iterations with no warmup time. All AutoStat "Single scenario analysis" runs are made for 30 iterations with no warmup time. This difference in the number of iterations is made considering the time constraint for the thesis. A very notable difference in the simulation and reality is the machine IMM1 is used abruptly in order to achieve the buffer full situation as required. That is only IMM1 is run for the initial 12 hours of simulation to fill in the primary buffers (Refer Appendix B) and achieve a real factory like condition. Therefore, the comparison of the results made in the results chapter will not include the effect of IMM1.

3.3 Current State Analysis

This analysis of the current state of IAC is an inevitable part of the thesis since understanding the operation of a factory is quite critical in creating a computer model of the same factory. Conducting the current state analysis mostly included interviews and discussions with the supervisors. Answers to questions were written and recorded. The combination of interviews and the follow-up discussions proved to be worthy, during which a lot of clarifications and corrections were made that helped in building a more accurate simulation model. The general method followed in executing the project is visualized in the below figure:

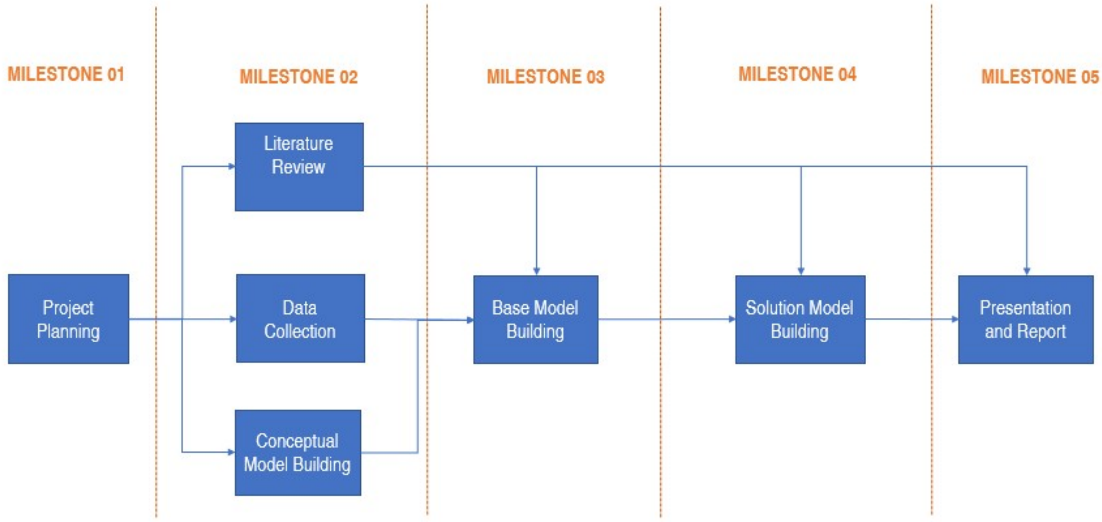


Figure 3.4: Visualization of the methodology.

The project was executed by approaching each milestone. Dividing the project into different phases assisted in following up the work and planning for the events. Weekly report on the work status provided credibility to the work done and was easily traceable. While base model remained to be the most time-consuming phase of the project, it was quite important to spend enough time in building a precise base model since solving the problems solely depends on the quality of the base model.

Milestones 1 and 2 were dedicated to understand the current state of the factory, learn and understand the system while milestone 3 was targeted to reproduce the digital copy of the system and milestone 4 was framed to improve the system. Milestone 5 was achieved in accordance the Jerry Bank's method in chapter 3.1 in a continuous mode and with several refinements. The current state analysis helped in identifying potential improvement areas in the system, identify risks/challenges that could hinder the model building and give a comprehensive insight into the operations. Interviews, which is a common technique of current state analysis was followed in this case.

3.3.1 Data Collection

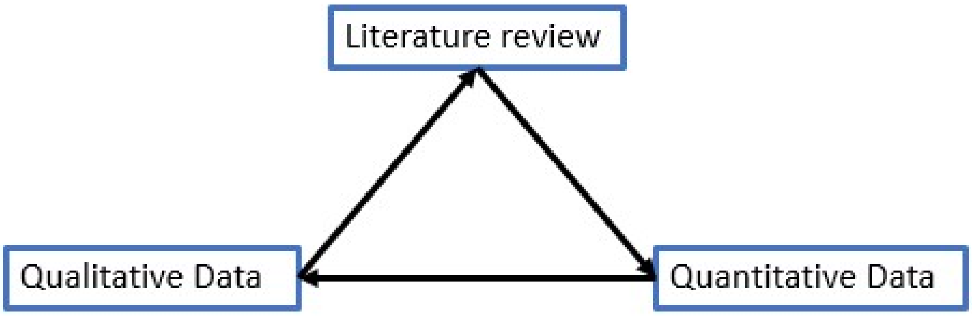


Figure 3.5: Visualization of the data triangulation.

The data collected was predominantly by the quantitative approach while understanding the collected data was done through a qualitative approach. To conduct a well-regulated data analysis, data triangulation was followed. Even though the thesis is not much research-oriented, small scale triangulation of data was done where the collected data were compared, interpreted and integrated into the base model. As visualized in the figure, each part of the triangulation validates each other thereby resulting in a quality data collection and analysis. The quantitative data are gathered from the company documents (Word/pdf documents and excel sheets) and the production activities over the past month were obtained through the company database upon request. The received data was very diverse where the production data is limited only to one particular day while the machine parameters were collected for over a few weeks. Few assumptions were made and confirmed to suite the simulation. Interviews with the manufacturing expertise of the company were the main source of qualitative data.

3.3.2 Interviews and Discussions

Semi-structured interviews were conducted with the supervisors at IAC. The interviews had both defined questions written on a book and also included some open-ended questions. These interviews were the main source to understand the IAC production system and Eton conveyor system. Follow up discussions were conducted to get better clarity of the production along with several brainstorming sessions. Few visits to the production floor were made for practical observation and keynotes made for having a better understanding of the production process. Digital data about the plant layout, machine parameters and operators were extracted from the IAC database and sent via mail, which later was filtered, sorted, analyzed and input into the simulation model. The quality of data collected was good since they were recorded data from the database but the data had to be modified to suit the simulation model. Few data were assumed.

4

Results

This chapter highlights the results obtained that are significant to the objectives of the thesis. The results are mainly the outputs of the AutoMod and AutoStat simulations. It also includes qualitative data findings.

4.1 Qualitative Data Findings

Qualitative data findings helped in understanding the complex manufacturing system of IAC's and served as a platform to build the simulation model more accurately and more specific to the objectives. The summary of questions and answers from the interviews conducted is as below:

Objective 1, that is having the right amount of hooks in the conveyors is quite crucial for IAC. Hooks consume space. Too many hooks slow up the travelling of the IP's in the conveyors and sometimes block the flow. If there are fewer hooks than required, then an IP that has finished being operated by a machine will wait for the hook to arrive thereby blocking the machine and the flow behind it. This again will lead to larger throughput time of the IP's. This is also found true during the simulation in AutoMod.

IAC has identified the flaming robot to be the current bottleneck machine in the system. Currently, there is one flaming robot which is fed by a single upstream buffer line and has two downstream buffer lines for the two product types. The same is also confirmed from the simulation results which is presented in section 4.2. IAC currently plans to invest in a new flaming robot. This forms the major part of objective three in evaluating the effects of an additional flaming robot in terms of throughput time of products and machine utilization.

Another interesting point raised was the challenge that IAC faces. IP's are produced in batches mainly to reduce tool changes and machine setups. But IP's are produced to stock as well and this stock is governed by the customer demand. Therefore, IAC already has most of the product types that the customer requires for the day in the stock and once it is consumed, new parts are ordered to be produced. The challenge is that the customer company sends the product requirement order according to their needs on a daily basis. So, it varies every day. The MES indicates what IP is required to be produced. The MES considers what type of products does the customer require for the day and what type of product does IAC now have in stock and in what quantity is it required. The production planning mainly needs to be done in the foaming machines. A high runner product variant for today may not be the same for the next week. The current practice at IAC is that according to the high runner, the foaming machine combination changes. For example, if V526 is the high runner today, then more foaming machines to produce V526 IP's than the V54X IP's. Some days, it is the other way around.

4.2 Base Model Analysis

A base model is nothing but a digital copy of the IAC production plant. The base model is built with the available/collected data, some assumptions and a production plan to achieve a particular day's production. The below results from the base model comes from the fact that 955 hooks were used in total.

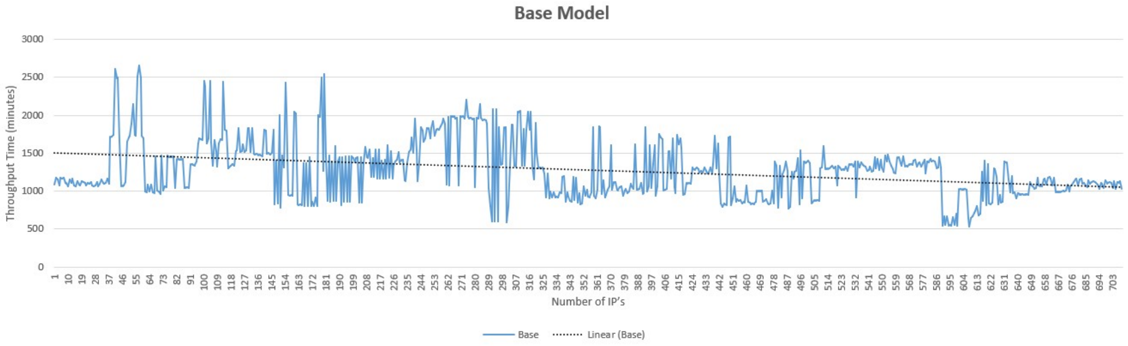


Figure 4.1: Throughput time of all the 709 IP's.

When the number of IP's were plotted against the throughput time of each of the IP's, a gradual descending trend line is observed as seen in figure 4.1. An ideal situation would be to have a horizontal/flat trend line indicating a stable production. A horizontal trend line indicates that on an average, all the IP's spend equal time in the production line. However, the ideal situation is not possible in reality due to production disturbances, buffer constraints and production planning.

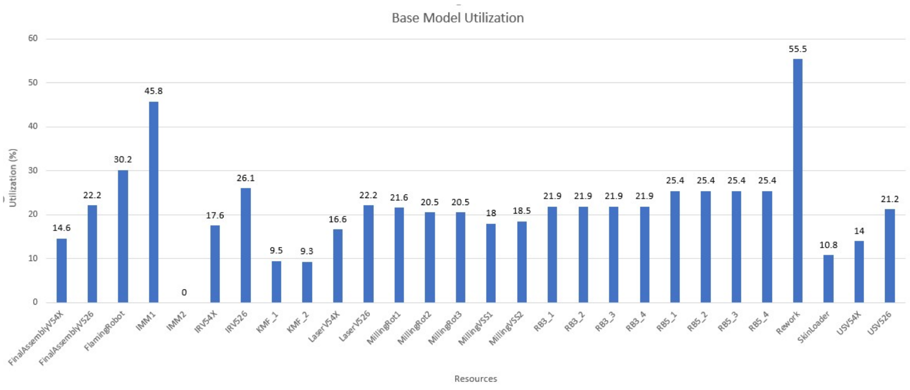


Figure 4.2: Utilization of all the resources.

As stated in the theory chapter, utilization method of bottleneck identification was identified to be most suitable to identify the bottleneck machines/resources and hence was followed. From figure 4.2, it is evident that the rework station with the highest utilization of 55.5% is the bottleneck. To identify the bottleneck machine in the system, only machines with the highest utilization was looked upon. Even though it seems that IMM1 with the utilization of 45.8% is the bottleneck machine, it is not to be considered since the IMM1 was used disorderly in order to achieve the buffer full situation as explained in chapter 3.2. This makes Flaming Robot with utilization 30.2% to be the bottleneck machine.

Production planning was input to the simulation model based on the authors experience. Production planning has a large impact on the simulation especially when the rework and scrap rates are considerably high and when parts are required to be produced in a particular sequence governed by a sorting mechanism in the later stages such as IAC practices. Henceforth, a well documented production planning preferably from the company can largely improve the results obtained. To evaluate the nature of production planning done for the given day's production, a distribution curve is plotted as below figure 4.3 and its characteristics mentioned in table 4.1.

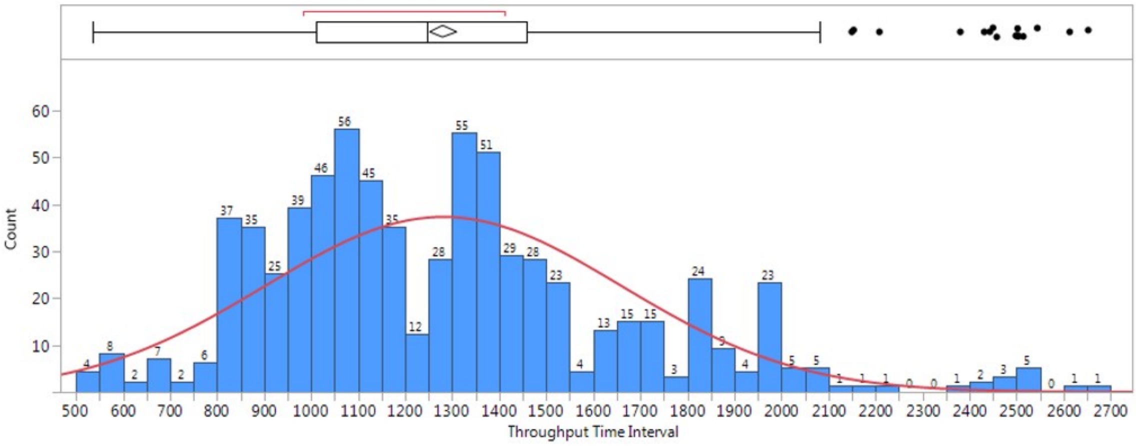


Figure 4.3: Distribution of throughput times of all 709 IP's.

Table 4.1: Characteristics of the distribution plot

Parameter	Value
Mean	1280.8565
Standard Deviation	378.74083
Std Err Mean	14.22391
Upper 95% Mean	1308.7826
Lower 95% Mean	1252.9304
N	709
Minimum	535.99284
Maximum	2652.4089
Median	1247.0756

4.3 Objective Specific Results

4.3.1 Results for Objective 1

To identify the optimum number of hooks required in the system, three simulation cases were considered in this case. One being a simple vary single factor analysis where the base model is run for 20 iterations and the number of extra hooks produced is varied. The resultant output of this simulation is shown in figure 4.4. The second simulation case here is to simulate the model with increased production disturbances meaning a poor production condition requiring a maximum number of hooks. The resultant output of this simulation is shown in figure 4.5. The third case is running the simulation model with no scrapped IP's and no machine failures meaning an ideal production condition requiring the least number of hooks. The resultant output of this simulation is shown in figure 4.6.

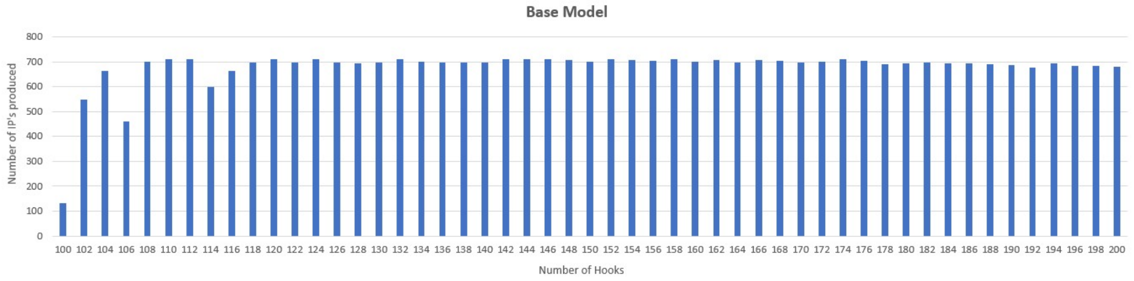


Figure 4.4: "Vary single factor analysis" - Hooks requirement for the base model.

The above graph indicates 120 to 174 number of hooks will yield 709 IP's.

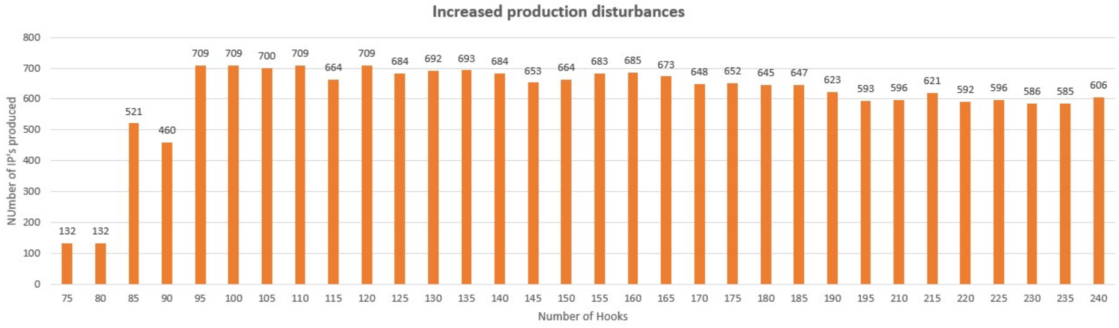


Figure 4.5: AutoStat run with increased production disturbances.

The above graph indicates the maximum requirement of hooks is event based and very much dependent on the production plan. For example, a base model is meant to produce 3 parts of type X and the production plan made was to produce 4 parts of type X to accommodate 1 scrap. But when the scrap rate is increased and the production plan remains the same, the required number of products fall short. If 2 products gets scrapped, there is 1 product short since the plan is to produce only 4 parts and the requirement is 3.

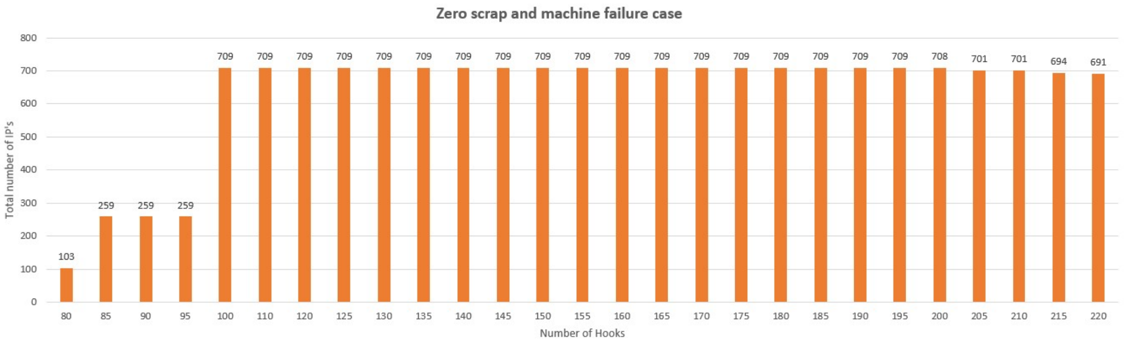


Figure 4.6: AutoStat run with zero scrap and zero machine failures.

The above graph indicates 100 to 195 hooks will yield 709 IP's.

4.3.2 Results for Objective 2

Single scenario analysis is used to identify which of the foaming machine combination is better. 30 iterations were run for each of the two models, one being the base model with 6:4 foaming combination and the other being the objective specific model with 7:3 foaming combination. Comparison of the outputs of the simulation is as below.

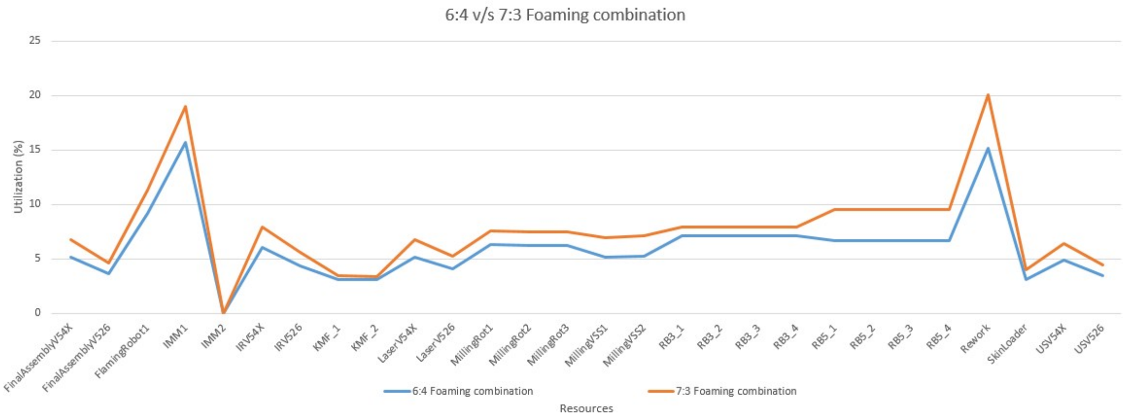


Figure 4.7: Comparison of machine utilization between base model (6:4 foaming combination) and 7:3 foaming combination model.

Figure 4.7 indicates using the foaming machines in the 7: 3 combination instead of 6:4 will yield considerable improvement in the utilization of RB5 foaming machines. Higher Utilization directly contributes to Overall Equipment Effectiveness.

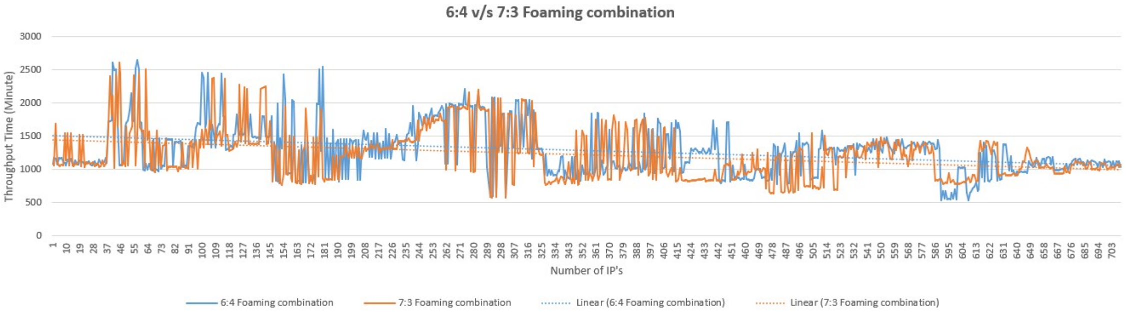


Figure 4.8: Comparison of throughput times between base model (6:4 foaming combination) and 7:3 foaming combination model.

Figure 4.8 indicates using 7 foaming machines to produce V526 IP's and 3 foaming machines to produce V54X IP's will yield in a shorter throughput time of the IP's. A uniform improvement in the trend line (orange dotted line being under the blue dotted line) indicates this particular method is effective throughout the production time.

4.3.3 Results for Objective 3

Both Single scenario analysis and vary one factor analysis is done in this case. Single scenario analysis is run to extract the machine utilization and throughput time of the IP's while vary one factor analysis is used to identify the effect of an additional robot on the hooks requirement.

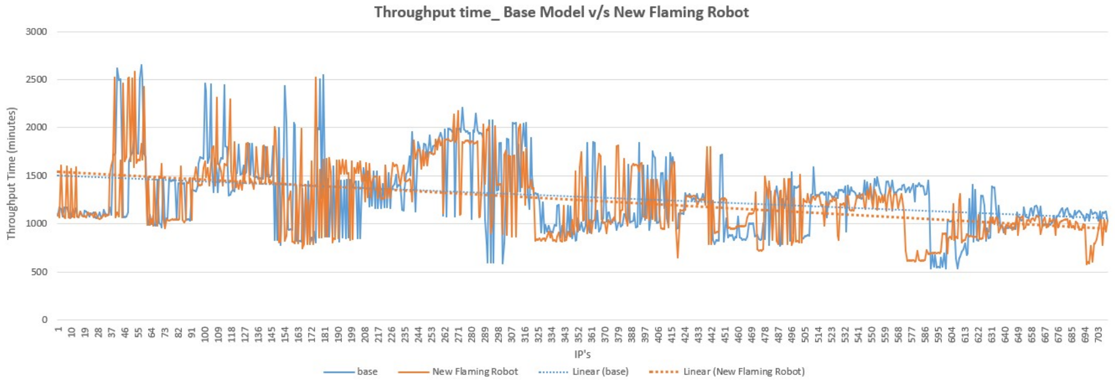


Figure 4.9: Comparison of throughput times between base model (1 flaming robot) and 2 flaming robots model.

In figure 4.9, the trend line clearly indicates investing in a new flaming robot will cut short the throughput time of the IP's thereby saving few production hours (46 minutes saved according to the simulation). However, it can also be seen that there is no significant improvement until the production of around the first 150 IP's. This may be due to the fact that all IP's are produced much faster now but have to spend at least 60 minutes before being laser scored according to the manufacturing procedures (Refer to Appendix B for more details).

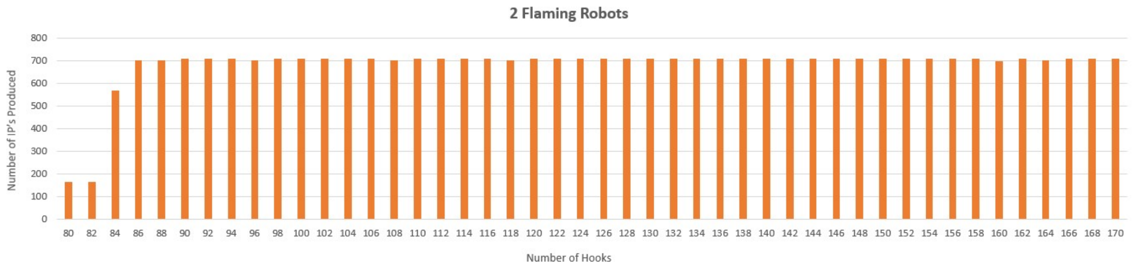


Figure 4.10: "Vary single factor analysis" - Hooks requirement for the 2 flaming robots model.

The number of additional hooks was varied to understand the effects of an additional flaming robot on the hooks requirement. Due to the faster availability of the IP's, hooks are released much faster than usual and therefore are easily available. Figure 4.10 indicates that as low as 86 hooks would be sufficient to get the required output.

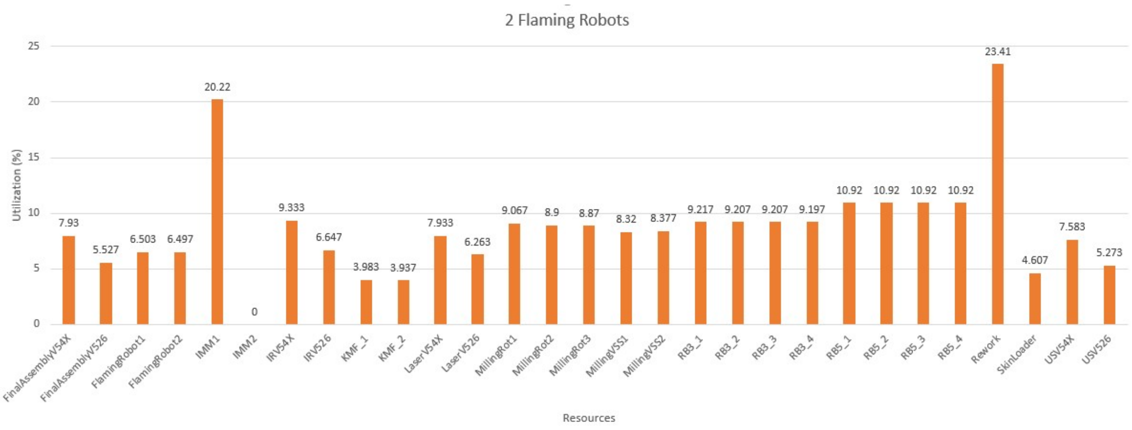


Figure 4.11: Utilization of all the resources.

Figure 4.11 clearly indicates that the flaming robot is no more a bottleneck machine. Instead, the new bottleneck machine is now the Round Table 5 foaming machine with the highest utilization of 10.9%. This again is based on the argument stated in chapter 4.2.

Table 4.2: Comparing machine operator utilization

Machine Operators	Utilization (Base)	Utilization (2 Flaming Robots)
USV526	27%	30%
IRV526	1.4%	1.5%
USV54X	40%	45%
IRV54X	1.2%	1.2%

Table 4.2 indicates the machine operators are also being utilized better when there are two flaming robots operating in the line.

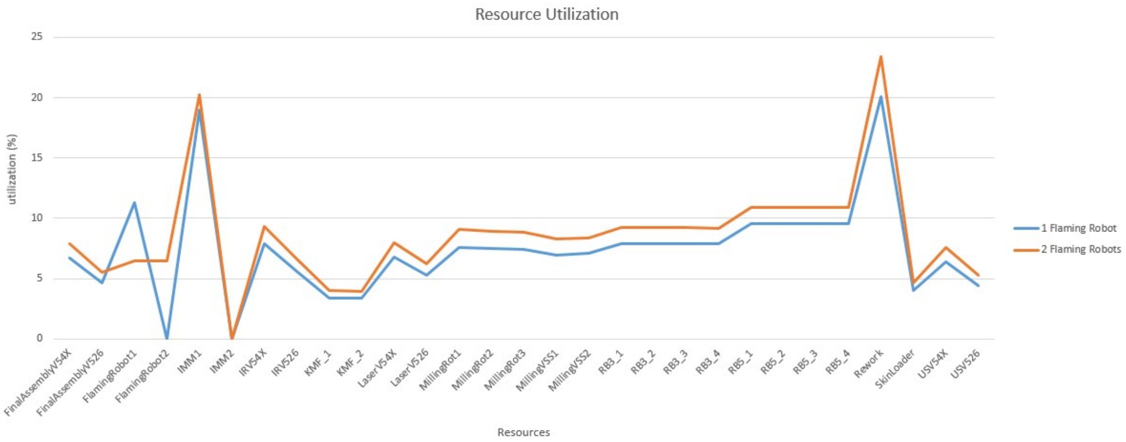


Figure 4.12: Comparison of machine utilization between base model (1 flaming robot) and 2 flaming robots model.

From figure 4.12, it is understood that using 2 flaming robots will enhance the utilization of all the resources thereby increasing the productivity. Since there are two flaming robots to heat the parts, the IP's are sent much faster to the following machines and hence those machines are less idle than they were in the previous case with one flaming robot.

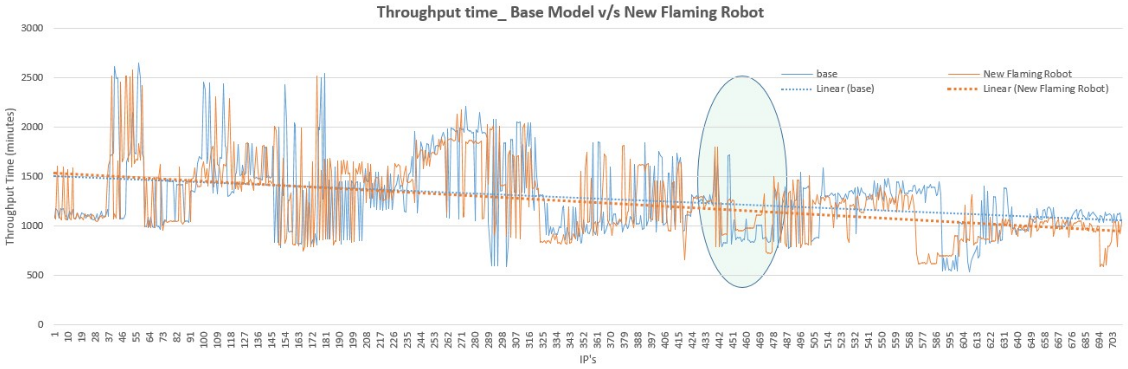
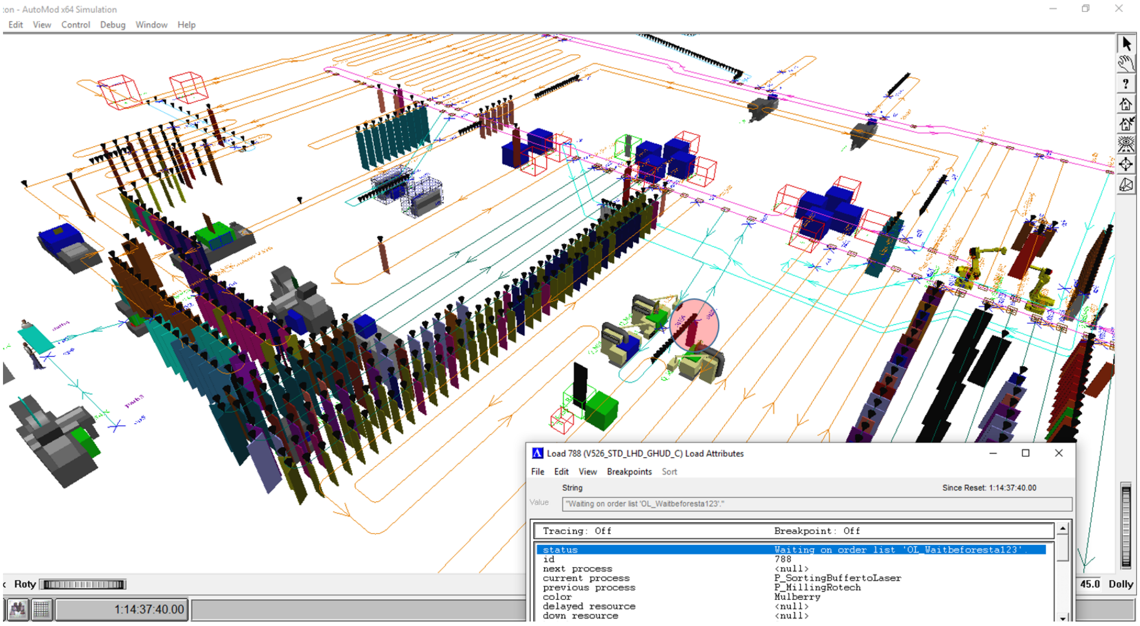


Figure 4.13: Anomaly in the behaviour.

When closely observed, there is some anomaly seen to exist in the graph. The encircled area in figure 4.13 shows that the blue curve is lower than the orange curve for a considerably longer period of time. This means having one flaming robot is better than 2 flaming robots sometimes. Or it could also mean that the two flaming robots are not being used up to the full potential due to some constraint in the line. The idea was to investigate this peculiarity and understand why the system is behaving so.



```
"Waiting on order list 'OL_Waitbeforesta123'."

Tracing: Off                    Breakpoint: Off

status                          Waiting on order list 'OL_Waitbeforesta123'.
id                              788
next process                    <null>
current process                 P_SortingBuffertoLaser
previous process                P_MillingRotech
color                           Mulberry
delayed resource                <null>
down resource                   <null>
```

Figure 4.14: Anomaly in the behaviour.

Investigating this peculiar case, it was found that all the IP's within that range belonged to V526_STD_LHD type. Also, these parts were the high runners for the day. Figure 4.13 is a screen shot of the simulation that shows a part (encircled in red) after being milled is not able to continue since there is no space in the buffer 6018. There is no space in the buffer 6018 because the IP's in this buffer is not moving to the welding buffer. This is because all the hooks in the welding buffer are used up and there is no free hook to take the incoming IP. This opens up two questions:
1) Could increasing the buffer capacity of 6018 help?
2) Could adding some hooks in the "transport buffer to welding" help?
Subsequent simulations were done to answer these questions and the answers are as seen below.

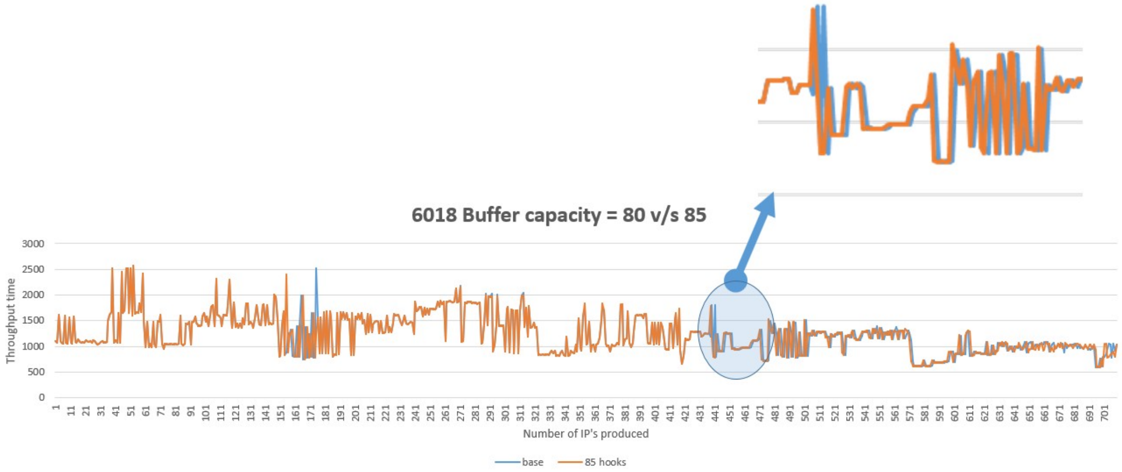


Figure 4.15: Comparison of throughput times between base model (1 flaming robot) and 2 flaming robots with increased buffer capacity model.

The buffer capacity of the 6018 buffer was increased by 5 and as seen in figure 4.14, there is no significant effect of it. This is because there is no space available in the conveyor line to accommodate additional hooks/parts. Therefore, this is not a good option.

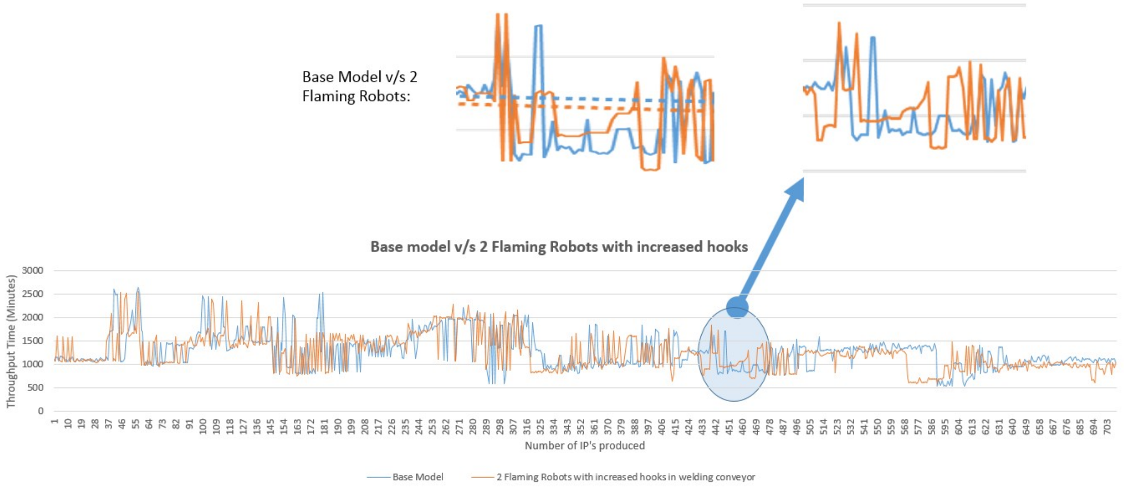


Figure 4.16: Comparison of throughput times between base model (1 flaming robot) and 2 flaming robots with increased number of hooks model.

Five additional hooks were supplied to the "transport buffer to welding" conveyor and as seen in figure 4.15, there is some change in the behaviour of the curve. Even though there is no great improvement here, it is evident that minor peaks present in the base model disappear in the new model, showing some improvement in the throughput time.

5

Discussion

This chapter scrutinizes the methodology used and the results obtained while addressing the influence of production planning on the simulation and the nature of the results obtained.

5.1 Summary

Jerry Bank's methodology is found to be a very suitable method to execute the simulation of the production process with ease, traceability and comprehensive. The model building was hassle free and comprehensible. Following each step in the methodology helped in keeping track of the activities and the progress in the model building phase. Though the results obtained are reasonable and close to reality, the accuracy of the results obtained can be improved a lot by enhancing certain processes of the methodology.

By successfully using this simulation technology, IAC can now take better decisions during production planning. Before IAC invest in an automated system, let this digital twin make sure it is designed to meet specific needs for today. IAC is yet to enter the digital manufacturing sector of industries and this simulation twin of the production system puts them into the basic level of the digital twins. With reference to figure 2.2, IAC seems to be in the stage 1 maturity of a digital twin which is very primitive and with this simulation model, IAC climbs a step up to stage 2 maturity. With reference to figure 2.3, it is understood that IAC enters into level 0 of digital twin with this simulation model. To predict the needs for future production and keep up with the competitive market, a higher level of digital twin is necessary which is more intelligent as explained in section 2.2. A lot of experiments can be done in the model before IAC implement the same in the real production plant. For instance, a new production plan is always welcomed to see the changes in productivity. An engineer can now visualize the changes being implemented in the model and determine which results and alternatives are statistically significant to make their decisions. The basic level of digital twin also implies IAC has a long way to go towards smart industries and this is only an introduction.

The maintenance data received was in terms of number of times a machine failed within a certain number of weeks and the total breakdown time. This data was modified to MTTR and MTTF simply by assuming a machine's MTTR and MTTF value to be the same. Having more accurate MTTF and MTTR values will bring out more accurate results. Another important thing to note is the simulation case run in AutoMod was for one day's production. This brought in a lot of uncertainties since a machine may not fail in a day in reality but the simulation made some machines fail constantly. Therefore, having the simulation run for a considerably longer period of time will again improve the results obtained. As a part of objective 1, the machine failures were doubled, rework rate increased from 15% to 25% and scrap rate increased from 2.25% to 3.75%, to imitate a bad production condition. This simulation case could be improved by putting in more relevant numbers rather than the assumed data. Digging further into the company maintenance database would give the numbers causing a bad production day in history. Again, these numbers would be helpful only for a long simulation run.

A Discrete Event Simulation, in this case starts from ground zero, that is a part is produced from the first machine in the production line while all other machines are idle, conveyors are still and the buffers are empty. This is not the case as IAC runs round the clock in shifts and at any given point of time, machines are running and buffers contain parts. This problem could be solved by running the simulation for a week's production or more and then including a suitable warm up time in AutoMod. In this thesis, to counter this particular problem, the model was coded where the initial 250 parts were made to wait in a certain buffer thereby providing a chance to manufacture all varieties of products.

Figure 4.3 in chapter 4.2 is of great interest here. A graph of the throughput time in intervals of 50 was plotted against the count of IP's that fall in the interval to understand the behaviour of the production plan. From the plot, it is understood that the bell curve is rather flat/wide indicating higher standard deviation. Conclusions can be drawn that a better production plan can be made resulting in a sharper bell curve with lower standard deviation, meaning more stable production leading to shorter throughput time of the IP's. A sharper bell curve indicates more parts lie close to the mean throughput time value, meaning more parts on an average spend the same time in the production line. Such a production plan will create a balanced flow of the parts throughout the system. Another important observation to be made is the multiple crests and troughs of the wave which is due to the high number of product variants. While some parts operated by a machine quickly passes on to the next machine, some parts needs to wait for some time in the buffer or are being sorted continuously adding to higher throughput time. Reducing the number of variants would enable robust production planning.

5.2 Future Scope

This thesis is focused only on the stated objectives governed by just two parameters which are the throughput time of the parts and the utilization of the machines. The work dealt with two challenges in parallel- To build an accurate simulation model and to ensure the model built is suitable to solve the defined objectives. Many questions on improving the base model for the simulation and the questions on evaluating the production system based on other parameters remain untouched.

It would be interesting to compare the bottleneck resources using various methods as stated in chapter 2.3 and get a better clarity at the results. Combining the simulation output along with the conventional method of bottleneck identification would thereby provide a good improvement. The simulation model itself can be improved a lot by incorporating some of the points raised in the previous section of this chapter. Enhancing and updating the base model will make it a closer twin of the production system than it is now, thereby producing better results. While using AutoStat proved to be worthy since many scenarios were considered during many iterations, it is understood that running even more iterations will produce even better results. Other than throughput time of the parts and the utilization of the machines, parameters like OEE, inventory size or buffer size, conveyor speed, additional resources (machines or operators), etc. can be a matter of interest. Inputting more accurate maintenance data and running the simulation for a longer production time will be beneficial as discussed earlier. This thesis work could not identify the maximum number of hooks required which could be an opportunity to include in the base model.

As discussed in the previous chapter, IAC is in a very primitive stage of digital twin after the implementation of this simulation model. This simulation model is built with the historical data which does not provide much flexibility and predictability in the system. By integrating real time data to the simulation model, IAC will climb to the next level of digital twin that is smarter and allows high fidelity as seen in figure 2.3. With more advancement, IAC can have a diagnostic system as in level 2 and a prognostic model as in level 3. By integrating machine learning algorithms and artificial intelligence, a very intelligent level 4 digital twin can be achieved. The ultimate aim for IAC would then be to reach level 5 digital twin which can make decisions for IAC. The company can make progress in the development of the digital twin that describes the physical process over time under no assumed conditions. These advancements in the future will give IAC a competitive edge over other manufacturers.

6

Conclusion

This master thesis is focused on improving the production system of IAC Group, understand how the changes/ modification of the production line affects the productivity and realize the potential of a "yet to implement" plan. From the results and discussions in the earlier chapters, it can be said that the purpose of the thesis is fulfilled satisfactorily. The output of the simulations can now be a base to take the decisions and plan production while the given suggestions can be used to execute the idea. IAC now has its basic level digital twin of the production plant. This could be IAC's first step towards digitalization which can be improved and made more smarter in the future thus providing IAC a leading advantage over other companies. With the integration of real-time data IAC can have advanced level of digital twin to analyze the complex production system.

Emphasizing on the highlights of the thesis, a simulation model representing the production plant as closely as possible is built. With the flexibility in the model to accommodate different product variants and production planning, IAC can use it for any future purposes. From the results of Objective 1, IAC can now estimate the minimum number of hooks it requires for a day's production. This will help in avoiding a shortage of hooks in the conveyor and parts will no longer have to wait for a hook. Results of objective 2 depict a higher utilization of all resources when the foaming machine combination is 7:3 instead of 6:4. With such a machine combination, IAC can greatly cut short the throughput time of all the IP's, thereby increasing productivity. From the results of objective 3, it is evident that by investing in an additional flaming robot, IAC production system improves a lot in terms of higher machine utilization and lower throughput time of the parts. Suggestions are also given to look into the buffer capacities of the high runners and increasing the number of hooks in the transport buffer, which will act positively in addition to a new flaming robot. IAC, with these small but effective changes can therefore improve the production system.

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A

Appendix A: Conceptual Model

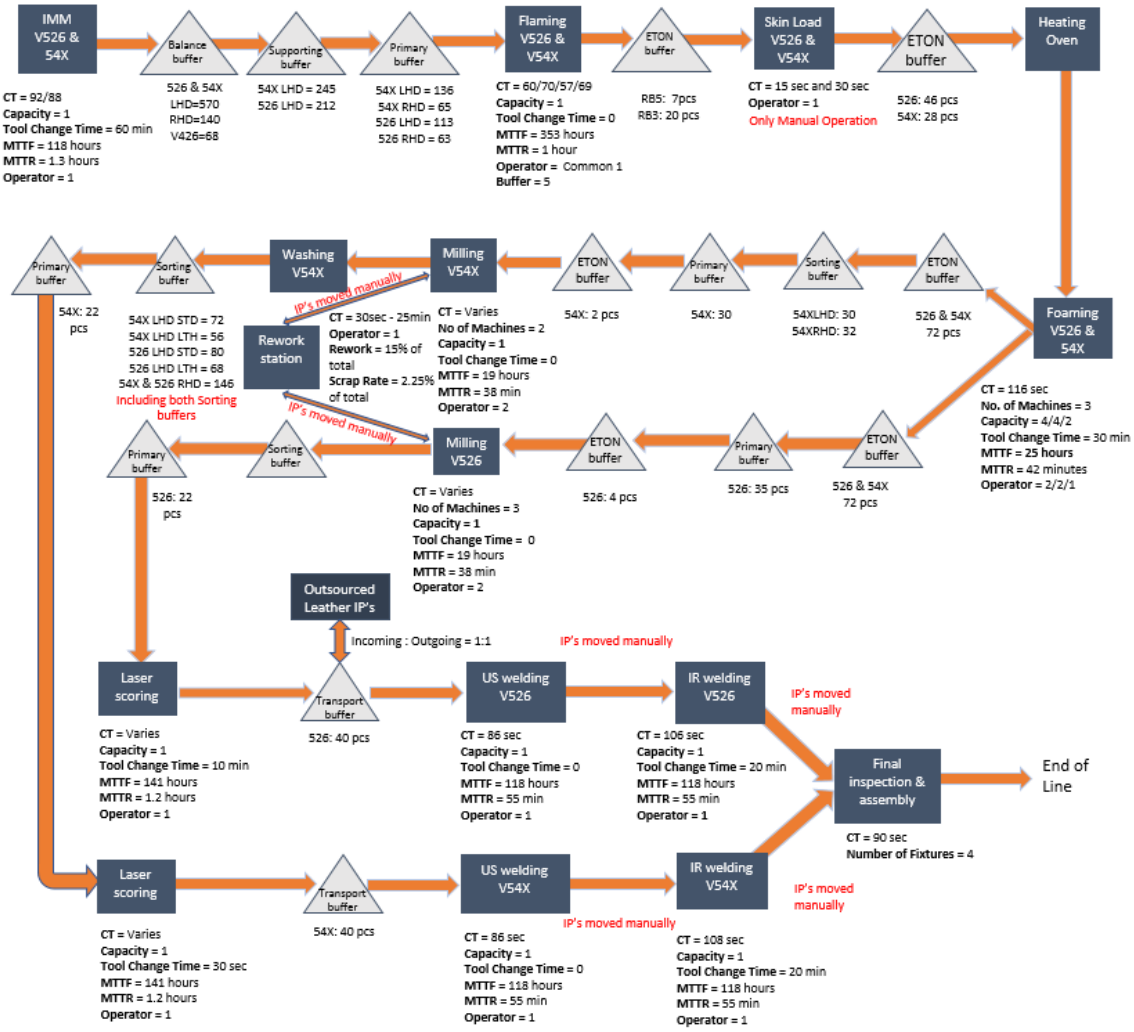

Figure A.1: Conceptual model of the simulation.

B

Appendix B: IAC Production Process

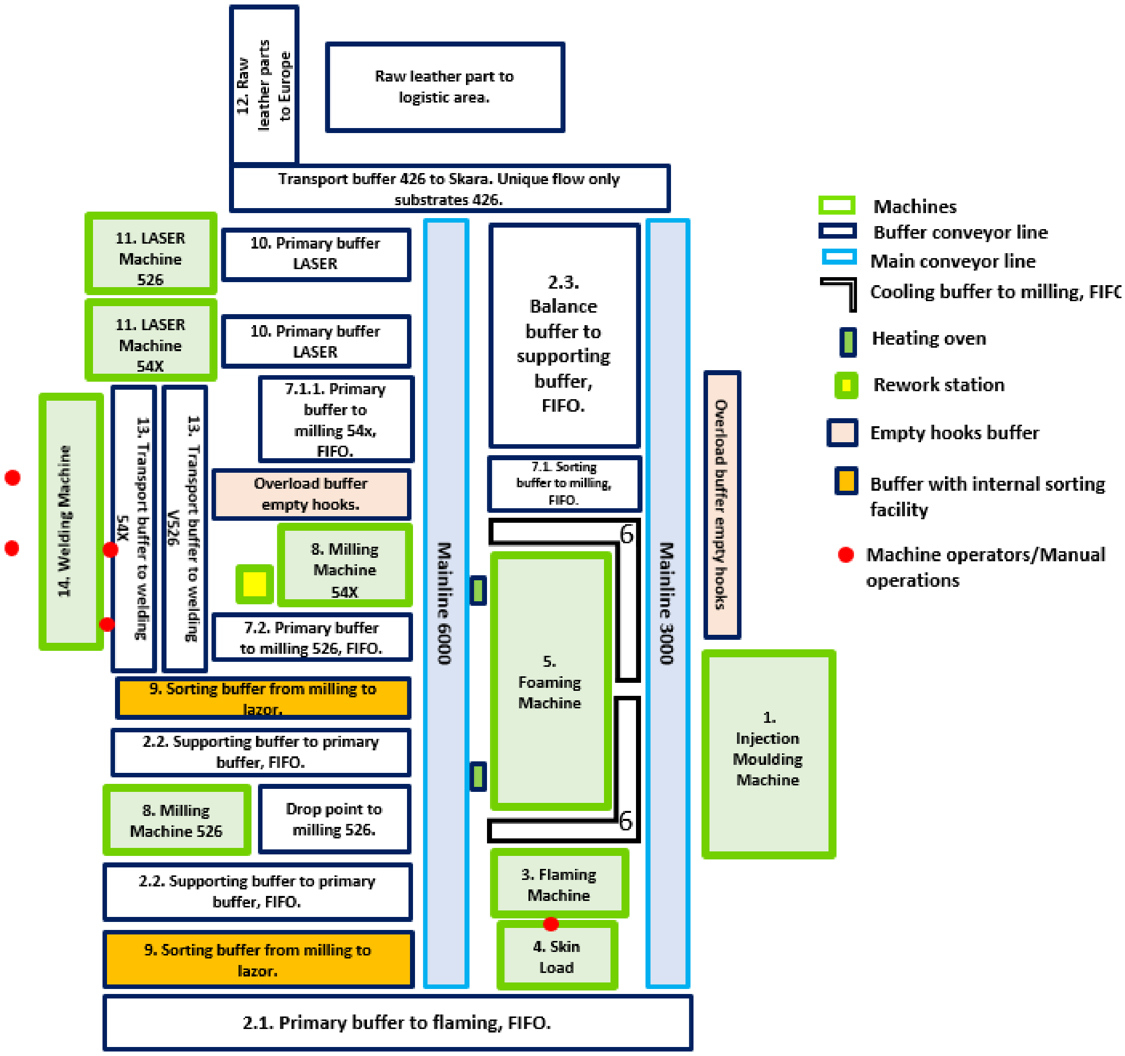

Figure B.1: Plant layout.

Factory Hours: Total production hours = 122 hours/week.
Monday to Friday, three shifts, 8 hours each shift. Sunday shift starts from 22.00. Saturday is a holiday.

Material Handling: Most of the material handling is done by the Eton conveyor system. The conveyor is unidirectional with a constant speed throughout the IP manufacturing process. IP's are moved in the overhanging conveyors with the help of hangers/hooks. At drop points/pick up points, the conveyor line dips down up to the level where a human operator can fetch the part or add a part. An exception is from the welding station until the final inspection and assembly station where the Instrument Panels (IP) are moved physically by human operators.

Conveyor Parameters:
Width = 100 mm (assumed)
Moving distance between two hooks and the stopping distance between two hooks varies depending on the conveyor line.
Hook width = 30 cm
Speed = 16m/min throughout.

Delivery of Raw Material: The Raw material is delivered in the form of plastic pellets in truckloads and stored in containers. It is made sure that the raw material is always available for the first machine in the manufacturing process which is the plastic injection moulding.

Injection Moulding: The first step in the instrument panel manufacturing process is the injection moulding machine (IMM). One machine can process any product variant provided appropriate tool change is done. IMM processes 4 product variants: V526 LHD, V526 RHD, V54X LHD and V54X RHD.

The injection moulded parts which are now called substrates are moved to a primary buffer with capacity 377, if filled up then to a supporting buffer with capacity 457 and then if filled up to the balance buffer with capacity 710. V426 IP's have separate buffer storage with capacity 68. RHD IP's move directly from balance buffer to the primary buffer. There is another safety buffer with capacity 1200 which is rarely used and therefore not considered in this model.

Flaming: After injection moulding, the substrates need to be flamed. One robot flames the substrate to ensure the surface is warm and sticky enough to assist skin loading. There is a small buffer for 5 substrates just before the flaming machine. The flamed IP's then move into a small buffer with capacity 7 for RB5 and capacity 20 for RB3 types. IP's going to KM foaming machine are stored in the RB5 buffer space.

Skin Loading: Skin is mounted manually onto the IP's of both V526 and V54X types. An operator calls the IP's from the flaming machine to the skin loading area and rearranges it in the order required by the foaming machines. The IP's then move towards the heating oven. Here V526 IP's are high runners meaning the demand for IP's are more, hence the IP's are produced in large numbers. V54X IP's are low runners meaning the demand for IP's is comparatively lesser than V526 IPs.

Foaming: Foaming is done in two turn tables RB3 and RB5, each with capacity 4. There is also another foaming machine KM with capacity 2. KM foaming machine is mostly used when a quick tool change is required. Any type of IP can be foamed in the machine. Most of the time, a turn table is used only when there are 4 IP's to be worked upon. A skin is loaded, then a substrate is loaded, then the robot fills in the foam and compresses and finally, the foam hardens before it is unloaded from the table. There are tools available always for high runners in the machine. Middle runners are produced for 1 shift after a tool change and then tools are changed back to high runners. RB3 is mostly used for V526 IP's. RB5 is used mostly for V54X IP's but also V526 can be run since V526 is a high runner.

Foamed IP's move into 2 cooling buffers with a buffer capacity of 72 each and the IP's require a cooling time of 30 minutes in each buffer. V54X RHD and V54X LHD type IP's move into sorting buffers with capacity 32 and 30 respectively. Then both RHD's and LHD's move into milling primary buffer with capacity 32 and then to a drop point buffer at VSS milling stations with capacity 2. V526 type IP's move into milling primary buffer with capacity 35 and then to a drop point buffer at Rotech milling stations with capacity 4. Tool change is done between LHD/RHD and LTH/STD of the IP's.

Milling: There are two kinds of milling machines. V526 IP's are milled in a standard milling machine, three of which are available. V54X are water jet cut, two of which are available.

V526 and V54X milled parts move into sorting buffers with capacity 422 and then to a LASER primary buffers with capacity 44 respectively. All RHD's are sorted in three sorting buffers and V526 and V54X LHD's are sorted in separate buffers based on LTH and STD types. There is no tool change between variants. Only water jet cut parts move into the washing process after the milling process.

Washing: Only V54X type IP's go through a washing process before they are move into sorting buffers. These parts do not stop anywhere but are washed while they move on the conveyor.

LASER Scoring: There are two LASER cutting machines each dedicated to V526 and V54X. Each LASER cutting machine can process 1 part at a time. The tool change is done only for LHD and RHD variants. V526 and V54X move into transport buffers with each capacity 40 respectively. However, part to be laser scored needs to be at least 60 minutes old from the time it has been foamed.

Welding: Two kinds of welding happen, US welding and then IR welding. There are two machines of each kind and each of them is dedicated for the V526 and V54X type IP's. The IP's are moved manually. There is one operator to move V526 type from US to IR and another operator to move V54X type from US to IR. If one of the welding machines breaks down, the rest of the welding machines will come to

halt since there is no buffer in between them.
The tool change between the variants in US welding is ignored as it takes very less time. Whereas, the tool change in IR welding happens between LHD/RHD for V526 IP's and between LHD/RHD & LTH/STD for V54X IP's.

Final Inspection and Assembly: V526 type IP's are moved manually from welding to final inspection by one operator and V54X type by another operator.

Rework: Most of the defective pieces come to the rework station from the foaming machine. The defective piece travels from the foaming process to milling process along with the other good IP's. Once the defective IP is milled, it will be sent to rework station. 15% of total IP's are reworked out of which 5% are scrapped.

Manning: There are totally 5 operators working on the shop floor. One common operator for the flaming and skin loading process, two operators are responsible for V526 and V54X IP's processes between US welding and IR welding respectively. Similarly, two operators are responsible for V526 and V54X IP's processes between IR welding and final inspection and assembly respectively. The walking speed of the operators in the simulation is assumed to be 1.4 m/sec.

Empty Hooks: The empty hooks are stored in two conveyor lines with capacity 130 and 400. The priority of empty hooks feeding the processing stations to carry IP's are as follows:
1) Empty hooks after the IP is unloaded at foaming machines travel back to empty hooks buffer storage with capacity 400.
2) Empty hooks stored in the buffer capacity 400 will only feed IMM1 and IMM2 to carry the processed IP's.
3) Empty hooks stored in the buffer capacity 130 will only feed empty hooks buffer line at foaming machines and milling machines to carry the processed IP's respectively.
4) Empty hooks after the IP is unloaded at laser machines travel back to empty hooks buffer storage with capacity 130.
5) Empty hooks after the V426 IP is unloaded travel back to empty hooks buffer storage with capacity 400.
6) IP's that are outsourced and return from Opole will travel on the fixed number of empty hooks in the closed conveyor.

Other Information: After the LASER scoring, the IP's that are supposed to be leathered are outsourced and return after a week. On an average, the ratio of incoming to the outgoing number of leathers IP's is 1:1, that is as one IP goes out of IAC, another leathered IP enters IAC which then goes to the transport buffers and then to the welding process. The IP's that are moving into Laser machines must have spent at least 1 hour in the production line since they left foaming stations. If not, they need to wait until it spends 1 hour.

C

Appendix C: Product Variants

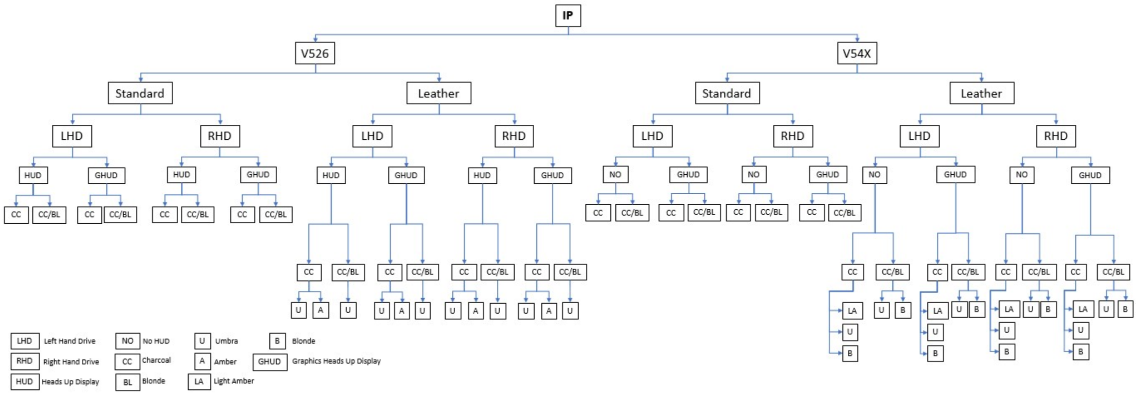

Figure C.1: Product Variants.

Product Variants: Classification of IP's:
Level 1: Based on vehicle type-V526 or V54X
Level 2: Based on vehicle luxury-standard or leather
Level 3: Based on drive- left hand or right hand
Level 4: Based on display-HUD, GHUD or No HUD
Level 5: Based on IP skin colour-CC or CC/BL
Level 6: Based on stitch thread colour- U, A, LA, B (only leather IP's).

There are totally 48 IP variants. Besides them, there is V426 variant which is only injection moulded at IAC and then outsourced. The production requirement of each of these variants differs daily.

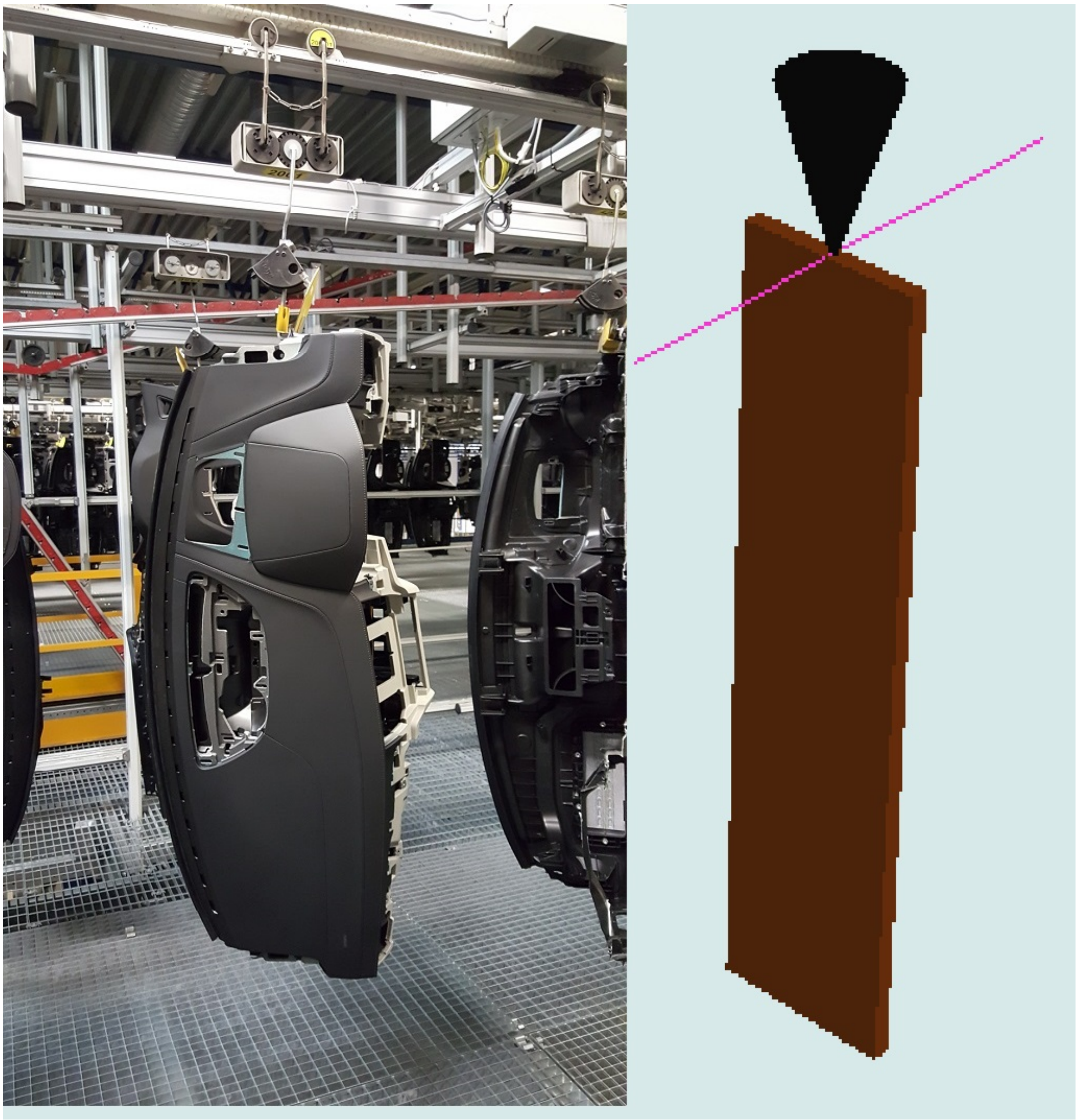

Figure C.2: An IP with a hook on the conveyor in reality (left) and in simulation (right).