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# Digital Twins for Sustainable Production

Modelling and Simulation of a Production System Towards a Digital Twin

Master's thesis in Production Engineering

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Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2021

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MASTER'S THESIS 2021

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Twin

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Arpita Annepanavar, Dhanush Krishnan Gopalakrishnan

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Cover: 3D visualization of a Discrete Event Simulation model of the drone factory created using Siemens Technomatix Plant Simulation .

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## Abstract

This master thesis is a part of a pilot study of a larger EU-funded Industrial project "Twin Goals" by European Institute of Innovation and Technology (EIT) in collaboration with Chalmers University of Technology. The primary purpose of this study was to investigate the possibility of using a Digital Twin for ensuring production sustainability. Previous research has indicated the potential of using Cyber-physical system (CPS) based Digital Twins for remotely monitoring and controlling the production processes by establishing a bi-directional flow of information between the virtual entities and the physical assets. This project attempts to use this information exchange to perform a real-time optimization of the production processes and increase the sustainability of the production system. The project was carried out in a test-facility for manufacturing drones at the Stena Industry Innovation Lab (SII-Lab), Lindholmen, Gothenburg.

This thesis followed a methodology that combines triangulation research methodology and banks methodology. The literature study was carried out to identify suitable Key Performance Indicators (KPIs) for measuring Triple Bottom Line (TBL) aspects of sustainability namely economical, ecological and social aspects. Qualitative and quantitative studies were performed during model building and the analysis phases. The DES model of the Drone factory was built on Siemens Plant Simulation platform with four scenarios that included, the current state (AS-IS scenario), an additional product variant (base scenario), a parallel station (experimental scenario 1), and a potential "operative digital twin" scenario with the dynamically re-balanced station (experimental scenario 2). The scenarios were evaluated by conducting experiments for varying customer demands and pallet sizes. Among the four scenarios, the results of experimental scenario 2 showed a positive impact both in the economic and environmental aspects of TBL. The operative scenario exhibited an ability to autonomously utilize the production resources ensuring that the production load on the system was evenly distributed among all the processing stations. This scenario decreased the waste and non-value adding activities in the process thereby contributing towards a higher throughput, decreased lead times and improved material and energy efficiencies. Enabling a data exchange between this operative scenario and the physical assets we can create a potential Digital Twin for production sustainability.

Keywords: Digital Twin, Discrete Event Simulation, Triple Bottom Line, Sustainability, Key Performance Indicators.

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Arpita Anneppanavar & Dhanush Krishnan Gopalakrishnan, Gothenburg, June  
2021

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# 1

## Introduction

This chapter provides a brief introduction to this thesis project. It explains in detail the project background, limitations, aim and the research questions that have been addressed as part of this master thesis project.

### 1.1 Background

The rapid advancements in the development of technologies such as data-acquisition systems, information technology and network technologies have enabled the transition towards the digitalization of manufacturing processes [1]. The digitalization of manufacturing has postulated the need to implement neoteric smart manufacturing technologies like the Digital Twin [2]. The Digital Twin can be used to help industries improve their production processes and competitiveness by optimising their productivity and quality, whilst reducing the overall consumption of energy and raw materials to ensure sustainable manufacturing [3].

The Digital Twin is a high precision virtual model of a physical system that can simulate the various states and behaviours of the physical entities thereby providing valuable insights about the system. The Digital Twin provides a capability to monitor the physical entities across their life cycle through realistically behaving virtual models that can detect and predict the physical processes efficiently in real time with the integration support provided by the use of Cyber-Physical Systems (CPS) [2]. This level of integration facilitates a bi-directional flow of information between the virtual and physical entities that can be used to implement real time optimisation of both the virtual and physical processes [2].

The negligent use of resources and its detrimental consequences has propelled the need for improving our environmental, economic and social sustainability. Naderi et al. [4] states that in order to establish sustainability in production, it is necessary to focus on measuring the Key Performance Indicators (KPIs) associated with the environmental, social and productive aspects. The new manufacturing paradigm has shifted towards establishing sustainability in production by leveraging the use of digitalization technologies such as the Digital Twin [5]. Ju Yeon Lee et al. [5] proposes an integrated modelling and simulation based life-cycle approach for evaluating the sustainability performance of the manufacturing industries.

The Stena Industry Innovation Laboratory (SII-Lab) is a research facility at Chalmers University of Technology. The drone assembly cell at the lab is a test-bed within Produktion-2030, Sweden's innovation program for sustainable production. This facility is used to study the implementation feasibility of various technologies for the digitalization of production. One of the projects "Twin Goals" focuses on how to develop a Digital Twin of the drone factory. The drone factory incorporates all aspects of a real world production system encompassing aspects of manufacturing such as logistics, assembly, quality control and delivery.

This master thesis project aims to integrate sustainability indicators in a simulation model of a drone assembly cell at the SII-Lab at Lindholmen, Gothenberg, Sweden. The project primarily focuses to identify suitable KPIs that can be used to assess the sustainability of the drone factory and integrate these KPIs into a DES model. Furthermore, this KPI integrated model can be used to identify a sustainable manufacturing scenario through changes in the production design or operations that can be used as a Digital Twin. This project also attempts to investigate the data points required to integrate the simulation model with the physical world for establishing a bi-directional flow of information that can contribute towards a Digital Twin.

## 1.2 Problem analysis

The drone factory at SII-Lab is capable of deploying Internet Internet of Things (IoT) and data management technologies for production control that involves the use of industrial connectivity software, Programmable Logical Controls (PLCs), and RFID sensor devices along the production lines [6], [7]. This level of automation enables smart manufacturing, but a decision support tool for real-time production improvements is missing. DES of the production system, being one of the Industry 4.0 technologies, can be a decision support tool enabling production optimization effectively and efficiently with lesser investments [8]. Therefore, modeling and simulation of the Drone factory will be one of the decision support tools that can help to make real-time decisions and thereby visualize overall performance of the system.

The majority of currently available studies include use cases of simulation of production system through DES, but the applications of measuring the performance of production system implemented to real-time production scenario is scarce [6]. Another area of studies related to DES that is scarce is that of the utilization of simulation data for sustainable evaluation, and improvements [6]. Further, for production systems to be able to provide enhanced design and manufacturing, it is necessary to focus on establishing a stronger sustainability culture [9]. Among the 17 Global Sustainable Development Goals (SDG) defined by United Nations, the goal 12 is to attain "Sustainable consumption and production" [10]. It is observed that only 18% of Swedish companies, organizations, and authorities mainly work with the goal 10, which is to achieve sustainable consumption and production [11]. This implies that there is a need for industries to work more towards the goal, "Sustainable consumption and production" and contribute to the overall SDG.

The Drone factory has not yet explored many opportunities for improvements that

contribute to a more sustainable process as currently real-time KPIs related to sustainability are not measured. To capture the overall performance of the factory in all three aspects of sustainability, the data required for estimating suitable sustainable KPIs need to be found.

With this identified research gap, the thesis aims to build a DES, which is, a decision support tool by utilizing the simulation data in calculating the suitable sustainable performance indicators which will help in real-time sustainable production performance management. The simulation data will be saved in the database and assessed with the aid of IoT to calculate the required KPIs and help for accurate production improvement decisions [6].

### 1.3 Project aim

This thesis project aims to enable sustainable production through a DES of the Drone Factory by incorporating feasible sustainability KPIs that will contribute towards creating a Digital Twin for real-time improvements of the production process.

### 1.4 Research questions

**Research question 1 (RQ1):**

Which are the most suitable KPIs to assess the sustainability of production systems through a DES model?

**Research question 2 (RQ2):**

How can DES be used to improve the sustainability of the production systems and what are the data points required for a real time decision making process that contributes towards a Digital Twin for sustainable production?

### 1.5 Project limitations

The scope to integrate sustainable KPIs is limited to only economical and environmental aspects of TBL. Regarding the social aspect, the project will only propose the most important social KPIs as the results from literature study. Further, the focus will be on sustainable KPIs that result in material and energy efficiency production aiming to transform the Drone factory into eco-efficient production and hence addressing environmental and economic sustainability. In order to estimate environmental KPIs, a compact environmental impact analysis will be conducted and does not conduct a detailed Life Cycle Assessment (LCA).

The project is limited to build the virtual entity (DES model) of the cyber world and do not focus on developing any service management system such as mobile dashboard system to monitor and track the integrated KPIs or any kind of data management system to handle the simulated data. The project limits the use of technology to modelling and simulation of production systems and do not consider

other Industry 4.0 technologies such as virtual reality, augmented reality, machine learning or artificial intelligence even during the development of the DES model.

## 1.6 Thesis outline

The outline of the thesis will be illustrated using the following Table 1.1 which describes the main contents of all the the six chapters in the report.

**Table 1.1:** Thesis outline

| Chapter               | Contents                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Introduction          | This chapter presents the Background, Problem analysis, Project aim, Research questions and Project limitations.                                                                                                                                                                                                                                                                                                                                  |
| Theoretical Framework | This chapter describes the background of concepts like Digital Twin, CPS, DES, Sustainable production through TBL and KPIs                                                                                                                                                                                                                                                                                                                        |
| Methods               | This chapter provides a description of the methods followed to answer the RQ1 and RQ2. The chapter includes a description of the steps followed to execute the Literature study, Qualitative studies and Quantitative studies carried out for the Banks methodology of simulation model.                                                                                                                                                          |
| Results               | This chapter presents the results of RQ1 and RQ2. The results of RQ1 consists of literature research results as list of recurring KPIs and reflecting of current studies of integration of sustainability tools with DES. The results of RQ2 consists of quantitative and qualitative study results obtained through Data collection, Model conceptualization, Environmental impact analysis and Experimental analysis of the selected scenarios. |
| Discussion            | In this chapter the methodology used, results obtained, research quality will be discussed in such a way that provides answers for each research question. In addition the future work will also be discussed.                                                                                                                                                                                                                                    |
| Conclusion            | This chapter concludes by highlighting the main findings and takeaways from the thesis.                                                                                                                                                                                                                                                                                                                                                           |

# 2

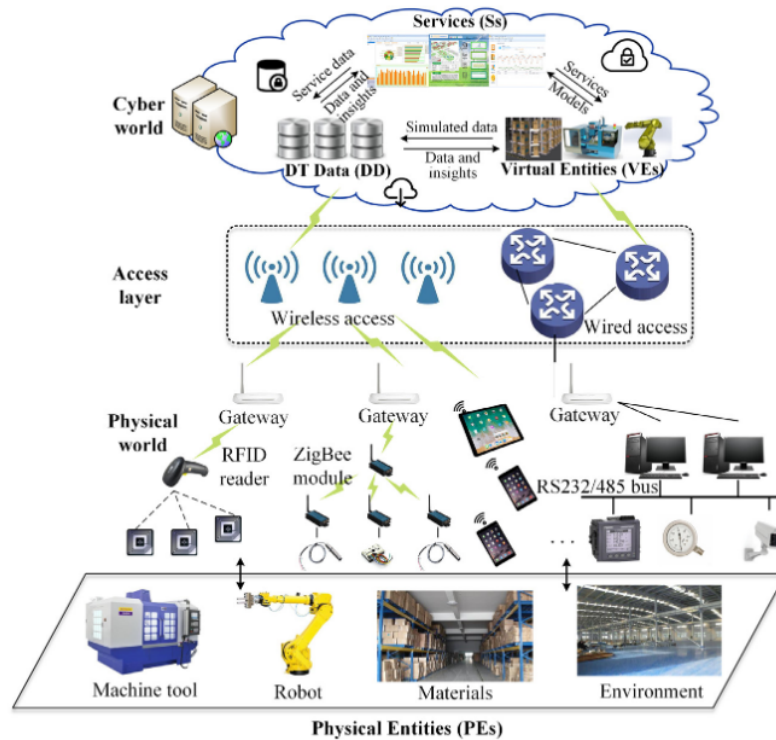
## Theoretical Framework

This chapter provides a description of the concepts and terms used and adopted in this thesis project. The chapter provides insights into the concepts of Digital Twin, Cyber-Physical Systems (CPS), Discrete Event Simulation (DES), Sustainability and Key Performance Indicators (KPIs).

### 2.1 Digital Twin

With the onset of the Industry 4.0 technologies that provide possibilities for easy integration of interconnected components of production processes have set a new manufacturing paradigm enabling the digitalization of manufacturing. Digitalization technologies enable virtual product and process planning through a virtual simulation of physical processes [12]. The simulation based process planning and optimization, combined with other technologies such as Cyber-Physical production elements enable real time monitoring and control of devices across the network infrastructures. This facilitates a direct integration and synchronization between the physical world and the virtual world [12]. This computerized virtual form of the physical process encapsulating all the information by sensing real time data of the concerned system assets is referred to as a Digital Twin [12]. The Digital Twin can hence simulate various scenarios of the physical world which can then be used to determine the most suitable operation among a set of different possibilities and hence execute the whole production process in an optimal way [1].

Since the Digital Twin is a high-fidelity virtual representation of the geometries, physical properties, behaviours and rules of the physical world the virtual models and the physical entities have similar appearance and behaviours that are identical. In addition, these identical virtual models can be connected through CPS for enabling bi-directional flow of information between the physical and virtual entities in real time [1]. This bi-directional dynamic mapping enables both the physical and virtual entities to co-evolve through feedback and thus directly optimize the operations and adjust physical process [1]. These features of the Digital Twin contribute towards achieving a higher efficiency, accuracy, sustainability and economic benefits in production [12].



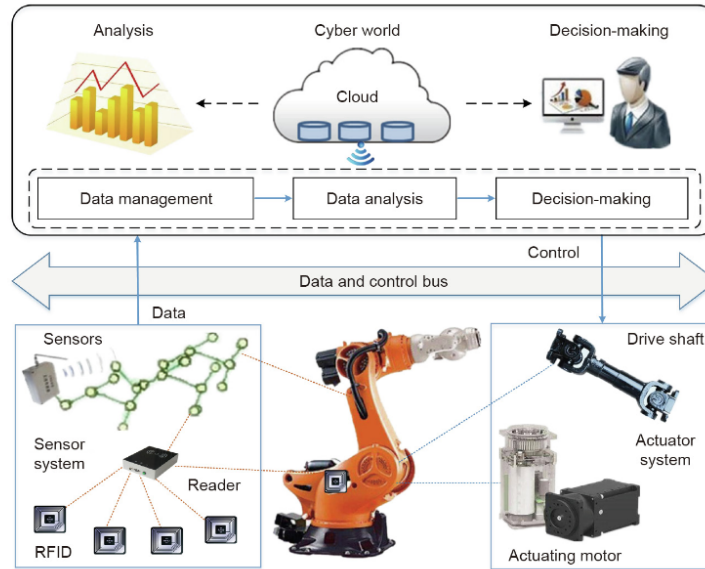
**Figure 2.1:** Framework for Digital Twin [1, Fig. 12.2]

### 2.1.1 Cyber-Physical Systems

The CPS is a concept that can integrate communication, computing and control capabilities into physical device such as machines and other resources on the manufacturing shop floor to monitor, control and co-ordinate the physical operations in real time [2]. The CPS framework makes use of devices such as advanced sensors and actuators, communication devices, embedded systems, cloud network etc. for integration with the physical world. These devices are capable of collecting real time data from physical objects which can be used by the cyber systems for further data analysis and decision making [7]. The CPS network can therefore transmit and receive data between the physical and virtual worlds through a feedback mechanism thereby forming a closed loop which allows for a seamless integration of the two worlds [7]. This level of intractability, scale-ability, reconfigure-ability and intelligence provided by the CPS network is important for the implementation of smart manufacturing.

An important technology that drives the CPS network is IoT, as it allows the collection and exchange of data through internet [7]. On the manufacturing shop floor the CPS network can be classified into three levels such as, unit level (e.g.: single machine), system level (e.g.: production line) and system of system level (SoS) (e.g.: whole manufacturing plant). At each of these levels the CPS network is deployed by using sensors, actuators, embedded systems to communicate, monitor and control the physical assets [2]. The individual elements of the Digital Twin such as the

virtual entities (VE), Physical entities (PE), Data service management systems or digital twin data (DD) and services (SE) can be connected through this CPS network through fusion algorithms for establishing a Digital Twin based CPS manufacturing on the production shop floor [7] as shown in the following Figure 2.2.



**Figure 2.2:** CPS based Digital Twin [2, Fig. 5]

### 2.1.2 Discrete Event Simulation

DES refers to creating a conceptual model of a system by utilizing complex computational and mathematical techniques for modelling, simulating and analyzing the behavior of the system under varying conditions [13]. The DES can be used for performing various experiments on the virtual model to draw conclusions from the outputs that help in the decision making process without actually disturbing the physical system [13]. Due to the complexities of the manufacturing systems the DES approach can be used for designing and experimenting these complex systems on a virtual interface.

The DES approach aids in easier analysis of the computer generated models through virtual simulations of different scenarios for production planning and control, bottleneck detection, design of transportation systems, stability analysis etc [14]. The DES tool provides several methods such as mathematical programming, combinational optimization and scenario analysis for modelling and solving these complex manufacturing systems [14]. This ability of DES to conduct experiments that cannot be performed on real manufacturing lines can help in providing insights that can lead towards improving the design and operational capabilities of the real world production systems. This method of optimizing the production process offers a more economical and sustainable approach for studying production improvements rather than the traditional trial and error methods of changing production layouts and processes [14].

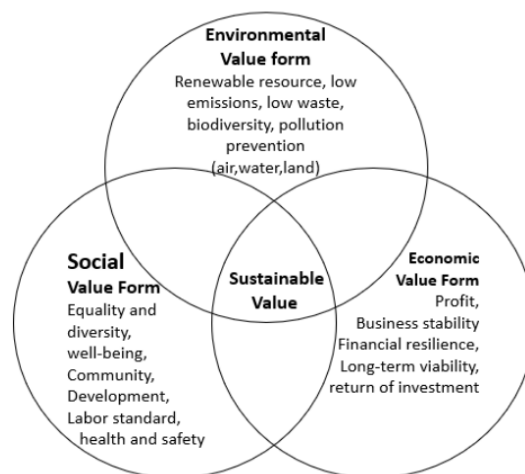
DES is therefore an integral part of the Digital Twin framework where the virtual entities of the physical world are created and modelled. The virtual world of the Digital Twin is completed by making use of data from the Enterprise Resource Planning, Manufacturing Execution System and DES for enabling smart manufacturing of the production shop floor [15].

## 2.2 Sustainable production

The sustainability concept was first introduced in 1987 by United Nations World Commission on environment and development [16]. Sustainable production is defined as "Sustainable production is creating goods by using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for employees, communities, and consumers and which are socially and creatively rewarding for all stakeholders for the short- and long-term future" [17]. Sustainable manufacturing helps to consume resources effectively and efficiently by minimizing the emissions and wastes and therefore conserve resource and energy for future generations [16]. In addition, the Industry 4.0 has marked its position by including various digital technologies put together modify the production inputs, processes and outputs enabling value creation across TBL of sustainability (Economic, Environmental and Social) [16]. The TBL will be explained in more detailed way in the following subsection 2.2.1.

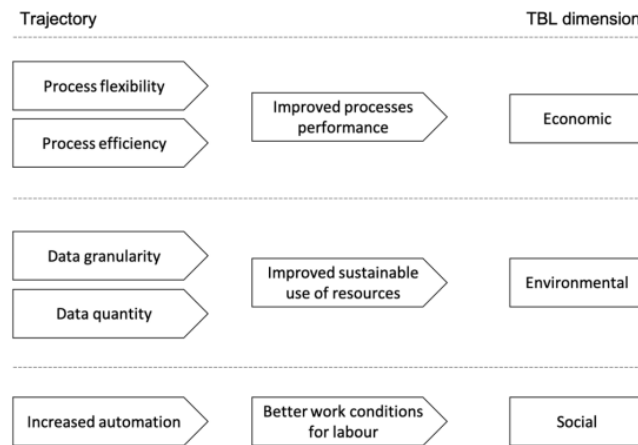
### 2.2.1 Triple Bottom Line

Sustainability is considered to be a multi-dimension concept known to include TBL that incorporates Environmental, Social and Economic perspectives of sustainability [16]. TBL aims to support the concept of sustainability in industries by being sustainable in three dimensions, economic, environmental and social. In other words, sustainable manufacturing from the perspective of the TBL aims to reduce environmental impact, care for society and at the same time be profitable and competitive in the market [18]. The TBL view of sustainability is shown below in Figure 2.3.



**Figure 2.3:** Triple Bottom Line of Sustainability [16, Fig. 1]

Industries are said to be sustainable if they consider value creation in a more holistic way and integrates environmental and social goals into its value creation process [19]. For instance, the value creation in social aspect and economic aspect is a main driver of social entrepreneurship [19]. Whereas, value creation in environmental aspect and economic aspect by solving environmental issues and simultaneously creating economic value will be termed as eco-entrepreneurship [19]. But the firm is said to be completely sustainable when it is capable of creating value in all the three aspects [19]. A recent article provides the trajectories for the TBL dimension as shown in the Figure 2.4 [16].



**Figure 2.4:** Trajectories of sustainability in Industry 4.0 [16, Fig. 2]

The author in the paper [16] proposes three trajectories of sustainability in the TBL perspective for the Industry 4.0 applications, see Figure 2.4. Firstly, the economic sustainability is the result of process flexibility and process efficiency can be achieved through improved process performance. Secondly, in-order to leverage the environmental sustainability performance, it is important to improve the capability in achieving data granularity and data quantity and therefore utilizing the technology in a more sustainable way. Lastly, increased automation leads to a more socially sustainable system by improving the labour working conditions, health, safety etc., [16]. The three dimensions of sustainability is described in the following subsections.

### 2.2.1.1 Environmental sustainability

The environmental perspective of sustainability aims for natural resource consumption and thus have less effect on the ecosystem by producing emissions that can naturally be absorbed by the nature [16]. Further, to be environmentally sustainable, industries need to minimize resource use, replace non-renewable resources to renewable resources and follow circular economy principles such as re-use, recycle, regeneration, re-manufacturing etc, [16]. Some environmental approaches mentioned by Glavic [17] are waste minimization, zero waste, LCA, Pollution control, eco-design, cleaner production and green chemistry. It is found that striving for environmental sustainability in any manufacturing industries will not only benefit the production process and products but also to the environment and the customers

[16].

### 2.2.1.2 Social sustainability

The technologies, automation and digital solutions in the current industrial revolution referred to as Industry 4.0 has caused several changes in the dynamics of human resources [20]. Galuppo [21] defines social sustainability as “the impact of products or operations on human rights, labor, health, safety, regional development, and other community concerns”. In other words, industries are said to be socially sustainable when there is value creation by focusing on its employees job satisfaction, quality of life, training opportunities, standard working conditions, safety, health etc. Thus industries need to strategically manage their human resources which will directly or indirectly be impacted by the organizational decisions [16]. Comparing Industry 4.0 with that of Traditional manufacturing, there is transformation of all the labour intensive industries into more socially sustainable industries [16].

### 2.2.1.3 Economic sustainability

The economic sustainability of TBL is concerned with the overall economic performance of industries. Industries become economic sustainable by creating value and balancing costs and revenues from production and distribution of products and services [16]. Industry 4.0 has a major role in transforming industries into more economically sustainable by substituting humans with more efficient resources, robots. This results in reduction of production costs and increase in productivity by reducing the lead times, and therefore improves the economic performance of the system [16].

## 2.3 Key Performance Indicators

Key Performance Indicators are measurable units that help industries grow by basing their decisions on the performance and achieving their set objectives. In other words, KPIs are used to find the improvement potential and evaluate the success of any industry [22], [20]. KPIs not only allow production managers to analyze the performance of the product and processes, but also help in managing all the production level activities such as resource allocation, modifying process parameters, production scheduling etc, [20]. This way the KPIs help the industries achieve their set objectives efficiently and effectively by continuous evaluation, monitoring and optimizing the production processes [22].

KPIs can be defined to different resources such as equipment’s, sub-processes or for overall production plant [20]. In order to visualize all the defined KPIs, the obtained value for the KPIs will be compared to the target value to fulfill the production objectives [23]. In addition, the optimization activities depend on to how near the performance value is to the target value [22]. However, the task of choosing appropriate KPIs is observed to be challenging as KPIs need to align with the set objectives that need to be accurate and production managers should gain a deeper

understanding of what is important to the industry before deciding the KPIs for any system [23].

Further, the design of KPIs must be flexible enough to measure the performance of industry in dynamic market conditions consistently [23]. For instance, the market requirement of transforming industries to more sustainable industries, has aroused the need of KPIs that are capable of assessing the sustainability aspect and achieve TBL goals set by industries [23]. Lastly, to define some of the KPIs, the performances that can be measured are such as energy, material, maintenance, control and operation, etc. [20]. The technologies, automation and digital solutions have resulted in the increased efficiency, productivity, flexibility and reduction in production costs, thus enabling sustainable development in industries [20].

### 2.3.1 KPI framework

As mentioned earlier, KPIs always associate with the set objectives used for benchmarking, reporting and improvement triggers in the production [18]. The KPI framework is a hierarchical structure consisting of elemental KPI at the lowest level and basic KPIs in the mid-level and comprehensive KPIs at the higher level [18]. The KPI categories are named as elemental KPIs, basic KPIs and comprehensive KPIs.

At the lower level, the elemental KPIs are the measures obtained from the data points for acquiring required information [18]. Examples for elemental KPIs are actual production time, planned busy time, rework quantity, good quantity and cycle time [18]. In the mid-level, the basic KPIs are the indicators which are often calculated by formulas containing elemental KPI values or measures. The basic KPIs are useful for predicting a particular trend resulting from the several data points or elemental KPIs [18]. Examples of basic KPIs are availability, quality ratio and effectiveness [18]. The comprehensive KPIs formed by several basic KPIs, for instance, mathematical formula for the KPI, Overall Equipment Effectiveness (OEE) requires values of the basic KPIs (indicators) such as availability, effectiveness and quality ratio [18].

The industries combine all the three levels of KPIs for decision making or benchmarking. When compared to elemental and basic KPIs, comprehensive KPIs are used by the company to check if its performance aligns to the objectives set by the industry [18]. Further, the measurement of KPIs is possible with an appropriate measuring equipment or a tracking system, databases for storing production data, service tools for transforming data into information and systematic decision making system [18]. The current infrastructure in Industry 4.0 has brought huge possibilities to track and capture every data point that increases the accuracy of analyses and decision making by production managers. For example, DES can be one among such Industry 4.0 technologies enabling accurate decision making based on the results of performance indicators calculated from the data collected from the databases and other service tools.

### 2.3.2 Sustainability KPIs

Sustainability KPIs are a set of performance indicators which will help to fulfill sustainable objectives of the industries [23]. The difference between traditional indicators and sustainability indicators is that both the types have different objectives. However, according to study in [18], about 90% of the existing KPIs contribute to the sustainable objectives of the industries. The results of sustainable KPIs help to assess the sustainable performance of the industries and therefore take necessary decisions that can fulfill TBL goals and hence achieve overall sustainability. In order to achieve sustainable objectives such as reducing environmental impact, eco-efficient manufacturing or green manufacturing, industries need to monitor certain parameters such as energy consumption, costs incurred in overall production, cost and type of materials used and their emissions [23]. For instance, the KPI material emissions provides necessary information by evaluating emissions caused by the material consumption and can be visualized by comparing it with the target value for material emissions that is considered to be sustainable. To carry out such sustainable assessments there are various methods and tools such as LCA, LCI, Impact assessment etc. [23].

# 3

## Methods

This chapter describes the overall methods followed during the project in detail as shown in the Figure 3.1. The methodology is the combination of triangulation research methodology [24] and banks methodology for modelling and simulation purpose. The triangulation methodology includes literature review, qualitative study and quantitative study. The results of each component of triangulation methodology will be used for validation of results of other. This method was carried out from the beginning task of finding appropriate sustainability KPIs until the task of completing the DES model. There were continuous qualitative and quantitative studies also known as mixed methods carried out during the modelling and simulation of the drone factory using banks methodology [24].

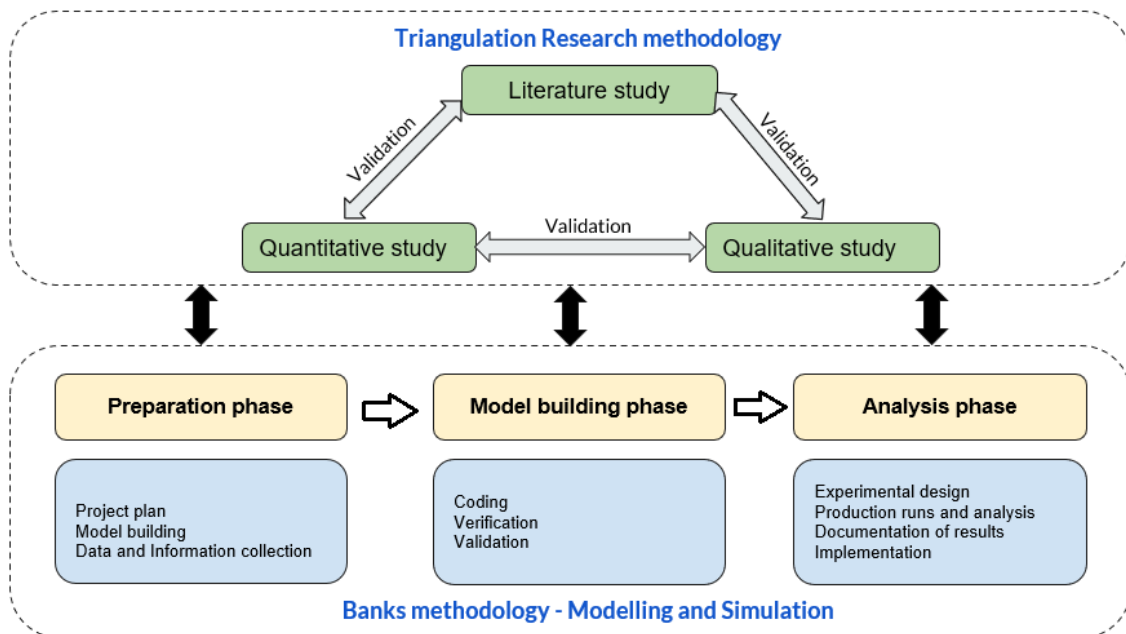


Figure 3.1: Research design

### 3.1 Literature study

The literature study helps to obtain background information of the subject. The purpose of carrying out the literature study was to study what has been researched about the sustainability KPIs in the DES and Digital Twin context, what kind of methods or frameworks are used and what kind of observations and results have

been obtained. The facts collected from the literature were used to make assumptions throughout the project. The goal was to use the literature results to integrate and build the DES model. Hence, the focus was to explore the most recurring or preferable sustainability KPIs that assist manufacturing industries to transform into more sustainable or eco-efficient manufacturing. In addition, the results were utilized to gain knowledge on KPI information and calculations to evaluate and select most suitable KPIs that can be measured and integrated in the DES model.

### 3.1.1 Search strategy

The research was carried out using different search engines for reaching the wider knowledge source. The database Scopus, provided by Chalmers library was used. The relevant papers were found using the keywords and screening process described below in the Figure 3.2.

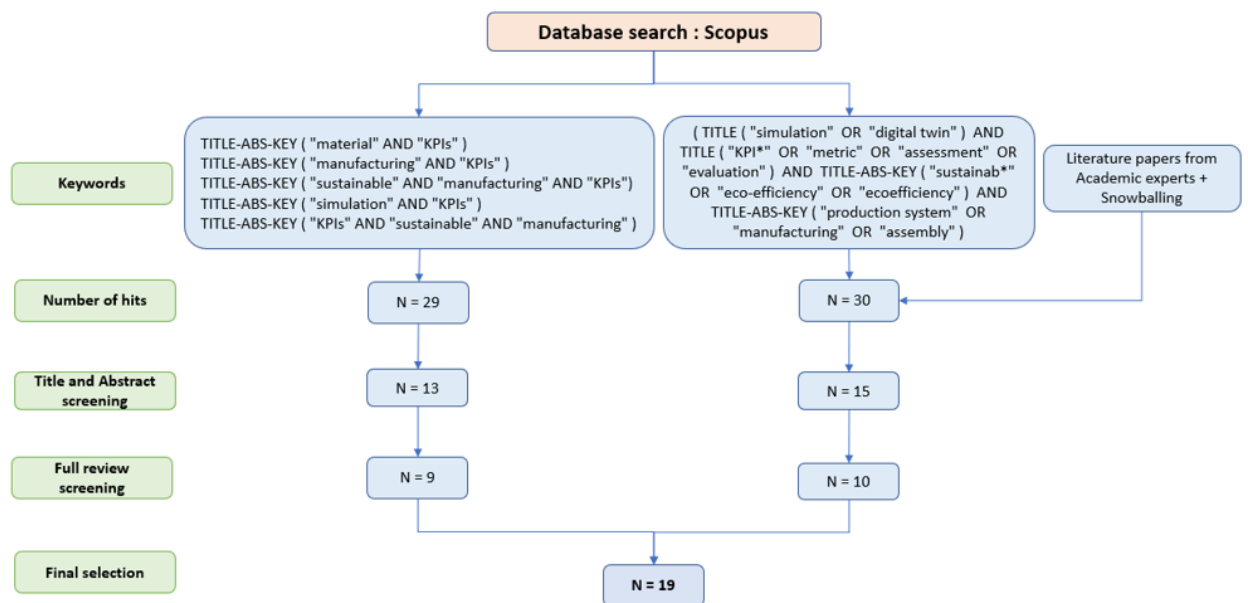


Figure 3.2: Search strategy

The keywords were further limited to the subject area Engineering, Environment, Business Management and Accounting, Computer science, Materials science, Energy and Social sciences, year of publication to 2015-2020 and the language of literature to English. The screening of papers was carried out in two steps, first step was by reviewing title and abstract and second step was by full reviewing the paper. The full reviewed papers were used for selecting most recurring sustainability KPIs for incorporating in the DES and reflect upon the current studies and the methodologies used in industries for building sustainable DES.

### **3.1.2 Identification of sustainability KPIs**

The selection of KPIs from the literature was based on the objective that the KPIs need to contribute to at least one aspect of TBL of sustainable manufacturing. The papers were fully reviewed and the KPIs in each paper were listed into categories of economic, environmental and social KPIs. Further, the papers selected for the full review were coded against each category of KPIs that each paper proposed using the Excel sheet. Lastly, the results of literature study showed the number of papers that have used every KPI to transform into more sustainable manufacturing.

### **3.1.3 Selection of KPIs for the DES model**

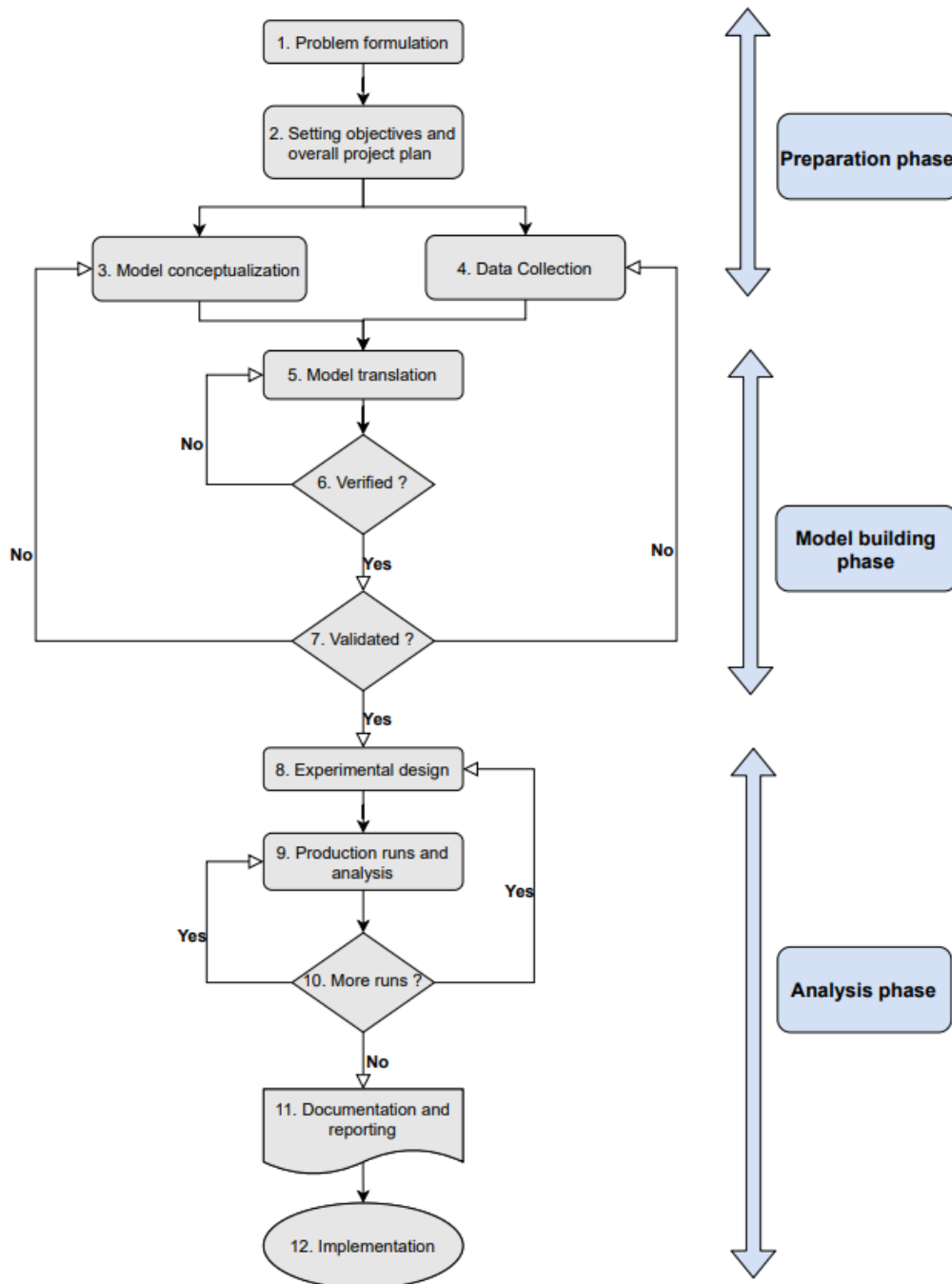
The environmental and economic KPIs were selected from the literature results for integrating the KPIs with the DES model. A quantitative analysis was carried out for KPI selection process where the literature results of economic and environmental results were studied and the most recurring basic KPIs were selected for integration purpose. To calculate each of these selected basic KPIs, the elemental KPIs were selected based on the relevance and data availability for calculations and obtain results in the DES of the Drone factory.

## **3.2 Simulation methodology**

The DES model was built based on the steps described by Banks methodology [25]. The methodology includes three main phases, preparation phase, model building phase and the analysis phase. The preparation phase includes problem formulation, project plan, data collection and conceptual model preparation. The model building phase includes model translation, verification and validation. Lastly, the analysis phase includes experimental design, production runs and analysis and documentation of the results. The steps followed in Banks methodology is illustrated in Figure 3.3 below. The tasks carried out during the three phases of Banks methodology shown in the Figure 3.3 will be explained in detail in the sections below.

### **3.2.1 Preparation phase**

In the first step of the preparation phase, problem formulation, a detailed problem analysis was carried out and the aim and purpose of the project was defined. In the second step, all the objectives that will fulfill the aim and purpose of the project were defined along with a detailed project plan that in addition to the problem analysis, aim and purpose, also included method, delimitation's and the timeline for the project. Further, the third and fourth steps, model conceptualization and data collection were carried out in parallel through both qualitative and quantitative studies. The third and fourth steps are explained in detail in the sections below.



**Figure 3.3:** Banks et.al's simulation methodology [25]

### 3.2.1.1 Model conceptualization

A conceptual model is a software independent description of the real system or a model that needs to be constructed [26]. The conceptualization process was carried out for four different concepts namely, AS-IS scenario, Base scenario, Experimental scenario 1 and Experimental scenario 2. Mapping the production system using process flow chart is one of the most widely used representation technique [27]. Therefore, each of the scenarios were described with a process flow chart helping to visualize the production flow information.

According to Robinson [26], the model needs to be based on both client and modeler perspectives. The AS-IS scenario represents the current state of the production system and was constructed based on the information collected through discussions with the SII-Lab which is one of the qualitative studies. The AS-IS concept was used as a reference to further modify and visualize other proposed concepts. For the base scenario, the requirement of the SII-Lab was considered for designing a production system that can process two variants in the same facility. The model and the process flow charts described the work procedure for each of the variants with defined production stages carried out at assigned assembly stations.

Further, for selecting the suitable scenarios for experimental analysis, a qualitative study was carried out by conducting discussions and brainstorming sessions with academic experts at Chalmers and representatives at SII-Lab. The conceptualization of multiple scenarios was drafted in the form of process flow chart and were used during discussions and brainstorming sessions. The objective of these sessions was to check the feasibility of the scenario for real-time implementation, to assess the sustainable aspects of the Drone factory and further fulfill the sustainable Digital Twin implementation. The other aspects considered included the time and data availability for building the intended scenario. The conceptual models of all the four scenarios namely, AS-IS scenario, Base scenario, Experimental scenario 1 and Experimental scenario 2 were used as a reference in the model building phase.

### 3.2.1.2 Data collection

The main objective for input data collection was to collect all the production data listed below:

1. Production parameters such as processing times, availability, MTTR (Mean Time To Repair), setup times and scrap processing times.
2. Work procedure of both the product variants.
3. Material related data of the both variant products 'Var A' and 'Var B'. The data such as material type, quantity of respective components in each variant, weights of all the components, scrap rate, rework rate and product cost.
4. Energy related data such as power consumed by the production equipment's in the production system for estimating total energy costs of the production system.
5. Material consumption data for manufacturing components of one unit of product of both variants 'Var A' and 'Var B'.

In the paper [28], the input data for the DES has been categorised into three categories based on the approach of collection reflecting the availability of data. The Figure 3.4 shows the three categories of input data.

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

**Figure 3.4:** Input data classification[28]

The data collection process for the Drone factory mostly belonged to the category B and C as the SII-Lab is a test-bed and not an actual manufacturing unit. The category A input data included the data of production parameters such as processing times of both variants, availability, MTTR, setup times and scrap processing times. In addition, the material related data such as material type and quantity were collected from the BOM (Bill of Materials) of each of the variants provided by the SII-Lab.

The work procedure of each product variant were collected from the SII-Lab in the form of assembly instruction documents and manual assembly video and this input data is categorised under category A. The work procedures for both the variants were understood to match the requirements of the conceptual models. For instance, 'Var A' follows a work procedure including three assembly stages whereas the base scenario demands for design of work procedures carried out in two assembly stages. The sequence of manual assembly activities were analyzed and was transformed into two stage assembly with balanced processing times for each stage.

Further, components information such as weights of each component was one of the category B data, which was manually collected by weighing components of both variants. The rest of the material related data such as scrap rate and rework rate belonged to category C and were assumed based on the standard industrial practices. Lastly, the energy related input data belonged to the category C input data as the Drone factory does not have any kind of technology for measuring the energy consumption of the production system. Therefore, the power consumed by the technical equipment used in the final assembly such as conveyor system, PLC, Human Machine Interface (HMI) were retrieved from the respective equipment manuals obtained from the support of literature and websites. Further, the energy consumption data was used to estimate the energy costs.

The input data, material consumption and product cost of both the variants belonged to category C input data. To make estimations on the material consumption for manufacturing components required for one unit of product, the technical specifications of 3D printing technology was collected from the product manual. The product manual was referred to collect efficiency rate of the 3D printer and further make estimations for material consumption for component manufacturing. In addition the cost of each product variant was estimated with the help of product weight data available and cost of respective powder materials from the literature sources.

### 3.2.2 Model building phase

The model building phase comprises of three steps which are model translation, model verification and model validation. In this master thesis, "Siemens Technomatrix Plant Simulation" which is later referred to as plant simulation is used as the simulation software for creating the DES model. The primary reason for using this software was because our examiner had created a conceptual model frame in plant simulation before starting this thesis. The secondary reason is the availability of an easy access to the academic version of the simulation tool. In this thesis the modelling object is a Digital Twin of an assembly line producing drones at the test facility in SII-Lab.

#### 3.2.2.1 Model translation

Plant Simulation is an object oriented software and hence modelling complex systems can be easily structured and managed. The object oriented programming method in Plant simulation enables users to make use of features such as attributes, classes, inheritances and derivations. The following Figure 3.5 is used order to explain the model building and translation more clearly. The Figure 3.5 is 2D representation of the assembly line at the lab which has been created by using inbuilt icons in plant simulation. The Event controller handles all the discrete events. The start time and the end times of the simulation are set in the event controller. The warm-up times of the production system if required are also to be set in the event controller. In this model the source is the start of the process and it is at this point where all the Movable Units (MU's) are created which are then shifted onto the next process in the simulation by using connectors.

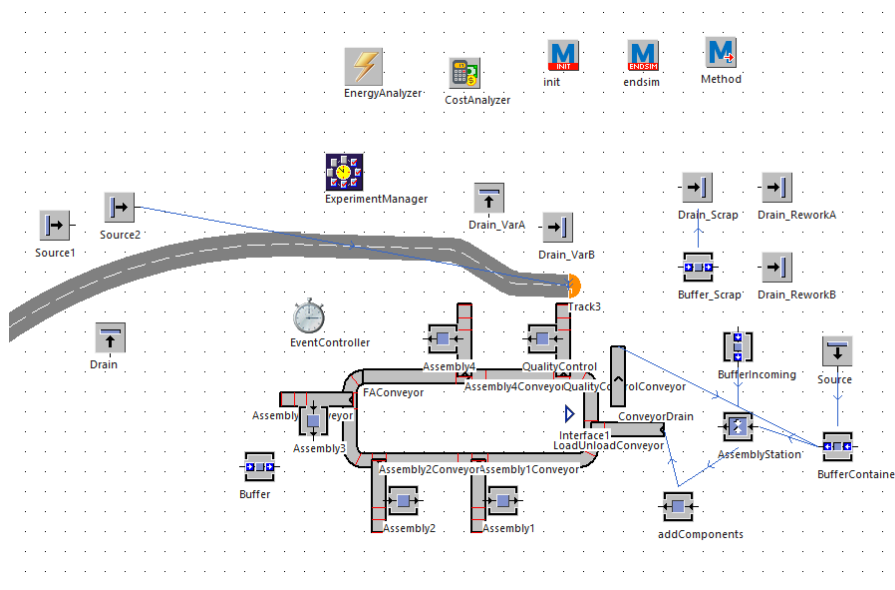
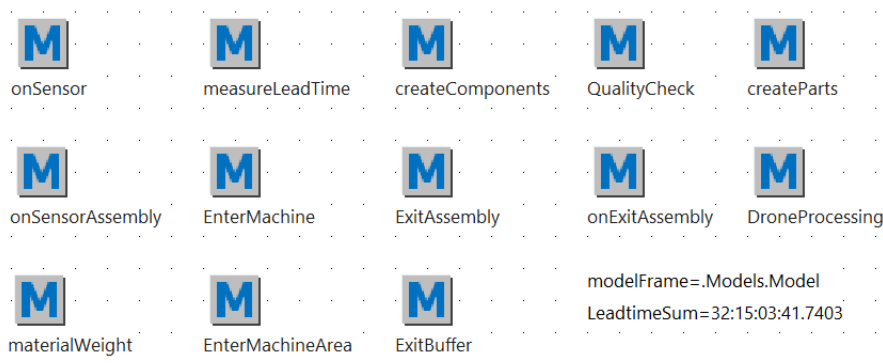


Figure 3.5: Model in Plant Simulation

In this model the source passes on the MU's to a buffer where it is stored until the MU's can be passed onto the next process. The capacity of the buffers can be set by the users. The conveyor system helps in moving the MU's from one station to another. The assembly stations are the objects where the individual components of the MU's are assembled. The MU's are held at these stations for certain duration of time (Processing Time) which is defined by the user. The drain receives the MU's and deletes them and this is the end of the simulation. The methods allows users to program custom functions. In this model several methods have been used as shown in the the Figure 3.6. Each of these methods run a program which determines the model behavior. Plant simulation uses its integrated programming language called the SimTalk which can be used in the methods for coding purposes. The program within these methods for the drone factory model is given in Appendix B .



**Figure 3.6:** Methods Frame of the Drone Factory Model in Plant Simulation

The object modelling along with the code directly translates to the system parameters and these can be effectively controlled by changing the code in the methods to mimic different behaviors of the simulation model. The simulation software also provides various methods to monitor the statistical performance of the model by displaying the attributes, methods and statistics in real time. Parameters or statistical values that show large deviations can be recorded and exported to Microsoft Excel for further analysis.

#### 3.2.2.2 Verification of DES model

According to the Banks methodology [25], verification of the DES model is defined as the process of checking if the model satisfies the requirements specified in the conceptual model. This process of verifying the DES model with the conceptual model was carried out after every change made during the model translation which also helped to examine the accuracy of logic used for transforming requirements into conceptual model and conceptual model into executable DES model [25].

The below questions were used for verifying the executable model (DES model) [25]:

1. Does the executable DES model shows the correct implementation of the conceptual model?
2. Does the executable DES model produce results in the intended format?

### 3.2.2.3 Validation of DES model

According to [25], validation is the process of confirming if the results which are in the form of conceptual model and executable model (DES model) satisfies all the requirements intended by the customer (academic and industrial experts). Every small change suggested by our customers had an huge impact on the results helping to obtain effective and credible results. Validation helped to examine the accuracy of representation of the real-world production system by the conceptual model and the simulation results obtained from the executable model (DES model). During building the model, it was being validated during supervision meetings by our examiner and further the final model was validated by the industrial experts at SII-Lab. The below points were taken under consideration for validation from academic and industrial experts [25].

1. To check if the conceptual model is the correct representation of the real-world production system.
2. To check if the results are credible and accurate when compared to the real-world production system.

### 3.2.3 Analysis phase

The analysis phase is the last stage of the simulation modelling which includes experimental design, production runs and analysis, documentation and implementation. Once the model has been validated. In this phase we design experiments based on the model. In this case experiments were designed to determine effective methods to increase production sustainability. The method in which the experimental design was made and conducted is explained in the following section. For the experimental design the following four scenarios of the production systems were chosen:

1. AS-IS Scenario
2. Base Scenario
3. Experimental Scenario-1
4. Experimental Scenario-2

A common set of production parameters were set for all the four scenarios to compare and identify the best operating scenario. Several parameters such as the Customer demand, product variants and the size of pallets were varied to determine the potential increase in throughput while maintaining the environmental KPI's to a minimum. The experiments were run on the experimental manager in plant simulation. Each experiment was run for a total time duration of 6 days and 10 replications to obtain stable and reliable values. The results of the experiments were obtained in a table which was exported to excel for further analysis. The details of the experiments and their results are presented in the results chapter.



# 4

## Results

### 4.1 Literature review

This section provides a detailed description of the results obtained from the literature review for identifying and selecting suitable KPIs to assess manufacturing sustainability. The section also reflects on the current studies on incorporating sustainability tools with the DES.

#### 4.1.1 KPIs for sustainable manufacturing

The literature review yielded several economic, environmental and social indicators that are commonly used by industries to address the TBL of sustainability for manufacturing processes. Naderi et al, [4], argues that it is necessary to identify the right set of manufacturing indicators to support the organizational decision making process to achieve the company objectives and goals.

Several criteria should be considered for the selection of KPI depending on the type and scale of the industry [29]. KPI selection therefore, requires multiple factors or parameters that have to be considered where the objectives of the KPIs must be defined to measure the effectiveness of the KPI against the selection criteria. The selected KPI can thus be used to measure and monitor the sustainability performance of the manufacturing floor [29]. This notion for selecting a few appropriate and valid KPIs rather than having numerous indicators to measure sustainability is further asserted by Paola Fantini et al. [30]. The author also suggests a holistic framework for selecting the KPIs by modelling the physical flows of a manufacturing system i.e products, materials, energy, emissions, among others from the input to the output phases [30].

Although most literature's proposed different methods of classifications and frameworks for KPI selection all papers commonly suggested that eco-efficiency indicators alone may not be sufficient for measuring the sustainability performance. This is attributed to the fact that there can be certain trade-offs between indicators due to the complexities and inter-dependencies among various products or materials and resource flows within the factory [31], [32]. Similarly another connection between economic and environmental sustainability found was that Weeber et al. [33] explains how energy efficiency measures to assess the energy consumption levels can either increase productivity and hence emission levels or decrease the emission levels and consequently decrease the productivity. There is hence a need to identify an ideal or neutral state to maintain a balance between the economic, environmental

and social sustainability [4].

Moreover, production sustainability cannot be measured only using environmental indicators such as emissions or energy consumption as some production KPIs such as material efficiency and productivity can also have an influence on how efficiently the resources are being used in the system [18]. Therefore, a quintessential parameter for a holistic KPI framework is to consider the impact of economic and social indicators for monitoring, controlling and improving environmental sustainability [18]. Hence, to fully capture a production system's performance it is necessary to include all the manufacturing performance indicators such as lead time, Overall Equipment Efficiency (OEE) and its components including availability, performance, quality, effectiveness, utilization rates etc.. whilst focusing on the TBL indicators. The TBL indicators include material and energy consumption, material and energy emissions, hazardous and non-hazardous wastes, share of reused or recyclable material etc. [30], [34], [35].

Further, while selecting the KPIs for sustainable production it is necessary to understand the purpose for measuring KPIs and their strategic implications that can help in design, implementation and the revision phases of the KPI life-cycle [18]. An important distinction to make here is the difference between measures and indicators. A measure is often a result of a direct measurement activity to acquire data or information, while an indicator can be a result of two or more measures providing a more comprehensive information that can be directly used for making predictions and decisions [18]. The following Tables 4.1, 4.3 and 4.2 provide a list of the important economic, environmental and social indicators respectively and their respective measures that have been identified from the literature study.

The identified economic, environmental and social indicators showed complex interrelations between them thereby creating an atmosphere of ambiguity for the decision makers to use these indicators strategically without compromising between them for making production shop floor improvements [31]. Furthermore, the modern production systems are dynamic due to the numerous uncertain factors that are constantly varying [32]. To overcome these difficulties and provide help towards the decision making process several researches propose the use of DES methods with integrated performance indicators to run virtual experiments and analyze the complex process flows for improving manufacturing sustainability [31], [5].

Nancy Diaz-Elsayed et al, [36] discusses on the potential benefits of using a combination lean principles and green manufacturing strategies to improve process sustainability. DES again plays a crucial role in simulating, optimizing and validating such a scenario of using a concoction of lean and green manufacturing strategies [36]. The KPIs contributing to the three pillars of sustainability, that is Environmental, Economic and Social aspects are listed as shown in the Figure 4.1.

**Table 4.1:** List of Economic Indicators.

| Environmental KPIs                                                                                                                                            | References |     |      |      |      |      |      |      |      |      |      |      |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|-----|------|------|------|------|------|------|------|------|------|------|
|                                                                                                                                                               | [4]        | [5] | [16] | [18] | [29] | [30] | [31] | [33] | [34] | [35] | [36] | [37] |
| Quality<br>(Rework Ratio,<br>Scrap Ratio,<br>First Pass Yield,<br>Storage and<br>Transportation loss<br>ratio, Product<br>Durability,<br>Product Reliability) | x          |     |      | x    |      | x    |      |      | x    |      |      |      |
| Cost<br>(Inventory, energy,<br>material, labor,<br>equipment,<br>maintenance)                                                                                 | x          | x   |      | x    |      | x    | x    | x    | x    | x    | x    | x    |
| Delivery<br>(Cycle-time,<br>lead-time, Takt-time)                                                                                                             | x          |     |      | x    |      | x    |      |      |      | x    |      | x    |
| Flexibility<br>(Batch size, process<br>flexibility,<br>volume, setup time)                                                                                    | x          |     |      | x    |      | x    |      |      | x    |      |      |      |
| Productivity<br>(Worker Efficiency,<br>Throughput Rate,<br>Overall Equipment<br>Effectiveness,<br>Availability,<br>Utilization)                               |            |     |      | x    |      | x    | x    |      |      |      |      | x    |

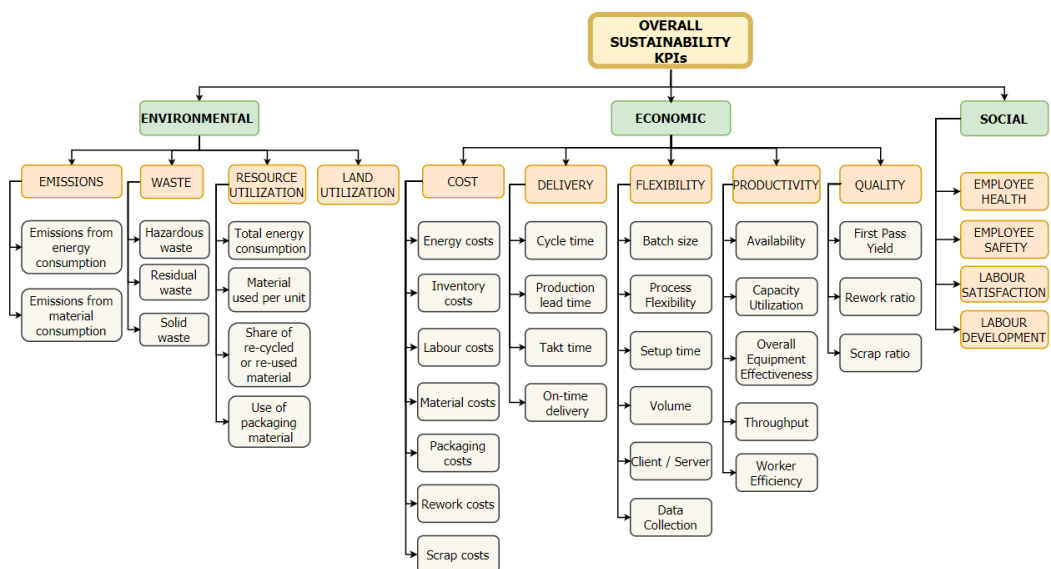
**Table 4.2:** List of Social Indicators.

| Social KPIs        | References |     |      |      |      |      |      |      |      |      |      |      |      |
|--------------------|------------|-----|------|------|------|------|------|------|------|------|------|------|------|
|                    | [4]        | [5] | [16] | [18] | [29] | [30] | [31] | [33] | [34] | [35] | [36] | [37] | [38] |
| Employee safety    |            | x   | x    |      |      |      |      |      | x    | x    | x    | x    |      |
| Employee health    |            | x   | x    |      |      |      |      |      | x    | x    | x    | x    |      |
| Labor satisfaction |            | x   |      |      |      |      |      |      | x    |      | x    |      |      |
| Labor development  |            | x   | x    |      |      |      |      |      |      | x    | x    | x    |      |

#### 4. Results

**Table 4.3:** List of Environmental Indicators.

| Environmental KPIs                             | References |     |      |      |      |      |      |      |      |      |      |      |      |   |
|------------------------------------------------|------------|-----|------|------|------|------|------|------|------|------|------|------|------|---|
|                                                | [4]        | [5] | [16] | [18] | [29] | [30] | [31] | [33] | [34] | [35] | [36] | [37] | [38] |   |
| Resource utilization (energy, water, material) | x          | x   |      | x    |      |      |      |      |      |      | x    | x    | x    | x |
| Emissions                                      | x          | x   | x    | x    | x    |      | x    | x    | x    | x    | x    | x    |      |   |
| Share of renewable resources                   |            |     | x    | x    |      |      |      | x    |      |      |      |      |      |   |
| Scrap / Waste (hazardous, residual, solid)     | x          | x   | x    | x    |      |      | x    |      |      |      |      | x    |      |   |
| Land utilization                               |            | x   |      |      |      |      |      |      |      | x    | x    |      |      |   |
| Noise pollution                                |            |     | x    |      |      |      |      |      |      | x    |      |      |      |   |
| Material efficiency                            |            |     |      |      | x    | x    |      |      |      |      |      |      |      |   |
| Energy efficiency                              |            |     |      |      | x    | x    |      |      |      |      |      |      |      |   |
| Quality                                        |            |     |      |      |      |      |      |      | x    |      |      |      |      |   |
| Share of reused /recycled material             |            |     |      | x    |      |      |      |      |      |      |      |      |      |   |
| Eco-efficiency                                 |            |     | x    |      |      | x    |      |      |      |      |      |      |      |   |



**Figure 4.1:** KPIs selected from Literature review.

### 4.1.2 KPI selection for the DES model of the Drone factory

It was found that most recurring basic environmental KPIs were emissions, resource utilization and waste and most recurring basic economic KPIs were cost, delivery, productivity and quality. In addition the elemental KPIs under each of these KPIs were selected based on the relevance and data availability for incorporating with the DES of the Drone factory. For instance, the elemental KPIs under waste such as hazardous and residual waste are not qualified in the Drone factory scenario, as only solid waste is produced. However, it was observed that additional measuring points had to be estimated by using the attributes obtained from the DES model, for analyzing the selected elemental KPIs through the DES. The Figure 4.2 shows the selected KPIs for integrating with the DES model.

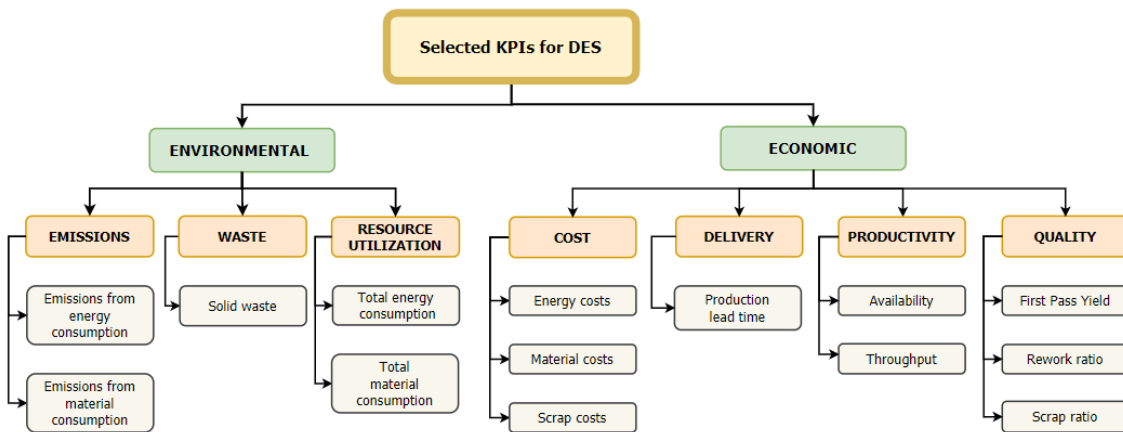


Figure 4.2: KPIs selected for the DES.

### 4.1.3 Description of selected KPIs

KPIs are often misinterpreted with different meaning and therefore it becomes important to describe each KPI in a detail way with description, scope and unit of measure [20]. The selected elemental KPIs were described as shown in the following list (refer Figure 4.2):

1. **Emissions from energy consumption:** It is the measure of total electricity consumed by all the equipment's used in the production system for producing N number of products. The scope or the KPI relevance is for overall process or product. The unit of measure is kgCO<sub>2</sub>eq.
2. **Emissions from material consumption :** The material related carbon emissions is used to depict the emissions from the unit process which processes number of types of materials with assigned quantity of the same. The scope is for the product and the unit of measure is kgCO<sub>2</sub>eq.
3. **Solid waste:** It is the quantity of scrap/solid waste generated to produce number of units in the production system. The scope or KPI relevance can be both for the process and the product. The unit of measure is kg.

4. **Total energy consumption:** It is the measure of total energy/electricity consumed for producing N number of products. The scope or KPI relevance can be for both process and work unit. The unit of measure is kWh.
5. **Total material consumption:** It is the measure of total productive material consumed in a system considering the efficiency of the system for producing N number of products. The scope or KPI relevance is for the process. The unit of measure is kg.
6. **Energy cost:** It is the total cost for consuming certain amount of energy (electricity) in the system while producing N number of products. The scope or KPI relevance is for the process and the unit of measure is SEK.
7. **Material cost:** It is the total cost of each component used for assembling a respective product variant. The scope or KPI relevance is for product and the unit of measure is SEK.
8. **Scrap cost:** It is the measure of sum of costs of all the components that have been scrapped in the production system while producing N number of products. The scope or KPI relevance is for the process and the unit of measure is SEK.
9. **Production lead time:** The total time taken for the product to reach the drain from the time it enters the production system. The scope can be for the process, work unit, type of variant and product. The unit of measure is time.
10. **Availability:** It is the percentage of time that the work unit is available out of total production time. The scope or KPI relevance is for a work unit or a station. The unit of measure is %.
11. **Throughput:** It is the measure of efficiency of the system in terms of quantity of products produced in a certain time. The scope or KPI relevance is for the process or production order. The unit of measure is quantity/time.
12. **First Pass Yield:** It is measure of number of good quality products against the number of inspected products at the quality station. The scope or relevance of the KPI is both for the product and the process which depends on the type of quality issue. The unit of measure is %.
13. **Rework ratio:** It is the ratio of number of rework products to the number of inspected products at the quality station. The scope or KPI relevance can be both for product and the process. The unit of measure is %.
14. **Scrap ratio:** It is the ratio of number of pallets with scrap components to the total number of pallets with good quality components. The scope or relevance of KPI is for the product and process. The unit of measure is %.

#### 4.1.4 Reflecting on current research for incorporating sustainable tools with DES

The author in the paper [6] highlights the capability of the DES in industries for obtaining a more efficient and optimized production system. It is observed that there are numerous case studies for the DES for the performance management. However, the main challenge is found to be implementation of DES for real-time production scenarios for optimization purposes which is possible through efficient data acquisition. Moreover, the literature highlights there is lack of effectively and efficiently managing and utilizing the simulation data [6]. The promising research area of building a platform by integrating DES and Virtual Reality (VR) that yields efficient improvements in the system was highlighted.

With today's major issues being material and resource consumption, environmental impact categories must be addressing these issues in any production system [39], [36]. The material and energy are found to be most important resources that needs to be efficiently used to achieve overall production improvements. In the paper [40], the author provides a generic framework for assessing the sustainability in terms of energy efficiency by using lean manufacturing strategy.

It is found that by combining the lean manufacturing and energy efficiency management, production costs will be lowered with increase the robustness to fluctuations in the energy costs and therefore help to estimate the environmental impacts of energy consumption. Further, the paper shows there are several sustainable Value Stream Mapping (VSM) techniques that map the carbon emissions of the manufacturing processes and capture the economic, environmental and social sustainability of the overall system. LCA being a similar method as VSM but is a more standardized process and utilizes public data available for any calculation [40].

However, VSM and LCA are not found as dynamic as they do not carry out the impact assessment on basis of the real-time manufacturing data [40], [39]. Therefore, DES is a more suitable tool to capture the real-time data and carry out the impact assessment based on the simulated data. However, for DES to be possible to carryout the impact assessment in parallel to simulating the production system, it requires sophisticated software skills and time availability to carry out in detail LCA. For a LCA, all the parameters that need to be measured in real-time have to be set for continuous real-time impact assessments [40], [39].

However, [39], [41] proposes a methodology of combining the less dynamic LCA and the dynamic DES whereas [36] provides methodology for combining lean and green strategies through DES. It is found that the proposed approaches are limited to data availability at a process level as the methodologies have been tested onto simple case studies and have obtained positive results through reducing overall production costs effecting the economical aspects of the sustainability. Because, it depends on the system capability to provide accurate data, knowledge and resources and data availability for such implementations [39]. In addition, [41] reflects that such integrated methods also are limited to the environmental parameters at a process level and to fully unfold the potential of the approach, product specific material consumption parameters has to be considered and simulated on a process level.

Nancy Diaz et.al, [36] proposed three steps for simulating, optimizing, and valuating performance indicators of a manufacturing system using lean and green strategies. The steps are modelling the current state, optimizing the system with lean and green strategies, and economic evaluation and implementation plan. These three steps provide performance valuation of discrete production system through DES where the DES model was evaluated with several lean and green strategies such as increase in quality by reducing defects, production lead time or set-up time reduction etc., For each of these strategies, the impact and the changes to be carried out in the DES were defined. However, the author does not use these strategies in the form of KPIs and knowing the importance of using the measures in the form of KPIs highlighted by [6], it is observed to have more consistent improvement scale compared to having different strategies every time.

Lastly, the role of Digital Twin is that it provides DES with rich-data environment [42]. DES utilizes this data effectively which paves the way for easy data accessibility for real-time optimization of production systems [42]. According to [42], there is sufficient research and development on the adoption of Digital Twin for optimization of products life-cycle. However, the research and development on utilizing Digital Twin for sustainable improvements in the manufacturing processes are lacking.

## 4.2 Modelling and simulation of the Drone factory

This section provides the results obtained from qualitative and quantitative studies performed during environmental impact assessment and Banks methodology for modelling and simulation of the Drone factory.

### 4.2.1 Model conceptualization

Model conceptualization is the third step in the Banks methodology, see 3.3. This section provides results of the concepts or scenarios built for the model building phase. For better understanding of the working of the Drone factory, the overview of the Drone factory was drafted as shown below in the Figure 4.3

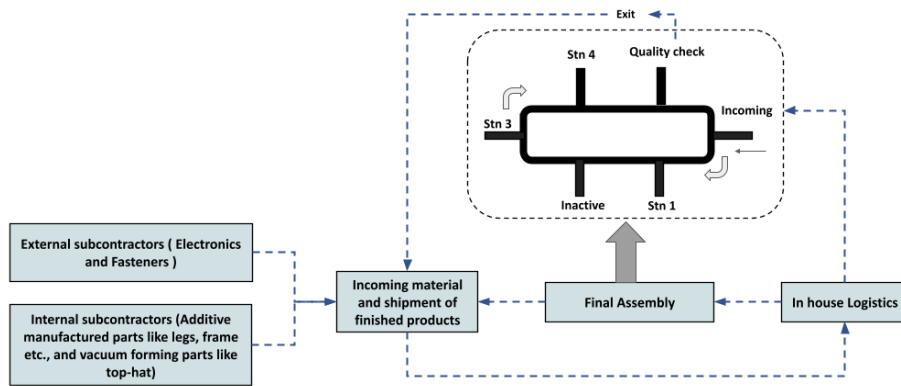


Figure 4.3: Supply chain of the Drone factory.

The conceptualization of the Drone factory for the DES model was divided into four different stages of concept models. The models evolved through the different stages or concepts as shown below in the Figure 4.4

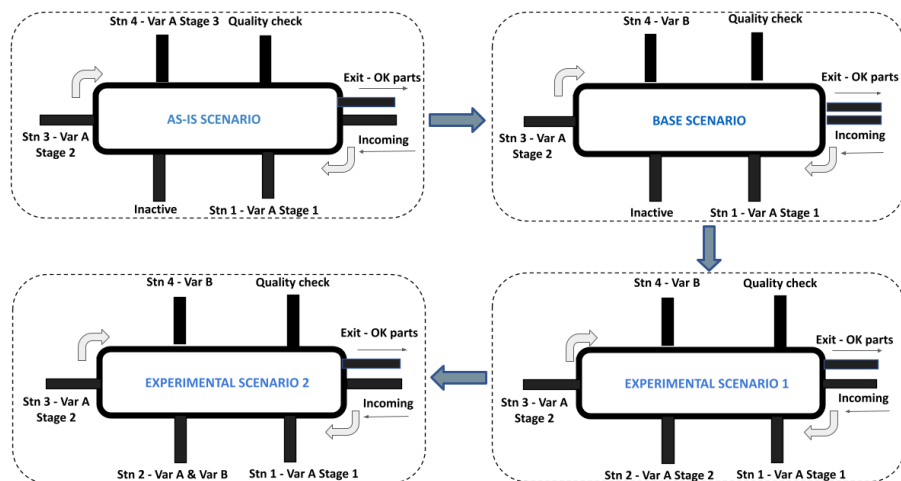
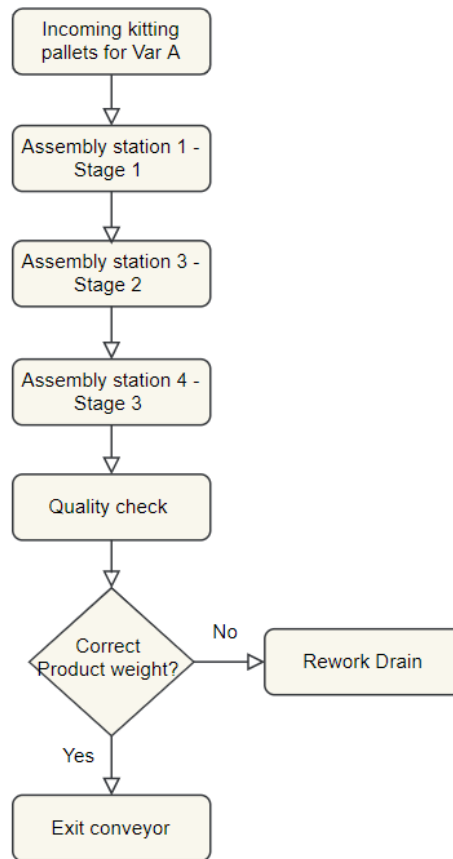


Figure 4.4: Conceptual models of all the scenarios.

The concepts are called as AS-IS scenario, Base scenario, Experimental scenario 1 and Experimental scenario 2. The work procedure for each of these scenarios will be explained in detail using the process flow charts mapped for the same.

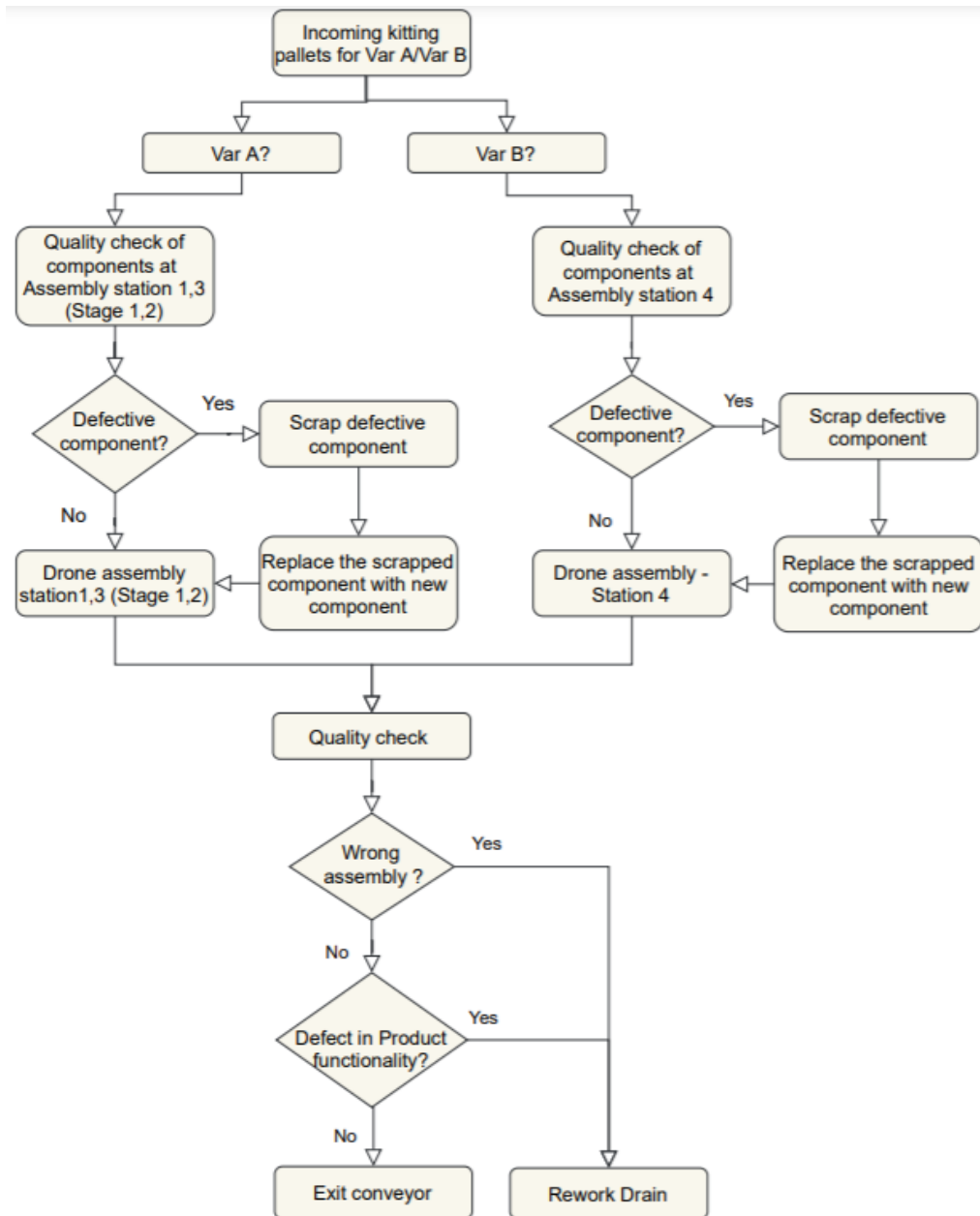
1. **AS-IS scenario:** The AS-IS scenario is the concept that reflects the current work procedure followed in the Drone factory. Currently, only assembly of one variant, 'Var A' is been carried out. The assembly process for 'Var A' includes three stages of manual assembly carried out at three different stations, 'Stn 1', 'Stn 3' and 'Stn 4', see AS-IS scenario in the Figure 4.4. The 'Quality check' station checks for the quality of the product by inspecting the correct weight of the product. The process flow chart for this concept is shown below in the Figure 4.5



**Figure 4.5:** Process flow chart for AS-IS Scenario.

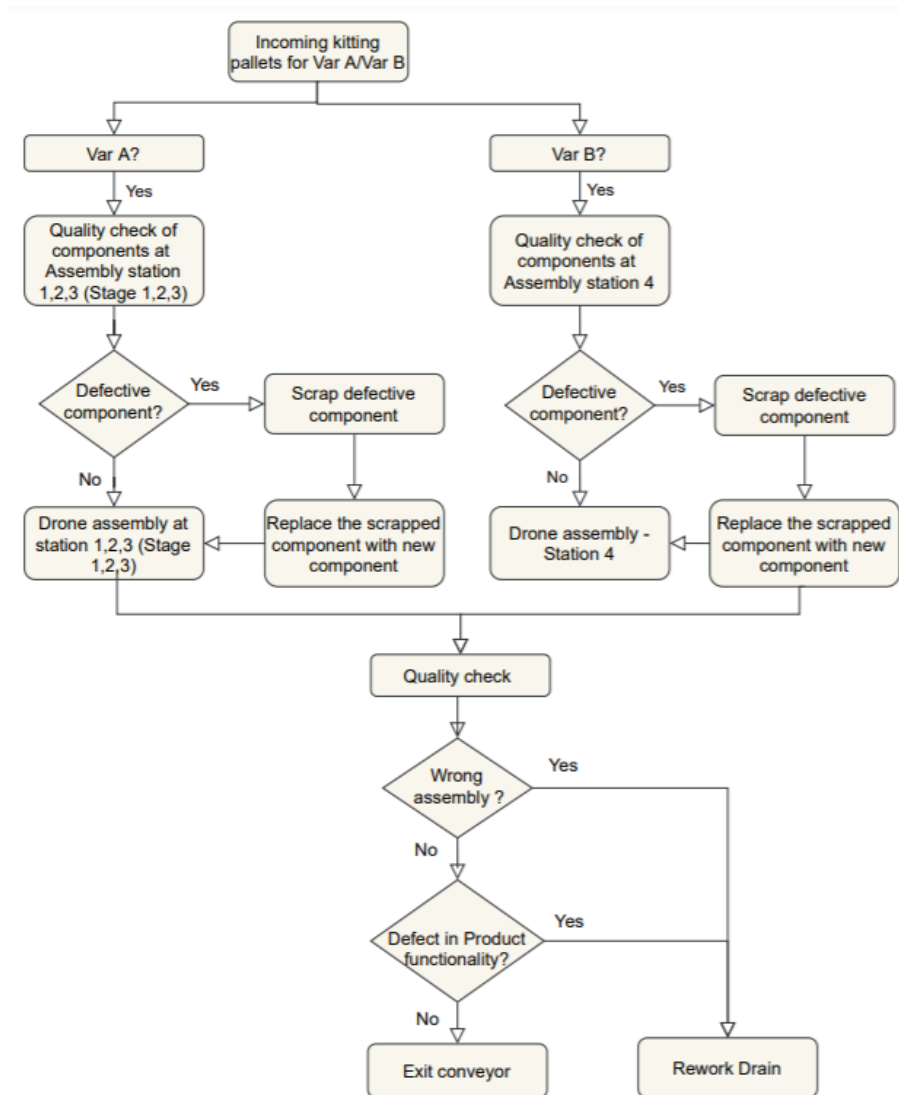
- Base scenario:** The base scenario concept was built for the final assembly to process two different product variants called as 'Var A' and 'Var B'. 'Var A' is assembled at manual assembly stations while 'Var B' is assembled at the automatic assembly station. So as per requirements for the base scenario, three manual assembly stations used for three stages of manual assembly in AS-IS scenario were converted to two manual assembly stations ('Stn 1' and 'Stn 3' for 'Var A') and one automatic station ('Stn 4' for 'Var B') 4.4.

Firstly, the components in the kitted pallet that arrives will be inspected for their quality at respective assembly stations before that specific stage of assembly takes place at each station. Which means, 'Var A', 'Stn 1' and 'Stn 3' are utilized for stage 1 and stage 2 assembly respectively. Further, the complete assembly of 'Var B', 'Stn 4' is utilized as automatic assembly station. Further, all the assembled drones are directed to the 'Quality check' station for quality inspection that includes inspecting the right assembly and product functionality. The process flow chart shown in the Figure 4.6 describes the the work procedure for the base scenario.



**Figure 4.6:** Process flow chart for Base scenario.

- Experimental scenario 1:** The Experimental scenario 1 included additional station as a parallel station, 'Stn 2'. In this scenario, 'Var A' is processed in three manual assembly stages carried out at 'Stn 1', 'Stn 2' and 'Stn 3' respectively. 'Var B' is processed in one stage at 'Stn 4' which is an automatic assembly station, see Figure 4.4. The quality check of components is carried out at each stations and quality inspection for inspecting right assembly and functionality is carried out for all the assembled drones at 'Quality check'. The process flow chart shown in the Figure 4.7 describe the concept of the experimental scenario 1.



**Figure 4.7:** Process flow chart for Experimental scenario 1.

4. **Experimental scenario 2:** In the Experimental scenario 2 concept, the 'Stn 2' is transformed from a parallel station in experimental scenario 1 to a dynamically re-balanced station. The station is designed to process manual assembly for both product variants, 'Var A' and 'Var B' and is utilized when there is requirement to increase the production capacity.

The station performs complete assembly of both variants and therefore the buffer state at the stations 'Stn 1' and 'Stn 4' is used as triggers for utilizing 'Stn 2'. The bottlenecks/blockages caused at 'Stn 1' (Stage 1 of 'Var A') and 'Stn 4' (complete assembly of 'Var B') due to increase in production demand will be prevented by utilizing a dynamic station. The quality check of components is carried out at each stations and quality inspection for inspecting right assembly and functionality is carried out for all the assembled drones at 'Quality check'. The details of work procedure for experimental scenario 2 is described through the process flow chart below in the Figure 4.8.

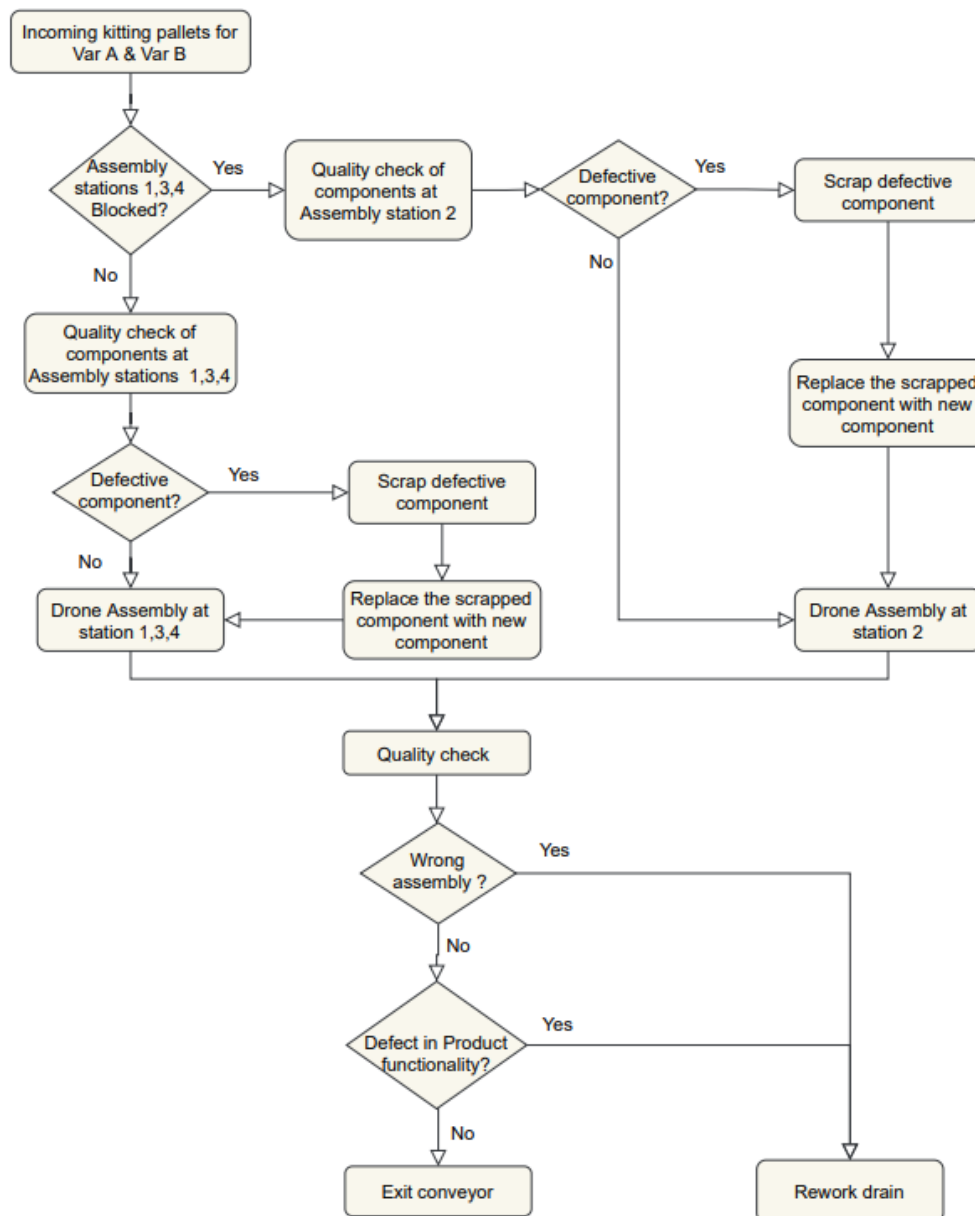


Figure 4.8: Process flow chart of the Experimental scenario 2.

#### 4.2.2 Data collection

Firstly, the data regarding production parameters such as processing times of both variants for respective scenarios, availability, MTTR, Scrap processing times and setup times were collected and is shown in the Table 4.4. As there is no set-up activity followed during assembly process of both the variants, the setup-times were considered to be 0 min. The scrap processing time was assigned to process defected components at stations during quality inspection activity at each station.

## 4. Results

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**Table 4.4:** Production parameters for the four scenarios.

| Experiment              | Station       | Processing time Var A (min) | Processing time Var B (min) | Availability (%) | MTTR (min) | Scrap Processing time (min) |
|-------------------------|---------------|-----------------------------|-----------------------------|------------------|------------|-----------------------------|
| AS-IS scenario          | Station 1     | 2.5                         | -                           | 70               | 0.5        | 1                           |
|                         | Station 2     | -                           | -                           | -                | -          | 1                           |
|                         | Station 3     | 4.4                         | -                           | 70               | 0.5        | 1                           |
|                         | Station 4     | 2.17                        | -                           | 70               | 0.5        | 1                           |
|                         | Quality check | 2                           | -                           | 70               | 0.5        | 1                           |
| Base scenario           | Station 1     | 4.4                         | -                           | 70               | 0.5        | 1                           |
|                         | Station 2     | -                           | -                           | -                | -          | 1                           |
|                         | Station 3     | 4.65                        | -                           | 70               | 0.5        | 1                           |
|                         | Station 4     | -                           | 3                           | 80               | 4          | 1                           |
|                         | Quality check | 2                           | 1                           | 70               | 0.5        | 1                           |
| Experimental scenario 1 | Station 1     | 2.5                         | -                           | 70               | 0.5        | 1                           |
|                         | Station 2     | 4.4                         | -                           | 70               | 0.5        | 1                           |
|                         | Station 3     | 2.17                        | -                           | 70               | 0.5        | 1                           |
|                         | Station 4     | -                           | 3                           | 80               | 4          | 1                           |
|                         | Quality check | 2                           | 1                           | 70               | 0.5        | 1                           |
| Experimental scenario 2 | Station 1     | 4.4                         | -                           | 70               | 0.5        | 1                           |
|                         | Station 2     | 10                          | 4                           | -                | -          | 1                           |
|                         | Station 3     | 4.65                        | -                           | 70               | 0.5        | 1                           |
|                         | Station 4     | -                           | 3                           | 80               | 4          | 1                           |
|                         | Quality check | 2                           | 1                           | 70               | 0.5        | 1                           |

#### 4.2.2.1 Material consumption data

The material details such as material type, weight of each component and the quantity of the components utilized were collected from product BOM's of 'Var A' and 'Var B' as shown in the Tables 4.5 and 4.6. It was found that 'Var A' is produced using ABS or Nylon components and 'Var B' is produced using Nylon PA components. The material cost of 1 kg of Nylon PA powder used for manufacturing components through 3D printing was found to be 1315 SEK/kg [43]. In addition, the costs of steel fasteners was assumed to be 20 SEK/kg. Using these values, the relative cost of components was estimated for both the variants based on their respective weights as shown in the below Tables 4.5 and 4.6.

**Table 4.5:** Components information for Drone variant 'Var A'

| Part name                 | Quantity | Material type | Total material weight (kg) | Material cost (SEK) |
|---------------------------|----------|---------------|----------------------------|---------------------|
| Ram                       | 1        | ABS/Nylon     | 0.002                      | 5.84                |
| Top cover                 | 1        | ABS/Nylon     | 0.018                      | 52.6                |
| Propeller Motor (2400 kV) | 4        | ABS/Nylon     | 0.024                      | 70.13               |
| Distance Motor            | 4        | ABS/Nylon     | 0.024                      | 70.13               |
| Battery                   | 1        | ABS/Nylon     | 0.024                      | 70.13               |
| Propeller 4X4R            | 2        | ABS/Nylon     | 0.004                      | 11.68               |
| Propeller 5X4R            | 2        | ABS/Nylon     | 0.004                      | 11.68               |
| Antenna                   | 1        | ABS/Nylon     | 0.008                      | 23.37               |
| Controller                | 1        | ABS/Nylon     | 0.06                       | 175.33              |
| Legs                      | 4        | ABS/Nylon     | 0.024                      | 70.13               |
| Frame                     | 1        | ABS/Nylon     | 0.066                      | 192.86              |
| Sub - frame               | 1        | ABS/Nylon     | 0.002                      | 5.84                |
| Fasteners                 | 18       | Steel         | 0.092                      | 1.84                |

**Table 4.6:** Components information for Drone variant 'Var B'

| Part name               | Quantity | Material type | Total material weight (kg) | Material cost (SEK) |
|-------------------------|----------|---------------|----------------------------|---------------------|
| Frame                   | 1        | Nylon PA      | 0.092                      | 151.22              |
| Topcover                | 1        | Nylon PA      | 0.024                      | 39.45               |
| Bottom Cover            | 1        | Nylon PA      | 0.02                       | 32.87               |
| Battery                 | 1        | Nylon PA      | 0.086                      | 141.36              |
| Antenna                 | 1        | Nylon PA      | 0.012                      | 19.72               |
| Propellor               | 4        | Nylon PA      | 0.016                      | 26.3                |
| Propellor Motor         | 4        | Nylon PA      | 0.04                       | 65.75               |
| Drone Legs              | 4        | Nylon PA      | 0.072                      | 118.35              |
| Control Box             | 1        | Nylon PA      | 0.032                      | 52.6                |
| PCB pannel sub-assembly | 1        | Nylon PA      | 0.08                       | 13.806              |
| Mounting Plate          | 1        | Nylon PA      | 0.08                       | 13.806              |
| Circuit Board           | 1        | Nylon PA      | 0.08                       | 13.806              |
| Voltage Unit            | 1        | Nylon PA      | 0.08                       | 13.806              |
| Motor Controller        | 4        | Nylon PA      | 0.08                       | 13.806              |
| Fasteners               | 8        | Steel         | 0.032                      | 0.8                 |

#### 4.2.2.2 Energy consumption data

The production system was divided into different areas of production that included four assembly station areas, one quality check area and a main conveyor area. It was observed that every assembly station and the quality check included equipment such as one PLC HMI and one monitor. The main conveyor area included one PLC HMI and one FA conveyor. The equipment name and the power rating of all the equipment considered is listed below in detail.

1. The FA conveyor used in the Drone factory is the Flexlink X-45 series conveyor system. The power rating for this product was observed to be 0.6748kW [44].
2. The PLC HMI used in the Drone factory is a product of Beijer and with a product series namely iX T7B-SM. The power rating for this HMI panel is found to be 0.014 kW [45].
3. The Monitors used in the Drone factory are DELL monitors with a power rating of 0.0174 kW and was collected from the technical specifications mentioned on the product.

The above power rating of each equipment was used to calculate the electricity consumed for one hour of simulation time. The formula used for calculating electricity consumed for one hour of equipment working was, Electricity consumed = Power consumption(in kW) \* number of working hours [46].

The Table 4.7 shows the total electricity consumed by the equipment in different production areas of the production system.

**Table 4.7:** Electricity consumed by equipments in different production areas

| Area          | Equipment's that consume Electricity | Power consumed by PLC HMI +Monitor[kW] | Power consumed by FA conveyor in [kW] | Electricity consumed in [kWh] |
|---------------|--------------------------------------|----------------------------------------|---------------------------------------|-------------------------------|
| Station 1     | PLC HMI+Monitor                      | 0.014 + 0.0174                         | NA                                    | 0.0314                        |
| Station 2     | PLC HMI+Monitor                      | 0.014 + 0.0174                         | NA                                    | 0.0314                        |
| Station 3     | PLC HMI+Monitor                      | 0.014 + 0.0174                         | NA                                    | 0.0314                        |
| Station 4     | PLC HMI+Monitor                      | 0.014 + 0.0174                         | NA                                    | 0.0314                        |
| Quality check | PLC HMI+Monitor                      | 0.014 + 0.0174                         | NA                                    | 0.0314                        |
| Main conveyor | PLC HMI+Conveyor                     | 0.014                                  | 0.6748                                | 0.6888                        |

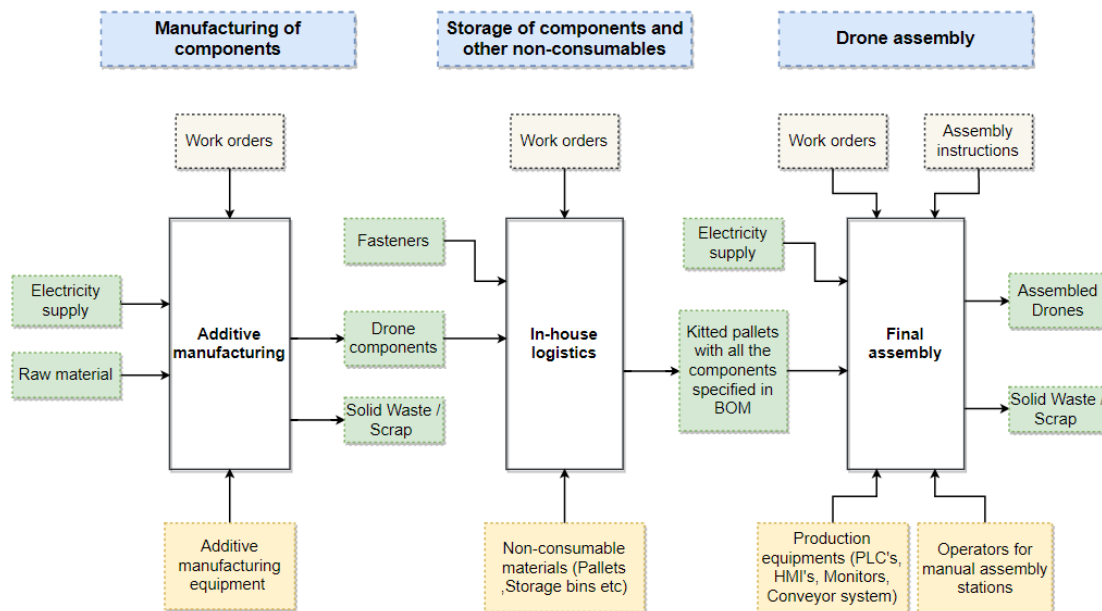
However, the power input data was incorporated in the DES by assigning power input values to each production areas and based on working conditions (operating, working, standby or failed) of each station during simulation period, the total electricity consumed at these areas was estimated. Further, for estimating the energy costs, the electricity price per kWh was found to be 46.5 SEK/kWh and relative energy costs were estimated dynamically based on the energy consumption results in the DES [47].

### 4.2.2.3 Environmental impact analysis

The above collected and estimated data for energy and material consumption was further used in carrying out environmental impact analysis by aiming to find the material and energy emissions caused by the material and energy consumption respectively. The environmental impact analysis was carried out as one of the quantitative studies for analyzing the environmental impact caused by the production system. According to paper [39], the most popular impact category was found to be Global Warming Potential (GWP) in kg CO<sub>2</sub>-Equiv. and is most important for accessing the impact of the process oriented production system. Therefore, CO<sub>2</sub> emissions were considered to be the type of environmental impact that is suitable for the supply chain of the Drone factory. It becomes crucial to set goals and scope of the assessment and then define the system boundaries for the assessment [39]. The goal and scope of carrying out impact assessment was that to find:

1. What are the material-related CO<sub>2</sub> emissions caused by processing material utilized for one unit of product?
2. What are the energy-related CO<sub>2</sub> emissions caused by the electricity consumption in the production system?

Further, the system boundaries were defined by studying the supply chain and defining the inputs and outputs at each stage of manufacturing. The input and output analysis was analyzed using IDEF0 model as shown in the Figure 4.9. The IDEF0 model resemble inputs and outputs (arrows that are pointing to right) where outputs of first two stages are inputs to the preceding stages, controls (arrows pointing downwards) and resources (arrows pointing upwards).



**Figure 4.9:** IDEF0 model for the Inventory analysis.

The Figure 4.9 shows that there are three main life-cycle stages in the supply chain that are additive manufacturing, in-house logistics and final assembly. The controls for additive manufacturing and in-house logistics stage is observed to be work orders

and for final assembly the controls are assembly instructions in addition to the work orders. The resources at each stages are equipment used in each stage respectively and operators in final assembly stage. However, operators are not included in the scope of the environmental impact assessment.

The first stage, the component manufacturing of Drone components is carried out using additive manufacturing also known as 3D printing technology. The technology is a powder based SLS (Selective Laser Sintering) technology and the name of the 3D printer used is "HP MultiJet fusion 5200 series". The main inputs for the 3D printer are found to be electricity and raw material in the form of Nylon PA powder. The outputs are the manufactured Drone components and the solid waste in the form of unused powder.

The second stage, is the in-house logistics, where all the manufactured components from the first stage are used for kitting purpose along with additional components such as steel fasteners which are received from the external subcontractors as shown in the Figure 4.3. The quantity of fasteners added to the kitting pallets depends on the quantity specified in the specific product variant BOM.

The third stage, is the final assembly where the main inputs considered are the kitted pallets that include kitted components (3D printed components and steel fasteners) and electricity supply for carrying out assembly process with the help of production system equipment's. The outputs are the assembled drones ('Var A' and 'Var B') and the solid waste in the form of scrapped components (defected components in the kitted pallet found at each station).

A compact inventory analysis was carried out for the first and second stage of supply chain that is additive manufacturing and in-house logistics for estimating carbon emissions of a unit of specific product variant. The technical specifications of the 3D printing technology were collected for estimating material consumption for manufacturing components required for one unit of the product. The specifications such as manufacturing efficiency and productivity were used for estimating the input material. For resource consumption which is the input mainly as material and energy consumption to be converted into material-related carbon emissions and energy-related carbon emissions, [48] provides equations as mentioned below in the Figures 4.10 and 4.11 respectively. The equation in the Figure 4.10 was used to fulfill the first goal and equation in the Figure 4.11 was used to fulfill the second goal of assessment defined.

$$Me(i) = \sum_{k=1}^w m^k(i) * EF(k),$$

**Figure 4.10:** Formula for Material emission calculation [48].

For  $Me(i)$  being the material emissions for the  $i$ th process, where  $k$  is the type of material and  $w$  is the number of types of materials processed,  $mk(i)$  is the mass of the  $k$ th type of input material for the process and  $EF(k)$  is the carbon emission factor of  $k$ th type of material.

$$Ee(i) = Etotal(i) * EF(elec),$$

**Figure 4.11:** Equation for Energy emission calculation [48].

For  $Ee(i)$  being the energy related emissions caused by the  $i$ th process, where  $E\_total(i)$  is the total electricity consumed by the  $i$ th process and  $EF(elec)$  is the carbon emission factor of electricity. To find the carbon emission factor for the electricity supplied to the production system, the parameters such as the area of electricity consumed and type of source that electricity is generated from was considered. Considering the electricity supply to Sweden being divided between different electrical areas, Gothenburg is found to be belonging to the third electrical area and is found to be utilizing mostly electricity that is generated from hydro-power [46]. Further, the carbon emission factor for electricity generated from hydro-power was found to be 0.02 kgCO<sub>2</sub> eq/kWh [46]. The Table 4.8 shows the example for estimation carried out for carbon emissions from each of the equipment's utilizing electricity.

**Table 4.8:** Estimation of Energy emissions from the production system.

| Area          | Total electricity consumed, $Etotal(i)$ [kWh] | Emission factor, $EF(elec)$ [kgCO <sub>2</sub> eq/kWh] | Energy emissions, $Ee(i)$ [kgCO <sub>2</sub> eq] |
|---------------|-----------------------------------------------|--------------------------------------------------------|--------------------------------------------------|
| Station 1     | 0.0314                                        | 0.02                                                   | 0.000628                                         |
| Station 2     | 0.0314                                        | 0.02                                                   | 0.000628                                         |
| Station 3     | 0.0314                                        | 0.02                                                   | 0.000628                                         |
| Station 4     | 0.0314                                        | 0.02                                                   | 0.000628                                         |
| Quality check | 0.0314                                        | 0.02                                                   | 0.000628                                         |
| Main conveyor | 0.6888                                        | 0.02                                                   | 0.01377                                          |

For fulfilling the first goal which is to find the material emissions caused by one unit of product variant, the following assumptions were made. The technical specifications of two different equipment used for manufacturing components for 'Var A' and 'Var B' were considered. The efficiency of equipment, material or powder type utilized and the emission factors for 3D printed components and steel fasteners is mentioned below.

1. The manufacturing efficiency of the equipment used for manufacturing 'Var A' components was observed to be 45% and manufacturing efficiency of the equipment used for manufacturing 'Var B' was observed to be 80% the manufacturing efficiency [49], [50].
2. As it was observed that 'Var A' components were manufactured using ABS and Nylon. For estimating material related emissions of 'Var A', the estimations are made by considering only Nylon material type for 'Var A'.

#### 4. Results

3. The emission factors of Nylon PA and Steel are found to be 7.9 kgCO<sub>2</sub>eq/kg and 1.77 kgCO<sub>2</sub>eq/kg [51]

to make estimations of material related carbon emissions from one unit, the material consumption for one unit production need to be calculated [48]. The Table 4.9 below shows the material consumption estimation made based on the efficiency of the two equipment used for manufacturing components for 'Var A' and 'Var B' respectively.

**Table 4.9:** Estimation of Material consumption for life cycle stage 1 and 2.

| Life-cycle stage                      | Components manufactured or utilized | Technology or Equipment         | Manufacturing efficiency [%] | Input material [kg] | Output material [kg] |
|---------------------------------------|-------------------------------------|---------------------------------|------------------------------|---------------------|----------------------|
| Stage 1 (Var A)<br>3D printing        | Var A components                    | ECOSINT P760 SLS                | 45%                          | 0.5777              | 0.26                 |
| Stage 1 (Var B)<br>3D printing        | Var B components                    | HP Multi-Jet fusion 5200 series | 80%                          | 0.625               | 0.5                  |
| Stage 2 (Var A)<br>In-house logistics | Fasteners for Var A                 | Pick and place robot            | 99%                          | 0.101               | 0.1                  |
| Stage 2 (Var B)<br>In-house logistics | Fasteners for Var B                 | Pick and place robot            | 99%                          | 0.03                | 0.3                  |

The material emissions were calculated using the above mentioned formula in the Figure 4.10. The material consumed is assumed to be the input material estimated in the Table 4.9. The Table 4.10 shows the material emissions estimations.

**Table 4.10:** Estimation of Material emissions of Var A and Var B.

| Material type                | Material emission factor ,EF(k) [kgCO <sub>2</sub> eq/kg] | Input material, mk(i) [kg] | Material emissions, Me(i) [kgCO <sub>2</sub> eq] |
|------------------------------|-----------------------------------------------------------|----------------------------|--------------------------------------------------|
| Nylon PA<br>Var A components | 7.9                                                       | 0.5777                     | 4.564                                            |
| Steel<br>fasteners for Var A | 1.77                                                      | 0.101                      | 0.1787                                           |
| Nylon PA<br>Var B components | 7.9                                                       | 0.625                      | 4.937                                            |
| Steel<br>fasteners for Var B | 1.77                                                      | 0.03                       | 0.05                                             |

The total material emissions for each product variants 'Var A' and 'Var B' was estimated by summing the respective material emissions obtained from 3D printed components and fasteners. The Table 4.11 below shows the material emissions of each unit of the drone.

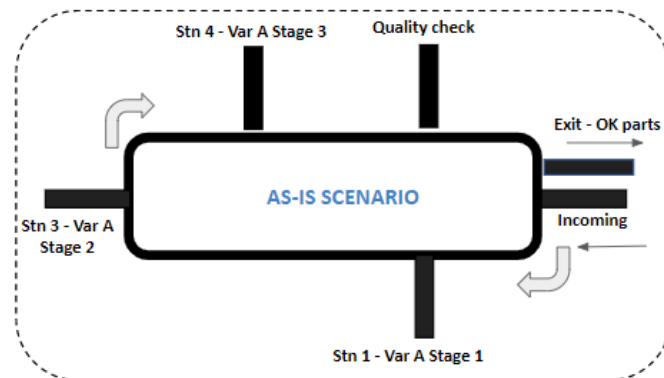
**Table 4.11:** Material emissions for Var A and Var B.

| Product variant | Total Material emissions,<br>Me(i) [kgCO <sub>2</sub> eq] |
|-----------------|-----------------------------------------------------------|
| Drone Var A     | 4.7                                                       |
| Drone Var B     | 5                                                         |

### 4.2.3 Experimental analysis

This section explains in detail the behaviour and the performance of the four manufacturing scenarios which are explained in the previous sections. The results of the experimental analysis are obtained from the experiment manager in plant simulation. All four scenario simulations were run for a time duration of six days with a warm-up period of one day with a total of ten replications for each scenario.

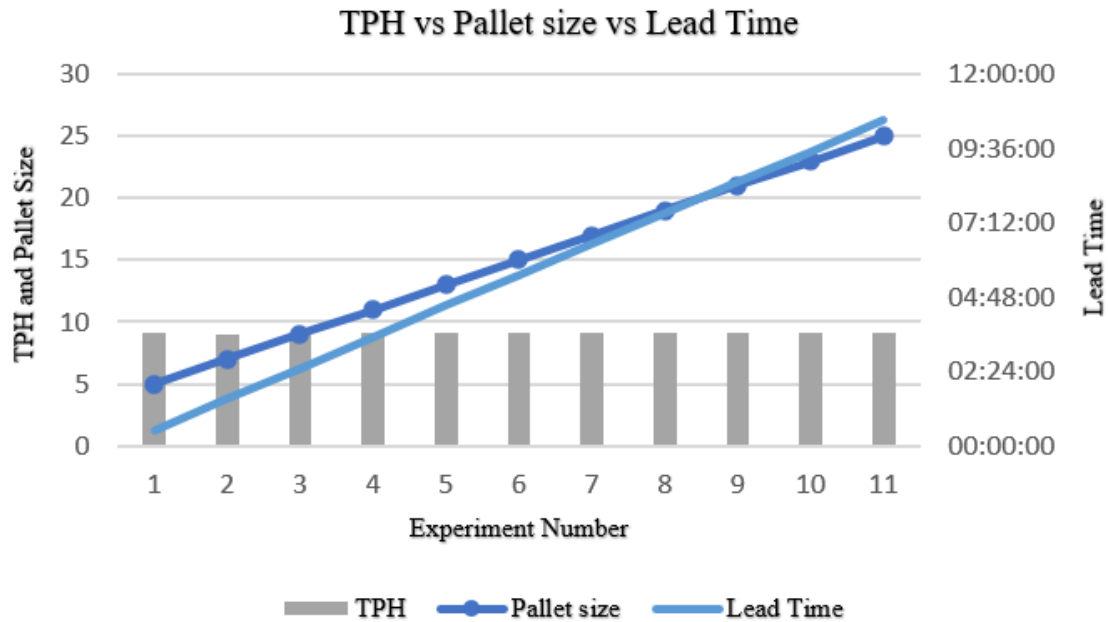
#### 4.2.3.1 Scenario 1: The AS-IS scenario

**Figure 4.12:** AS-IS scenario

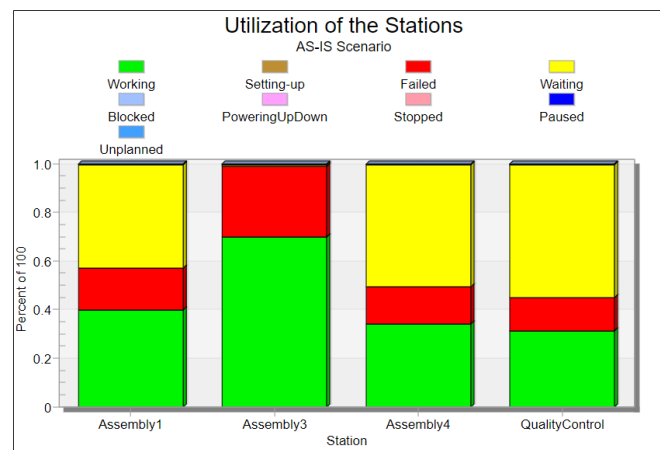
The AS-IS scenario is a replica of the drone manufacturing facility at SII-lab. Since this scenario involves only a single variant of the drone and the lab is introducing another variant into the existing production line this scenario was only used to validate the statistical results of the simulation model. In the AS-IS scenario, the testing was performed by varying the number of pallets as the input control. Since in this scenario there are four stations in which three are assembly stations and one quality control the the minimum number of pallets entering the system was set to five. A total of twelve pallet sizes or number of pallets were selected starting from five to twenty-five pallets to identify their effect on the throughput and the integrated sustainability KPIs. The following Tables 4.12 and 4.13 shows the simulation results of the throughput and sustainability KPIs for varying pallet sizes of the AS-IS scenario.

**Table 4.12:** Throughput analysis for varying pallet sizes (AS-IS scenario).

| Pallet Size | Throughput | ThroughputPerHour | Lead Time |
|-------------|------------|-------------------|-----------|
| 5           | 1091.7     | 9.09              | 00:30:57  |
| 7           | 1086.1     | 9.05              | 01:30:57  |
| 9           | 1089.2     | 9.07              | 02:30:57  |
| 11          | 1086.7     | 9.05              | 03:30:57  |
| 13          | 1090.1     | 9.08              | 04:30:57  |
| 15          | 1088.9     | 9.07              | 05:30:57  |
| 17          | 1089.7     | 9.08              | 06:30:57  |
| 19          | 1086.9     | 9.05              | 07:30:57  |
| 21          | 1091.1     | 9.09              | 08:30:57  |
| 23          | 1091.9     | 9.09              | 09:30:57  |
| 25          | 1086.8     | 9.05              | 10:30:57  |

**Figure 4.13:** TPH vs Palletsize vs Lead Time (AS-IS)

From the Table 4.12 and Figure 4.13 we can infer that the TPH remains almost constant with increasing pallet sizes. It is observed that there is a drastic increase in the lead times with increasing pallet sizes and this can be attributed to the fact the individual assembly stations have very long processing times. This accompanied with lower availability rates due to manual assembly and inspection creates a bottleneck in the system when the number of input pallets are increased. This leads to a block in the production line by occupying space on the FA conveyor. Figure 4.14 shows the resource utilization statistics of the individual stations for when the number of input pallets are 7. From the Figure 4.14 it can be inferred that the assembly station 3 has a very high utilization rate which increases the waiting times of the station 4 and quality control thereby creating a bottleneck in the production line.



**Figure 4.14:** Resource Utilization Statistics of AS-IS scenario with (7 Pallets).

**Table 4.13:** KPI analysis for varying pallet sizes (AS-IS scenario).

| Pallet size | Total Production Cost (SEK) | First Pass Yield (%) | Total Material Consumption (kg) | Total Energy Emissions Per Part (kgCO <sub>2</sub> eq) | Total Material Emissions (kgCO <sub>2</sub> eq) |
|-------------|-----------------------------|----------------------|---------------------------------|--------------------------------------------------------|-------------------------------------------------|
| 5           | 870949.22                   | 95.78                | 393.56                          | 0.00176280                                             | 5356.20                                         |
| 7           | 876617.22                   | 95.79                | 391.55                          | 0.00177188                                             | 5369.41                                         |
| 9           | 878821.22                   | 95.81                | 392.66                          | 0.00186683                                             | 5373.04                                         |
| 11          | 876921.22                   | 95.79                | 391.76                          | 0.00187094                                             | 5371.29                                         |
| 13          | 879498.02                   | 95.82                | 392.98                          | 0.00176543                                             | 5367.26                                         |
| 15          | 878593.22                   | 95.82                | 392.56                          | 0.00186730                                             | 5371.63                                         |
| 17          | 879118.02                   | 95.82                | 392.83                          | 0.00186610                                             | 5384.91                                         |
| 19          | 876997.04                   | 95.80                | 391.83                          | 0.00177055                                             | 5381.75                                         |
| 21          | 870341.22                   | 95.82                | 393.35                          | 0.00186374                                             | 5382.44                                         |
| 23          | 870721.22                   | 95.82                | 393.64                          | 0.00186249                                             | 5384.79                                         |
| 25          | 876928.23                   | 95.83                | 391.80                          | 0.00187081                                             | 5381.30                                         |

The above Table 4.13 shows the results of the sustainability KPIs for varying pallet sizes. From the table it can be observed that with the increasing pallet sizes the total production costs increase even though the total throughput decreases with increasing pallet sizes. This is because as the lead times increases the associated overhead production costs keep increasing even though the throughput per hour obtained from the system remains constant. A similar trend can be observed with the material and energy emissions which also depicts a slight increase in their values due to increasing utilization rates of the resources. As the utilization rates of the resources go on increasing the number of bottlenecks within the system also increases which adversely affects the sustainability KPIs and the throughput of the system. The Figure 4.15 shows the energy consumption statistics of the AS-IS scenario. Since the quality of the products from the production system was assumed to have a permissible defect rates up-to five percent the simulation results for the first pass

yield yielded a uniform value of 95% for all the experiments. A detailed report of the KPI measures and the elemental KPIs obtained from Plant simulation is given in appendix A.

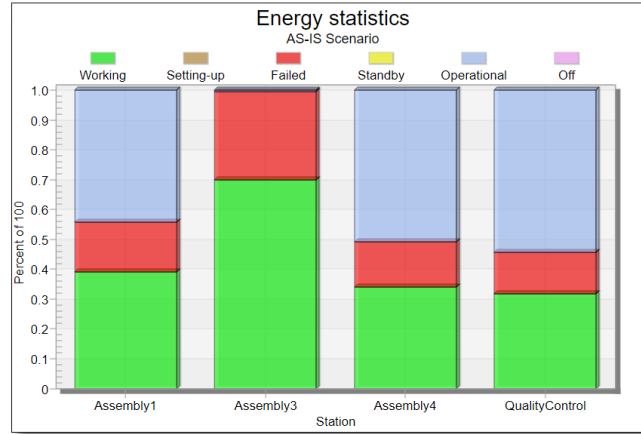


Figure 4.15: Energy Utilization Statistics (AS-IS)

4.2.3.2 Scenario 2 : The Base scenario

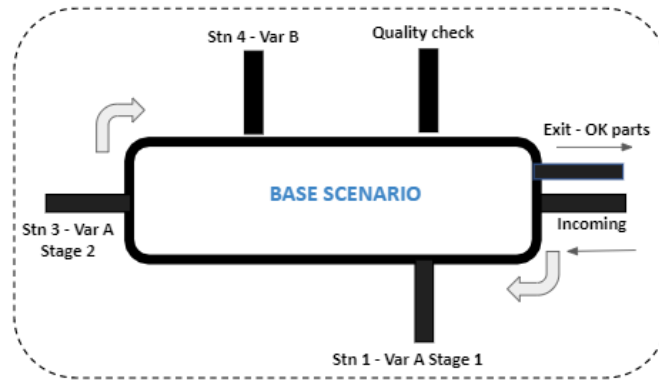
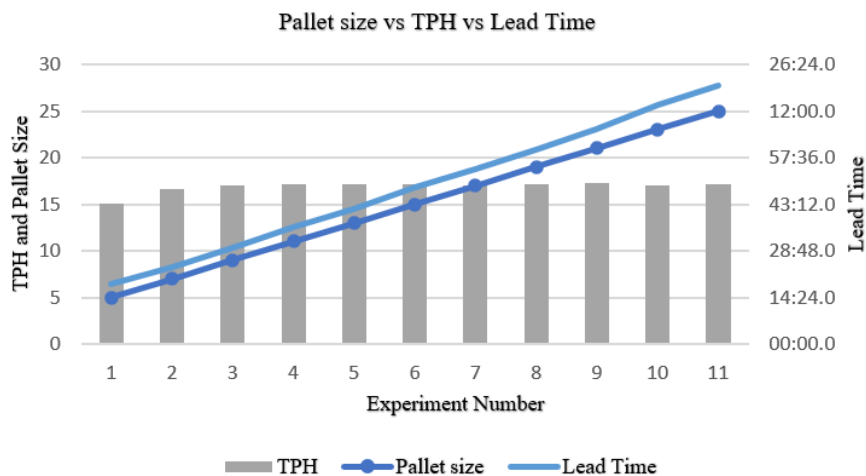


Figure 4.16: Base scenario

The Base scenario is the planned future state of production at the SII-Lab which involves the production of two different variants of the drone. The working of the Base scenario and the production parameters are explained in the section model conceptualization. The base scenario was tested against two input parameters, firstly varying number of input pallets and the second varying customer demand for the two variants. Similar to the AS-IS state a total of twelve pallet sizes or number of pallets were selected ranging from five to twenty-five to identify the most suitable number of pallets that the system can process to maximize the throughput whilst maintaining the production and sustainability KPI values at nominal levels. The following Tables 4.14 depict the statistics obtained from the simulation of this scenario.

**Table 4.14:** Throughput analysis for varying pallet sizes (Base scenario).

| Pallet size | Throughput | ThroughputPerHour | Lead Time |
|-------------|------------|-------------------|-----------|
| 5           | 1812.6     | 15.10             | 18:32.2   |
| 7           | 1988.6     | 16.57             | 23:46.9   |
| 9           | 2040.6     | 17.00             | 29:57.6   |
| 11          | 2056.6     | 17.13             | 35:58.9   |
| 13          | 2057.7     | 17.14             | 41:53.2   |
| 15          | 2065.8     | 17.21             | 48:17.4   |
| 17          | 2046.9     | 17.05             | 54:05.3   |
| 19          | 2063.8     | 17.19             | 01:00:03  |
| 21          | 2066.9     | 17.22             | 01:06:22  |
| 23          | 2046.9     | 17.05             | 01:13:56  |
| 25          | 2059.8     | 17.16             | 01:20:02  |

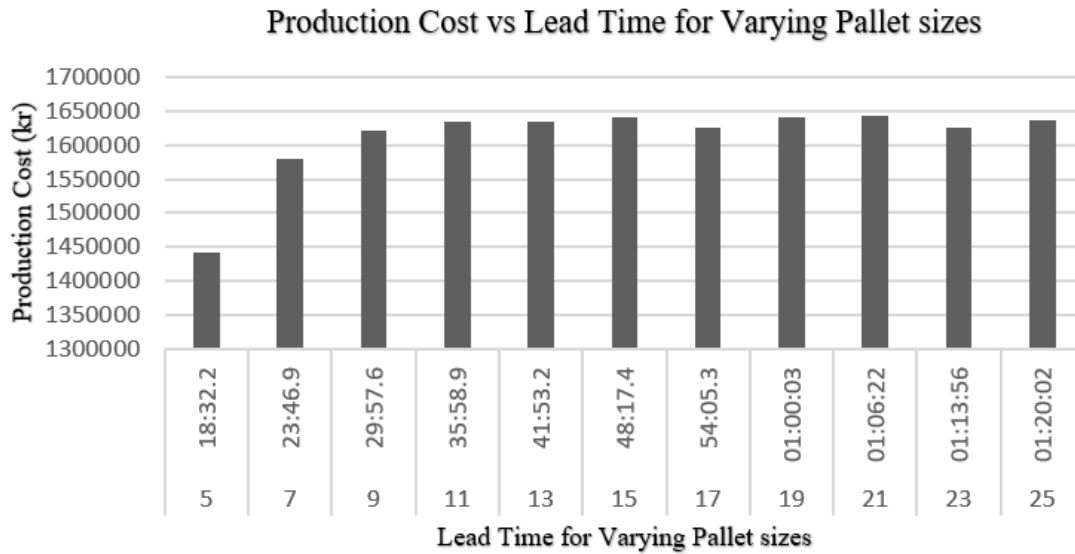
**Figure 4.17:** Pallet size vs TPH vs Lead Time (Base Scenario).

The results in the Table 4.14 and Figure 4.17 depicts that the total throughput of the system has increased when the number of pallets entering the system increases. Although, the total throughput shows an increase it is interesting to note that the TPH of the system increases with the increase in the number of pallets from five to nine and from that point on-wards the TPH remains constant throughout for any change in the pallet sizes. The data therefore indicates that its most suitable to limit the number of pallets to nine as any further increase would mean that the production system has a significantly higher lead time for a marginal increase in the total throughput and TPH. Moreover the increasing lead times further increase the associated production costs as shown in the Figure 4.18 due to the increase in the utilization rates of the production resources such as material, energy, transportation and inventory. This can be further inferred from the production and sustainability KPIs as shown in the Table 4.15. Therefore it can be concluded that there aren't any significant economic, environmental or social gains that the current production system or the base scenario can achieve when the number of pallets in the system is more than nine.

#### 4. Results

**Table 4.15:** KPI analysis for varying pallet sizes (Base scenario).

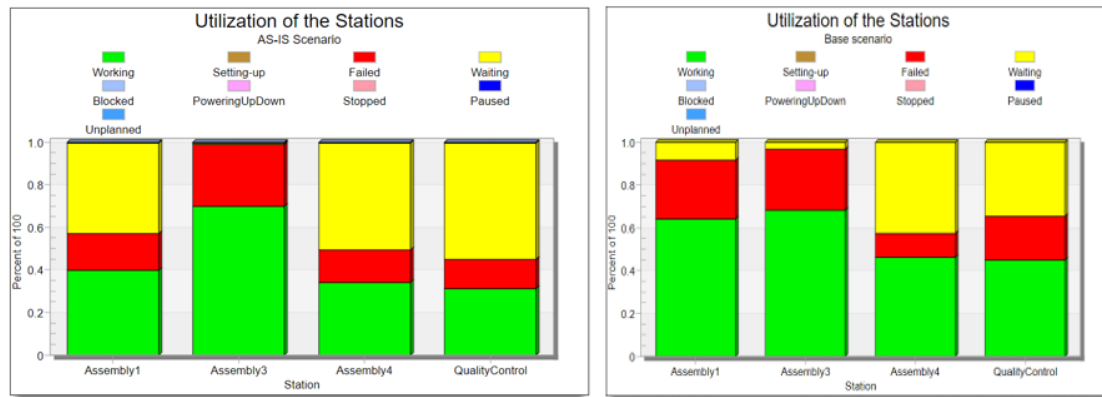
| Pallet size | Total Production Cost (SEK) | First Pass Yield (%) | Total Material Consumption(kg) | Total energy Emissions Per Part (kgCO <sub>2</sub> eq) | Total Material Emission (kgCO <sub>2</sub> eq) |
|-------------|-----------------------------|----------------------|--------------------------------|--------------------------------------------------------|------------------------------------------------|
| 5           | 1441092.19                  | 95.92                | 734.95                         | 0.001061948                                            | 9164.95                                        |
| 7           | 1579362.91                  | 95.99                | 806.73                         | 0.000968144                                            | 10047.79                                       |
| 9           | 1620961.47                  | 95.96                | 827.93                         | 0.000943371                                            | 10313.30                                       |
| 11          | 1633861.16                  | 95.95                | 833.71                         | 0.000935956                                            | 10394.40                                       |
| 13          | 1634516.86                  | 95.96                | 833.80                         | 0.000935705                                            | 10397.56                                       |
| 15          | 1640768.39                  | 95.99                | 837.77                         | 0.00093196                                             | 10439.17                                       |
| 17          | 1625926.91                  | 95.98                | 829.68                         | 0.000940445                                            | 10341.93                                       |
| 19          | 1639700.41                  | 95.96                | 836.71                         | 0.000932871                                            | 10432.09                                       |
| 21          | 1642101.07                  | 95.94                | 838.48                         | 0.000931325                                            | 10448.45                                       |
| 23          | 1626203.10                  | 95.96                | 829.40                         | 0.000940505                                            | 10344.01                                       |
| 25          | 1635852.45                  | 95.99                | 834.86                         | 0.000934605                                            | 10406.97                                       |



**Figure 4.18:** Production Cost vs Lead Time for varying pallet sizes.

From the above data it is clear that optimal number of pallets for the base scenario is nine and any further increase has a negative impact on the sustainability KPIs due to increasing resource consumption and higher emissions even though the system can achieve a higher total throughput which is still not justified by the associated increase in production costs and lead times. A detailed report of all the sustainability and productivity KPIs such as the scrap ratio, rework ratios, utilization efficiencies, cycle times and the emissions obtained from plant simulation for 11 experiments are given in appendix A. Furthermore by comparing the resource utilization rates of the AS-IS scenario and the Base scenario as shown in the Figure 4.19 it is evident that the Base scenario has a much better performance than the AS-IS state since the assembly station 1 and assembly station 3 seem to to be utilized almost at an equal

rate compared to the AS-IS state where assembly 3 had the highest utilization rate thus resulting in a bottleneck that hindered the performance of the system.



**Figure 4.19:** Resource Utilization Statistics for AS-IS vs Base Scenario with (9 pallets).

Furthermore the Base scenario was tested against another input parameter "customer Demand" with the selected optimum number of pallets for the two drone variants. A total of three experiments with 10 replications of the following demand percentages were carried out for further analysis.

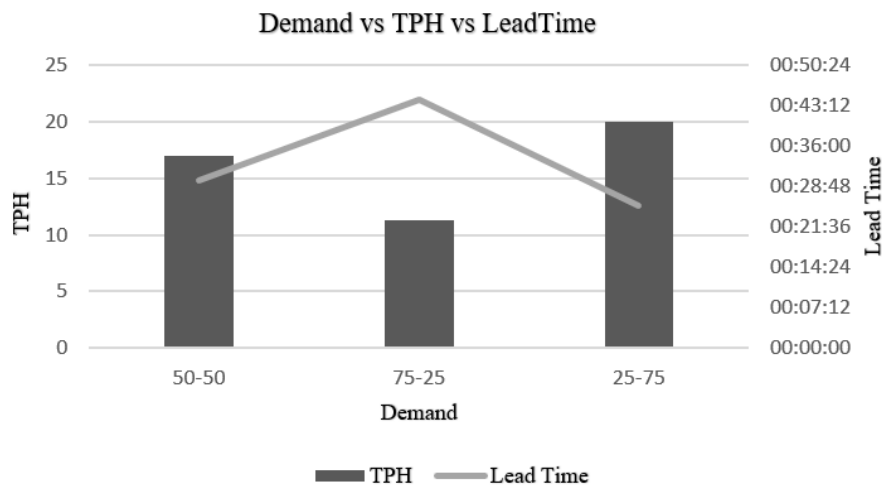
**Table 4.16:** Customer Demand Table.

| Demand Var A (%) | Demand Var B (%) |
|------------------|------------------|
| 50               | 50               |
| 25               | 75               |
| 75               | 25               |

The following Table 4.17 presents the results on the effect of changing customer demand on the selected production system KPIs.

**Table 4.17:** Throughput Analysis for Varying Customer Demand (Base Scenario).

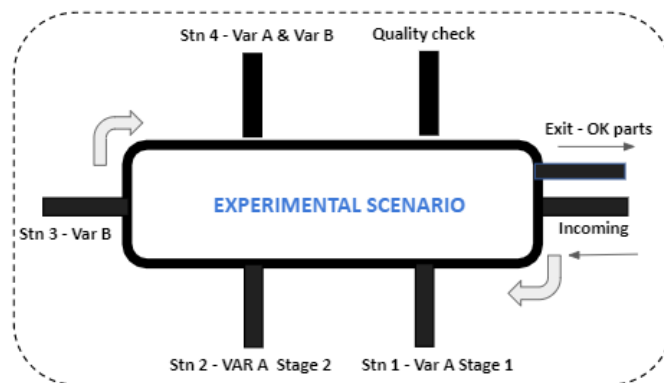
| Demand(A-B) | Throughput | Throughput Per Hour | Lead Time |
|-------------|------------|---------------------|-----------|
| 50-50       | 2040.6     | 17.00               | 00:29:58  |
| 75-25       | 1361.8     | 11.34               | 00:44:11  |
| 25-75       | 2396.8     | 19.97               | 00:25:25  |



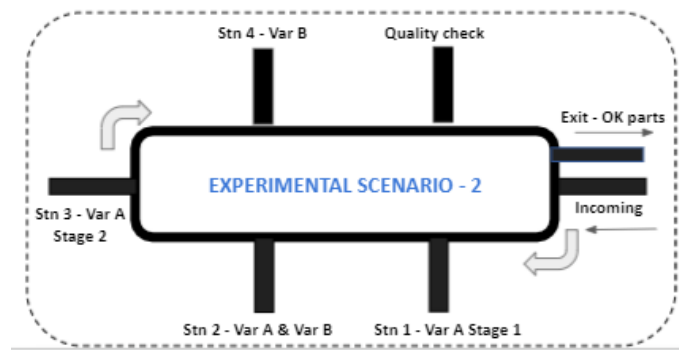
**Figure 4.20:** Impact of Customer Demand on TPH and Lead Time.

From the above Figure 4.20 and Table 4.17 we can observe that the TPH is better when the the demand ratios between 'Var A' and 'Var B' is between 50-50 and 25-75 when compared to the ratio 75-25. This is because the processing times of 'Var A' is much higher due to a manual assembly and a larger number of components in 'Var A' compared to the automated assembly and fewer components in 'Var B'. Since the base scenario yielded high utilization rates for the assembly stations that resulted in bottlenecks along the production line which adversely affected the productivity and sustainability KPIs, the following improvement scenarios were conceptualized.

1. **Experimental scenario 1:** In this scenario a parallel assembly station was added and the production stages were re-balanced on these stations as shown in the Figure 4.21. A detailed explanation about how this scenario operates has been explained in the section under model conceptualization.
2. **Experimental scenario 2:** In this scenario the parallel assembly station was intended to be used as a flexible station or a dynamically re-balanced station which would be activated whenever one particular station is being highly utilized as shown in the Figure 4.22. A detailed explanation about how this scenario operates has been explained in the section under model conceptualization.



**Figure 4.21:** Experimental scenario 1: Parallel Assembly Station.



**Figure 4.22:** Experimental scenario 2: Dynamically Re-balanced Station.

#### 4.2.3.3 Base scenario vs Experimental scenario 1 vs Experimental scenario 2

This section presents results for the experiments performed on the three scenarios with common input variables. All three scenarios were tested with an optimum pallet size or the optimum number of pallets identified in the previous section for varying customer demands. The following Table 4.18 presents the cumulative results of the experiments performed with a confidence interval (CI) of 95% for all three scenarios.

**Table 4.18:** Throughput analysis of Selected Scenarios

| Scenario                 | Demand (A-B) | Throughput | TPH(+/-CI)     | Lead Time |
|--------------------------|--------------|------------|----------------|-----------|
| Base Scenario            | 50-50        | 2040.6     | 17.00(+/-0.24) | 00:29:58  |
|                          | 75-25        | 1361.8     | 11.34(+/-0.18) | 00:44:11  |
|                          | 25-75        | 2396.8     | 19.97(+/-0.26) | 00:25:25  |
| Experimental Scenario: 1 | 50-50        | 2177.5     | 18.14(+/-0.22) | 00:28:02  |
|                          | 75-25        | 1449.0     | 12.07(+/-0.17) | 00:38:03  |
|                          | 25-75        | 2398.4     | 19.98(+/-0.29) | 00:25:28  |
| Experimental Scenario: 2 | 50-50        | 2571.4     | 21.42(+/-0.18) | 00:23:39  |
|                          | 75-25        | 1859.9     | 15.49(+/-0.18) | 00:32:54  |
|                          | 25-75        | 3233.7     | 26.94(+/-0.21) | 00:18:25  |

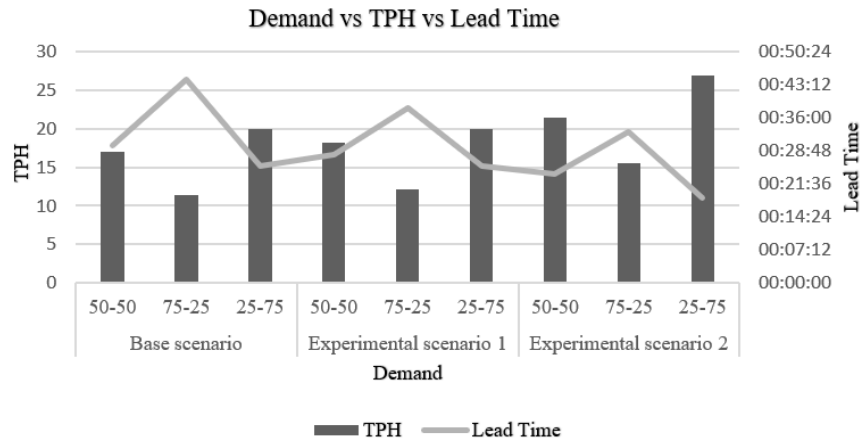


Figure 4.23: Demand vs TPH vs Lead Time.

From the above graphs and results we can infer that the both the experimental scenarios provide a much higher throughput and TPH when compared to the base scenario in all the the three demand variations. The lead times in which the experimental scenarios achieve these throughput's are also much lower than that of the base scenarios indicating that the system performance has been improved by the modifications made in these cases. In the experimental scenario 1 the increase in the throughput and the TPH values can be attributed to the fact that the addition of a parallel station can alleviate the load on assembly station 3 which had a high utilization rate in the Base scenario due to the long processing times of Var A. However with the addition of this new parallel station it can be observed from the Figure 4.24 that the bottleneck station now shifts to assembly station 2 or the parallel station. This is because in this scenario the parallel station is used only for processing the resource intensive Var A whose production stages and cycle times have been re-balanced on three station rather than on two stations as it was done previously in the base scenario. Although this additional parallel station can be re-balanced in several different ways due to the high processing times associated with Var A the bottleneck keeps shifting between Assembly stations 1, 2 and 3.

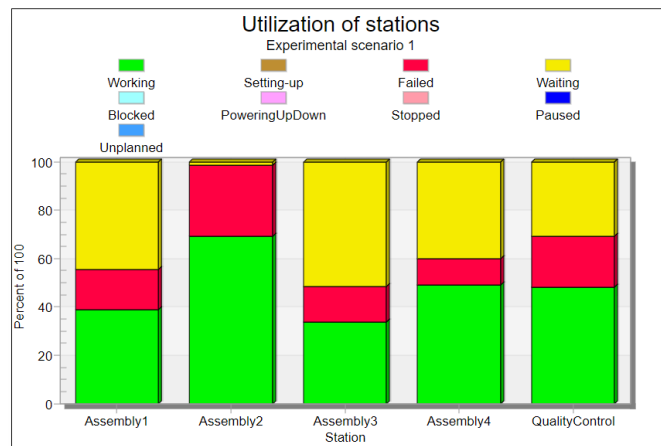
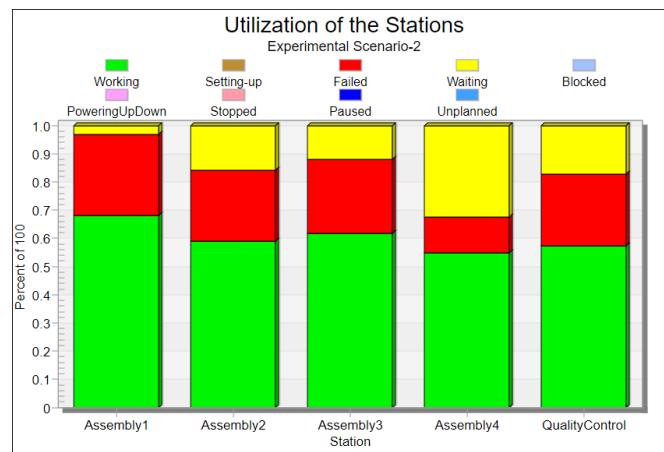
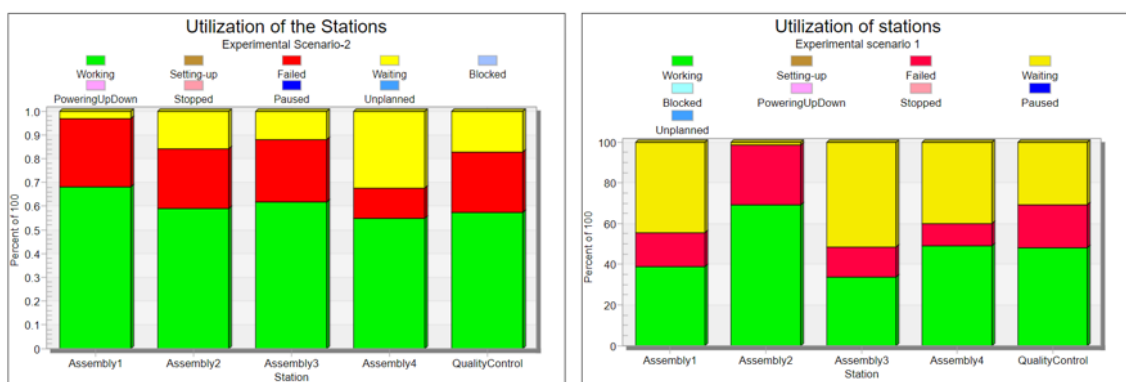


Figure 4.24: Resource Utilization Statistics for Experimental Scenario 1.

The above graph depicting the resource utilization rates for the experimental scenario 1 is a clear indication of the of the reason why we observe only a marginal increase in the TPH when compared to the base scenario. However in case of the experimental scenario 2 where the additional station is used as a dynamically re-balanced station we can notice a significant increase in the TPH and this because the stations are utilized more efficiently and the utilization rates are almost equal across all the stations. The idea behind using the additional station as flexible station instead of a parallel station was to alleviate the load on the station that is getting highly utilized thereby avoiding a shifting bottleneck situation as seen in experimental scenario 1. This enables the production system to work seamlessly without any obstructions or stoppage along the production line thereby improving the overall system performance. The comparison of the resource utilization statistics between the two experimental scenarios is shown in the Figure 4.26.



**Figure 4.25:** Resource Utilization Statistics for Experimental Scenario 2.



**Figure 4.26:** Resource Utilization Statistics of Scenario 2 vs Scenario 1.

Furthermore another important aspect to be considered is the sustainability of the production processes. While the system is able to achieve a higher productivity through increased TPH and decreased lead times it is essential to keep a check on whether these improvements have come as a trade-off against the environmental

#### 4. Results

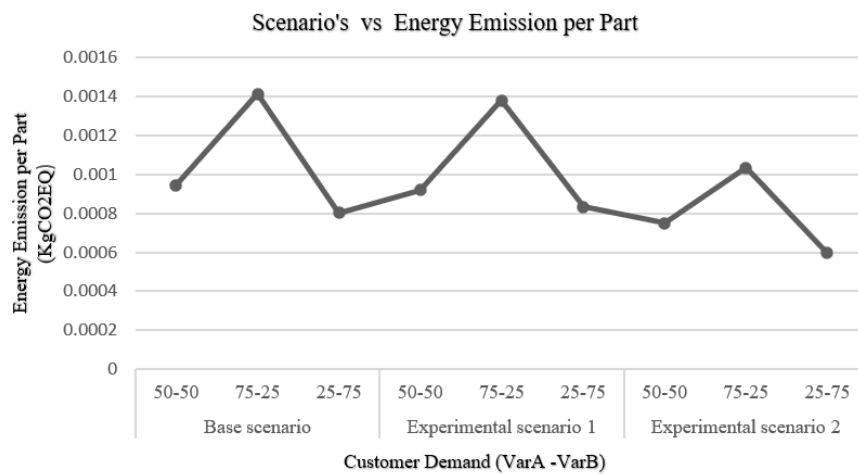
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KPIs. The following Table 4.19 provides us with the results of the sustainability KPIs for the three scenarios.

**Table 4.19:** KPI analysis of Selected Scenarios.

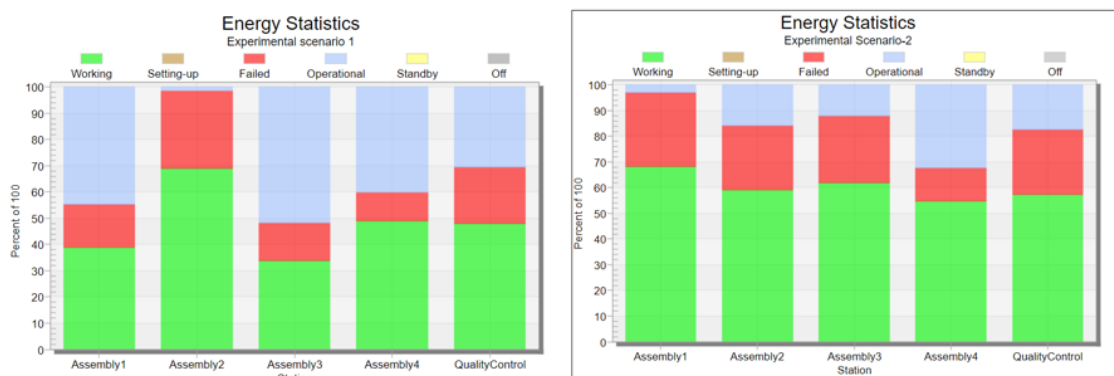
| Scenario       | Demand (A-B) | Total Production Cost (SEK) | Scrap Ratio | Rework Ratio |
|----------------|--------------|-----------------------------|-------------|--------------|
| Base Scenario  | 50-50        | 1620961                     | 0.892       | 4.01         |
|                | 75-25        | 1084545                     | 0.906       | 4.13         |
|                | 25-75        | 1902294                     | 0.923       | 3.98         |
| Exp Scenario 1 | 50-50        | 1730500                     | 0.868       | 4.07         |
|                | 75-25        | 1153612                     | 0.829       | 4.11         |
|                | 25-75        | 1904242                     | 0.922       | 4.00         |
| Exp Scenario 2 | 50-50        | 2039796                     | 0.163       | 3.97         |
|                | 75-25        | 1477873                     | 0.242       | 4.05         |
|                | 25-75        | 2564882                     | 0.253       | 4.00         |

| Scenario       | Demand (A-B) | Total Energy Consumed [kWh] | Total Energy Emissions per Part [kgCO <sub>2</sub> eq] | Total Energy Emission [kgCO <sub>2</sub> eq] | Total Material Emission [kgCO <sub>2</sub> eq] |
|----------------|--------------|-----------------------------|--------------------------------------------------------|----------------------------------------------|------------------------------------------------|
| Base Scenario  | 50-50        | 96.216                      | 0.0009433                                              | 1.924                                        | 10313.30                                       |
|                | 75-25        | 96.216                      | 0.0014136                                              | 1.924                                        | 6781.21                                        |
|                | 25-75        | 96.216                      | 0.0008031                                              | 1.924                                        | 12296.95                                       |
| Exp Scenario 1 | 50-50        | 99.984                      | 0.0009185                                              | 1.999                                        | 11011.69                                       |
|                | 75-25        | 99.984                      | 0.0013805                                              | 1.999                                        | 7215.05                                        |
|                | 25-75        | 99.984                      | 0.0008340                                              | 1.999                                        | 12308.87                                       |
| Exp Scenario 2 | 50-50        | 96.216                      | 0.0007484                                              | 1.924                                        | 12986.45                                       |
|                | 75-25        | 96.216                      | 0.0010348                                              | 1.924                                        | 9254.39                                        |
|                | 25-75        | 96.216                      | 0.0005951                                              | 1.924                                        | 16594.24                                       |



**Figure 4.27:** Comparison of Energy Emissions Per Part.

From the Table 4.19 and the Figure 4.27 it is evident that the experimental scenario 2 has the least amount of total energy emissions and energy emissions per part when compared to the base and experimental scenario 1. This is primarily because in the operative scenario 2 the assembly station 2 is activated only during a certain interval unlike in scenario 1 where the parallel station is always in the working state.



**Figure 4.28:** Energy utilization statistics of scenario 1 vs scenario 2.

From the above Figure 4.28 showing the energy utilization statistics of scenario 1 vs scenario 2 we can infer that the stations in scenario 1 are at an operational state for a longer duration when compared to scenario 2. The issue with the stations having a larger operational duration than working duration's is that they still consume energy in this state for even though they do not contribute towards processing new drones or towards any value-adding work. This increases the associated energy emissions and the corresponding energy emissions per part. Moreover since in the current production system of the drone factory where the energy consumed in working and operational states are the same it is a clear indication that it is beneficial to use the additional station as a dynamically re-balanced station. This is because scenario 2 has a higher working duration for the assembly stations thus resulting in a much lower energy consumption and emissions while contributing towards a

higher productivity and value-adding work when compared to scenario 1.

In the second scenario it can also be observed that the scrap ratio and the rework ratio decreases mainly due to the fact that station 2 is responsible for the entire assembly of the drones which decreases the margin of error for incorrect assemblies and defected components. However the material emissions and the production costs increase but this is because as the throughput increases the associated material consumption also increases due to which we incur higher production cost and material emissions. The results of the simulation therefore show us that instead of using the additional station 2 as a parallel station if we use it as a flexible and dynamically re-balanced station we are able to achieve a higher TPH with lesser lead times and improve but also decrease the emissions and waste generated thereby improving the overall sustainability of the production process.

# 5

## Discussion

This section provides an in depth analysis on how this master thesis project was carried out and the results obtained. The findings of the following research questions are discussed in detail in order to achieve the objectives and purpose of this master thesis.

### 5.1 Research Question 1

RQ1: Which are the most suitable KPIs to assess the sustainability of production systems through a DES model?

Production systems are said to achieve sustainability when they are capable of creating value in all the three dimensions of sustainability which are represented as the TBL. Being economically, environmentally and socially sustainable means that the system needs to choose different alternatives or scenarios in such way that the operations of the system have a balanced effect on indicators that reflect the 3 dimensions of sustainability. For example, increasing quality and customer satisfaction with decrease in emissions and production costs. This can be possible through effective performance management and decision making. KPIs play an important role in the measurement of performance of a production system, and also in assessing the improvement potential of the system. This supports the evaluation of success rate of the production system by making decision making simpler from a management perspective.

The search strategy for the literature study was to obtain the most suitable sustainable KPIs that are proposed by the literature in the context of production systems using DES and DT. The literature shows that the selection of KPIs in the industries are not clearly understood and defined, and depends on the description of each elemental KPI that organisation has defined. The method of categorization of KPIs obtained from literature, included KPIs in three levels such as elemental, basic and comprehensive. The elemental level KPIs were the measures and were used to estimate basic level KPIs and further these basic level KPIs used for estimating comprehensive level KPIs. As the measures were to the elemental level, this helped in broadening the improvement opportunities for the DES model and validate the KPI results obtained from the DES. For instance, First Pass Yield (FPY), scrap ratio and rework ratio being the elemental KPIs of the basic KPI, quality, the values obtained had to sum up to 100%, which is said to be a valid result.

Incorporating right set of KPIs will make decision making more effective and accurate [26]. The selection of KPIs need to consider to evaluate the objectives of the KPIs against the objectives of the production system. The objective of the production system is to attain material efficiency and energy efficiency in the production system that will lead to fulfill TBL aspect of sustainable production. For the project, the KPIs proposed by the literature were evaluated against the objectives of the production system. However, the project was limited to incorporate economic and environmental KPIs in the DES. therefore, the most recurring economical basic KPIs were selected such as quality, delivery, productivity and cost and the most recurring environmental basic KPIs were selected such as resource utilization, emissions and waste. Further the elemental KPIs were selected based on the relevance to the Drone factory and possibility to estimate using the attributes obtained from the DES of the Drone factory. For example, the selected basic economic KPI, cost include elemental KPI, labour cost along with material and energy cost. But in the case of the Drone factory, which is a test-bed, there is no real manufacturing taking place with assigned labour cost. Hence, only the elemental KPIs that are relevant and feasible for measuring using the attributes obtained in the DES model were estimated.

The modelling was carried out by adding the missing energy and material data for measuring the selected KPIs. Not all the necessary data was available for measurement by using the attributes in the DES. The measures such as emissions from material and energy consumption were obtained by performing a compact environmental impact analysis (quantitative analysis) with defined goals and system boundaries. In addition, the material and energy information was added into the model for the selected KPIs to be incorporated in the DES of the Drone factory and hence achieve the objectives of the production system. In case of real-time production system, collecting data in most detailed level will have significant impact on the results of the assessment. However, as the project was for the test-bed and with a limited amount of data, our goal and scope was to obtain and estimate values to incorporate the impact analysis results with the simulation model and carry out experimentation. As this is the first step towards combining the assessment model with the DES model, the method for analyzing the environmental impact was decided to be simpler with limited range of boundaries considered without compromising on the necessary KPIs.

## 5.2 Research Question 2

How can DES be used to improve the sustainability of the production systems and what are the data points required for a real time decision making process that contributes towards a Digital Twin for sustainable production?

DES is a very effective and valuable tool to evaluate and analyze complex manufacturing operations which involves numerous product and process variabilities. Simulations are a cost effective and reliable source for analyzing different production practices and strategies. The Siemens Technomatix Plant Simulation which used as the DES tool in this master thesis is a remarkably versatile software that helps us to intuitively monitor the model performance through the use of various animation features which are in-built in the software. Moreover the object-oriented programming capabilities in the software enables us to keep a track of the MU's and their components in the object class library. Complex models, which can mimic the behaviour of a real world production system can be simulated by using DES to study the performance of these systems and determine how they can be improved. Therefore, it serves as an ideal platform which can be used to model and study how to improve the sustainability of the production systems whilst being able to achieve a high productivity. To measure and improve the sustainability of the drone factory at SII-Lab the project contributed towards creating a replica of the production facility that is able to replicate the behaviour of the current production system to degree of accuracy that is acceptable by the SII-Lab.

In order to measure the sustainability through DES we were able to set user defined attributes for the objects and resources in Plant simulation. Based on the user defined attributes the software has the capability to provide key statistics about the performance of the model through various methods such as show attributes and methods. The necessary data required to measure the sustainability KPIs such as material and energy emissions, waste and resource utilization was provided as input data into the DES which were then used for measuring the sustainability of the system. In order to improve the production system's sustainability multiple scenarios were created from the base model. One of the more important findings from the literature suggested the quality improvements for zero-defect manufacturing (ZDM). ZDM is a manufacturing strategy whose main objective or goal is to decrease or mitigate the production errors and disturbances thereby preventing defects in products [52]. Although ZDM contributes towards reducing the costs of the company resources associated to treating defected products it also helps reduces waste and improves the sustainability. In other words the ZDM strategy tries to eliminate all non-value adding activities in a process [52]. The Base scenario was created to conform with this idea to identify the scrap and rework at the individual assembly stations where the defects in products can be monitored thereby improving the quality and reducing the waste generated due to defected products. Industries could therefore try to adopt the ZDM scenario by changing the design of the production system by installing high speed cameras and sensors with image recognition software's at the assembly stations to identify the scrap and incorrect assemblies.

However, for this project the ZDM scenario could be simulated on the Plant simulation software through a code which made the model to identify the scrap components at individual assembly stations to decrease the number of faulty products arriving at the quality station.

From a digital twin perspective, the ZDM scenario could not be controlled in real time for sustainability improvements as it involved a design change of the production system. It was necessary to identify an operative scenario that could be controlled in real time to achieve the economic and environmental aspects of sustainability. The experimental scenario 2 which suggested the use of an additional assembly station which shall be activated only when the capacity of any other station has become maximum making it the bottleneck station. This way we create a dynamically re-balanced station that can alleviate the load on the highest utilized stations, hence avoiding a bottleneck situation along the production line. It can be argued that the extra station can also be used as a parallel station where the processing times can be re-balanced to avoid the bottlenecks as in case of the experimental scenario 1. However, from the experimental results and analysis it was observed that although a parallel station can help in avoiding the bottlenecks it accounts for a higher energy emission as it is always in the active state when compared to the operative scenario where the station is activated only for a certain duration of time hence consuming lesser energy resulting in lesser emissions. Moreover, the customer demand in a real world situation keeps changing dynamically and hence when the demand is low the load on the system decreases which makes it redundant to use the additional station as a parallel assembly station.

Therefore, from a digital twin perspective it is necessary for this identified operative scenario to establish a bi-directional flow of information between the physical and virtual entities. This real-time data exchange is necessary, so that the system can discern at what point during the production run should it activate the the additional assembly station. In order to establish these connections certain data points from the simulation model must be collected which can be set as triggers so that the system can autonomously take decisions on when to activate and deactivate the stations. Some of the triggers that can be used for this purpose are by measuring the work in progress of the products, utilization rates of the assembly stations, buffer capacities of the assembly stations and the position of the products on the conveyor lines. Collecting and monitoring data from these data points and implementing the required connections for this data to be exchanged between the physical and virtual entities, we can create a digital twin that is capable of making our production systems more sustainable.

### 5.3 Future work

In order to achieve the entire TBL aspects of sustainable production apart from economic and environmental factors we also need to consider the social factors such as employee health, safety, satisfaction, development etc. which is not being assessed in this master thesis project due to the lack of data availability for measuring these aspects. This is primarily due to the fact the SII-Lab did not have dedicated shop-floor workers to perform the assemblies of the drone since it is a facility for testing neoteric manufacturing technologies. However, the SII Lab provides the possibility of testing ideas in a realistic production scenario, which could allow measuring social factors with the right data, resources and sensors.

As learnt from the literature results, there is limited research that focuses on creating a framework or a methodology for integrating environmental impact analysis tools such as LCA with the DES model for a more dynamic and sustainable decision making. LCA is said to have less dynamicity as it uses standard values for its estimation purpose and therefore needs to be updated manually when the parameters in the DES model change. There are currently few methodologies or frameworks for integrating the DES with such tools, but these are limited to the complexity of the production system, data availability and resources. The scope for the future work can be to contribute to creating a framework for integrating a suitable environmental impact analysis tool with the DES of any production system. The framework must be designed for multiple levels of complexity in industries. However, the data availability or capturing with suitable resources is essential for more accurate impact analysis to be carried out. The impact analysis must be compact but be capable to provide production managers (decision makers) without compromising on the overall impact assessment. The assessment needs to provide information mainly for efficient resource utilization and therefore resulting with positive economic and environmental impacts.



# 6

## Conclusion

This master thesis project aimed to contribute towards measuring and implementing the TBL aspects of sustainability at the SII-Lab through a DES that can contribute towards creating a Digital Twin to monitor the process across its life cycle. The SII-Lab provides us with the flexibility to build and test different types of production setups such a continuous, line, job flow or as in this project a discrete production system. This flexibility combined with the potential of bi-directional information flow between the physical and virtual entities shows the effectiveness of the SII-Lab to test the feasibility of a digital twin. DES is an efficient method to create a high fidelity virtual representation of the production facility. As the model behaviour could easily be changed by changing the system parameters and the corresponding production performance of the system could be evaluated. The prospects of using DES for the modelling and simulation of the production systems to study, implement and improve the sustainability aspects of the production process has proved to be an efficient method through this project which can further be explored by manufacturing organizations. This process provides a cost-efficient solution to analyze multiple manufacturing scenarios to identify the best system in a virtual environment.

A key takeaway from the literature review was that most industries face a challenge in being able to set up KPIs that can help them asses the sustainability of their production processes. Through this project we have been able to identify and classify sustainability metrics that can provide a clear understanding of what is happening during the process. These identified indicators can aid in making decisions to improve production sustainability without making any trade-offs or compromises on overall productivity. Through the integration of these sustainability indicators into the virtual entities we can evaluate the production systems for their economic, environmental and social performance. The data obtained from these performance indicators in the virtual models can be used to create triggers for selecting a manufacturing scenario to ensure production sustainability. With the advancement of digitalization technologies such as CPS, we will be able to create a Digital Twin that can autonomously control and monitor the production process for ensuring sustainability in production.



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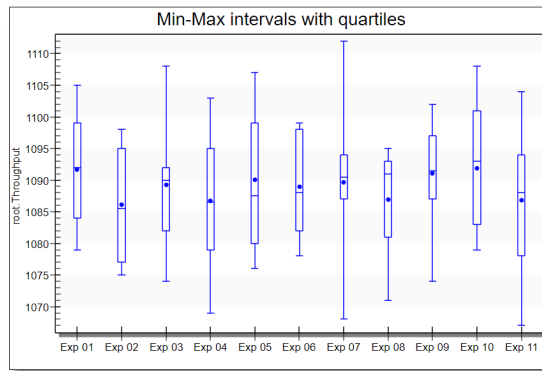
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# A

## Appendix 1

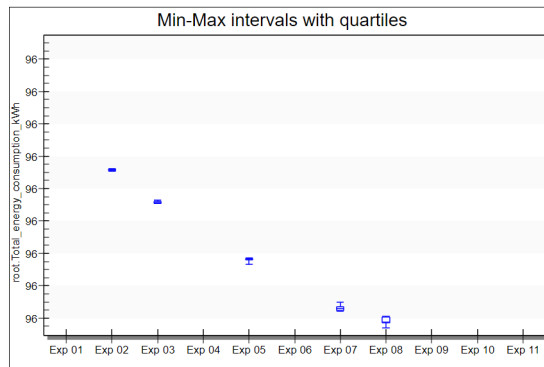
### A.1 Results of ASIS scenario experiments



| Experiment | root.Throughput | Standard Deviation | Minimum | Maximum | Left interval bound | Right interval bound |
|------------|-----------------|--------------------|---------|---------|---------------------|----------------------|
| Exp 01     | 1091.7          | 9.47569991552363   | 1079    | 1105    | 1084.9161533185     | 1098.4838466815      |
| Exp 02     | 1086.1          | 9.31486267566522   | 1075    | 1098    | 1079.43129997633    | 1092.76870002367     |
| Exp 03     | 1089.2          | 9.10189235514297   | 1074    | 1108    | 1082.68376976906    | 1095.71623023094     |
| Exp 04     | 1086.7          | 10.7914575269387   | 1069    | 1103    | 1078.97417562973    | 1094.42582437027     |
| Exp 05     | 1090.1          | 11.0599377132991   | 1076    | 1107    | 1082.18196519277    | 1098.01803480723     |
| Exp 06     | 1088.9          | 8.11651266108864   | 1078    | 1099    | 1083.08922317379    | 1094.71077682622     |
| Exp 07     | 1089.7          | 11.7761529277492   | 1068    | 1112    | 1081.26921212449    | 1098.13078787551     |
| Exp 08     | 1086.9          | 8.17108723894814   | 1071    | 1095    | 1081.05015212128    | 1092.74984787872     |
| Exp 09     | 1091.1          | 8.41229259277761   | 1074    | 1102    | 1085.07746829278    | 1097.12253170722     |
| Exp 10     | 1091.9          | 10.1592869390989   | 1079    | 1108    | 1084.62675943702    | 1099.17324056298     |
| Exp 11     | 1086.8          | 11.6790410565234   | 1067    | 1104    | 1078.43873649221    | 1095.16126350779     |

Figure A.1: Evaluations of the 'Throughput' for 11 different number of pallet sizes

Evaluations of the output value 'root.Total\_energy\_consumption\_kWh'

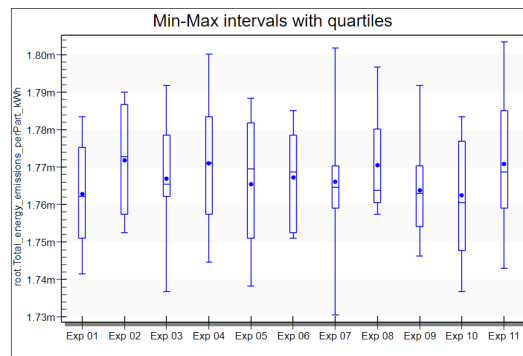


## A. Appendix 1

| Experiment | root.Total_energy_consumption_kWh | Standard Deviation   | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|-----------------------------------|----------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 96.215999999717                   | 0                    |                  |                  |                     |                      |
| Exp 02     | 96.215999999515                   | 1.79826553646481e-06 | 96.215999999508  | 96.215999999523  | 96.2159987125366    | 96.2160012873665     |
| Exp 03     | 96.215999999315                   | 1.27156575520833e-06 | 96.215999999309  | 96.215999999329  | 96.2159990895917    | 96.2160009102714     |
| Exp 04     | 96.215999999136                   | 0                    |                  |                  |                     |                      |
| Exp 05     | 96.215999999896                   | 1.27156575520833e-06 | 96.2159999998932 | 96.2159999998972 | 96.2159990895562    | 96.2160009102358     |
| Exp 06     | 96.215999999802                   | 0                    |                  |                  |                     |                      |
| Exp 07     | 96.2159999998664                  | 1.79826553646481e-06 | 96.2159999998641 | 96.2159999998698 | 96.2159987124514    | 96.2160012872813     |
| Exp 08     | 96.2159999998581                  | 1.27156575520833e-06 | 96.2159999998538 | 96.2159999998612 | 96.2159990895183    | 96.216000910198      |
| Exp 09     | 96.2159999998588                  | 0                    |                  |                  |                     |                      |
| Exp 10     | 96.215999999281                   | 0                    |                  |                  |                     |                      |
| Exp 11     | 96.216000000306                   | 0                    |                  |                  |                     |                      |

Figure A.2: Evaluations of the 'Energy consumption' for 11 different pallet sizes

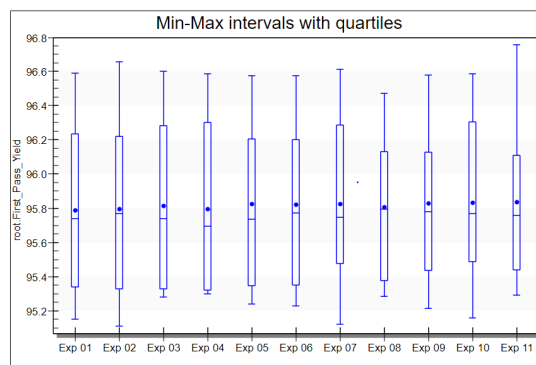
Evaluations of the output value 'root.Total\_energy\_emissions\_perPart\_kWh'



| Experiment | root.Total_energy_emissions_perPart_kWh | Standard Deviation   | Minimum             | Maximum             | Left interval bound | Right interval |
|------------|-----------------------------------------|----------------------|---------------------|---------------------|---------------------|----------------|
| Exp 01     | 0.00176280153144324                     | 1.52946396038053e-05 | 0.0017414660633479  | 0.00178342910101894 | 0.00175185178725061 | 0.00177375127  |
| Exp 02     | 0.00177188775585397                     | 1.51839895819573e-05 | 0.00175256830601004 | 0.00179006511627816 | 0.001761017228267   | 0.00178275828  |
| Exp 03     | 0.0017668385969251                      | 1.47182331511763e-05 | 0.00173675090252583 | 0.00179173184357413 | 0.00175630147662632 | 0.0017773756   |
| Exp 04     | 0.00177094960661556                     | 1.76008044605765e-05 | 0.00174462375339826 | 0.0018001122544418  | 0.00175834883200302 | 0.00178355038  |
| Exp 05     | 0.00176543230430043                     | 1.7858203224513e-05  | 0.00173831978319597 | 0.00178840148698688 | 0.00175264725266707 | 0.00177821735  |
| Exp 06     | 0.00176730292685603                     | 1.31635773496341e-05 | 0.00175097361237272 | 0.00178508348793839 | 0.00175787885356159 | 0.00177672700  |
| Exp 07     | 0.00176610297008784                     | 1.90997977602753e-05 | 0.00173050359711996 | 0.00180179775280648 | 0.001752429035623   | 0.00177977690  |
| Exp 08     | 0.00177055701852757                     | 1.33839339769303e-05 | 0.00175736986301116 | 0.00179675070027746 | 0.00176097518743284 | 0.00178013884  |
| Exp 09     | 0.00176374612539195                     | 1.36574621634881e-05 | 0.0017462068965492  | 0.00179173184357277 | 0.00175396846989405 | 0.00177352378  |
| Exp 10     | 0.00176249631343135                     | 1.63756386837785e-05 | 0.0017367509025259  | 0.00178342910101826 | 0.0017507265996693  | 0.00177421996  |
| Exp 11     | 0.00177081381461698                     | 1.90717243012824e-05 | 0.00174304347826143 | 0.00180348641049722 | 0.00175715997851356 | 0.0017844676   |

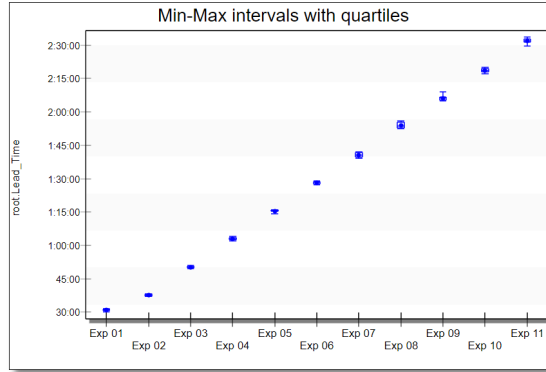
Figure A.3: Evaluations of the 'Energy emissions'

Evaluations of the output value 'root.First\_Pass\_Yield'



| Experiment | root.First_Pass_Yield | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|-----------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 95.7886066553759      | 0.52816792464543   | 95.1499118165785 | 96.5879265091863 | 95.4104804742087    | 96.1667328365431     |
| Exp 02     | 95.7942534403679      | 0.532040495562665  | 95.1091703056769 | 96.6549295774648 | 95.4133548067657    | 96.1751520739701     |
| Exp 03     | 95.8129765525301      | 0.518324829850255  | 95.2797202797203 | 96.5998256320837 | 95.4418972435326    | 96.1840558615275     |
| Exp 04     | 95.7962597349212      | 0.504713703991771  | 95.3002610966057 | 96.584938704028  | 95.4349249083166    | 96.1575945615258     |
| Exp 05     | 95.8246364591158      | 0.47273075868205   | 95.2380952380952 | 96.572934973638  | 95.4861988748614    | 96.1630740433701     |
| Exp 06     | 95.8204269608541      | 0.484549714551     | 95.2296819787986 | 96.572934973638  | 95.4735279452263    | 96.1673259764818     |
| Exp 07     | 95.823008478636       | 0.51710369341448   | 95.1219512195122 | 96.611642050391  | 95.4528034060993    | 96.1932135511727     |
| Exp 08     | 95.8047265235391      | 0.452967537392586  | 95.2846975088968 | 96.4695498676081 | 95.4804378321745    | 96.1290152149037     |
| Exp 09     | 95.8276827472737      | 0.447497020238348  | 95.2127659574468 | 96.5789473684211 | 95.5073105106274    | 96.1480549839201     |
| Exp 10     | 95.8299005817649      | 0.480078246161271  | 95.1584507042254 | 96.584938704028  | 95.4862027814845    | 96.1735983820452     |
| Exp 11     | 95.8363322519701      | 0.477752060109528  | 95.2930728241563 | 96.7572304995618 | 95.4942998156912    | 96.178364688249      |

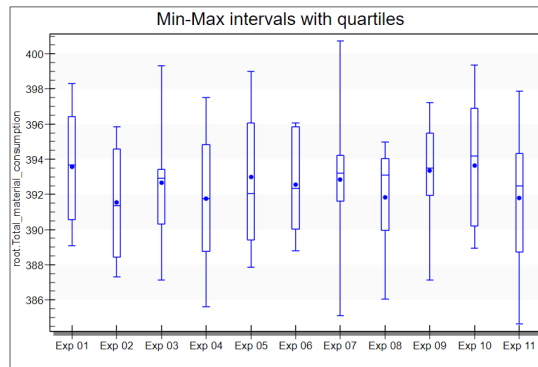
Figure A.4: Evaluations of First Pass Yield



| Experiment | root.Lead_Time | Standard Deviation | Minimum      | Maximum      | Left interval bound | Right interval bound |
|------------|----------------|--------------------|--------------|--------------|---------------------|----------------------|
| Exp 01     | 30:57.3559     | 27.7945            | 30:08.7466   | 31:31.8737   | 30:37.4573          | 31:17.2546           |
| Exp 02     | 37:35.4298     | 22.4163            | 37:05.4018   | 38:05.6269   | 37:19.3815          | 37:51.4781           |
| Exp 03     | 50:10.4848     | 23.7223            | 49:40.5711   | 50:54.3457   | 49:53.5015          | 50:27.4680           |
| Exp 04     | 1:02:59.6786   | 42.4553            | 1:01:57.3587 | 1:04:06.2426 | 1:02:29.2840        | 1:03:30.0733         |
| Exp 05     | 1:15:25.0224   | 38.1774            | 1:14:03.4848 | 1:16:04.2124 | 1:14:57.6904        | 1:15:52.3544         |
| Exp 06     | 1:28:15.7322   | 38.6297            | 1:27:11.2592 | 1:28:56.5747 | 1:27:48.0764        | 1:28:43.3880         |
| Exp 07     | 1:40:38.7351   | 1:00.7532          | 1:39:17.4301 | 1:42:03.2031 | 1:39:55.2407        | 1:41:22.2296         |
| Exp 08     | 1:53:56.6570   | 1:20.4922          | 1:52:25.6182 | 1:56:04.3765 | 1:52:59.0310        | 1:54:54.2830         |
| Exp 09     | 2:06:13.1388   | 1:12.9379          | 2:04:56.7505 | 2:08:56.2825 | 2:05:20.9210        | 2:07:05.3565         |
| Exp 10     | 2:18:43.0757   | 55.7519            | 2:17:03.0363 | 2:20:05.3270 | 2:18:03.1618        | 2:19:22.9897         |
| Exp 11     | 2:31:51.1218   | 1:16.1605          | 2:29:37.9157 | 2:33:39.0101 | 2:30:56.5969        | 2:32:45.6467         |

Figure A.5: Evaluations of Lead time

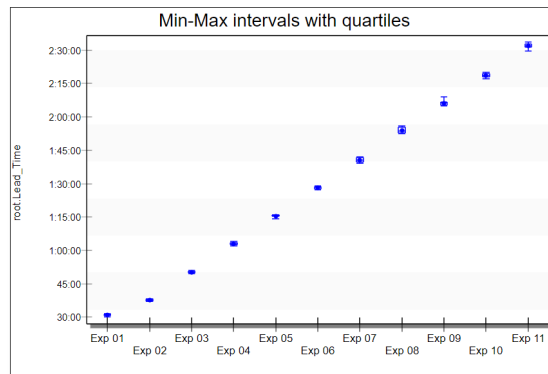
Evaluations of the output value 'root.Total\_material\_consumption'



| Experiment | root.Total_material_consumption [kg] | Standard Deviation [kg] | Minimum [kg] | Maximum [kg] | Left interval bound [kg] | Right interval bound [kg] |
|------------|--------------------------------------|-------------------------|--------------|--------------|--------------------------|---------------------------|
| Exp 01     | 393.5698                             | 3.3983838577105         | 389.072      | 398.292      | 391.136827738201         | 396.002772261799          |
| Exp 02     | 391.5538                             | 3.27840766903037        | 387.308      | 395.83       | 389.206721136757         | 393.900878863243          |
| Exp 03     | 392.6698                             | 3.20149540752035        | 387.138      | 399.304      | 390.377784192221         | 394.961815807779          |
| Exp 04     | 391.7698                             | 3.81440071891855        | 385.624      | 397.504      | 389.038992788961         | 394.500607211039          |
| Exp 05     | 392.9822                             | 3.96304298907745        | 387.858      | 399.012      | 390.144976758469         | 395.819423241532          |
| Exp 06     | 392.5618                             | 2.81469089678731        | 388.79       | 396.064      | 390.546705424417         | 394.576894575583          |
| Exp 07     | 392.8382                             | 4.17629665293931        | 385.112      | 400.744      | 389.848304114463         | 395.828095885537          |
| Exp 08     | 391.8326                             | 2.9311778519822         | 386.058      | 394.988      | 389.734110039223         | 393.931089960777          |
| Exp 09     | 393.3538                             | 2.99703460107099        | 387.138      | 397.204      | 391.208161850409         | 395.499438149591          |
| Exp 10     | 393.6418                             | 3.67339956988804        | 388.932      | 399.364      | 391.011938385114         | 396.271661614886          |
| Exp 11     | 391.8082                             | 4.17782691519108        | 384.618      | 397.864      | 388.81720856853          | 394.79919143147           |

Figure A.6: Evaluations of Material Consumption

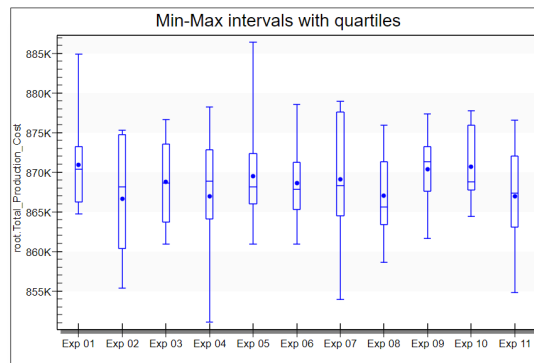
## A. Appendix 1



| Experiment | root.Lead Time | Standard Deviation | Minimum      | Maximum      | Left interval bound | Right interval bound |
|------------|----------------|--------------------|--------------|--------------|---------------------|----------------------|
| Exp 01     | 30:57.3559     | 27.7945            | 30:08.7466   | 31:31.8737   | 30:37.4573          | 31:17.2546           |
| Exp 02     | 37:35.4298     | 22.4163            | 37:05.4018   | 38:05.6269   | 37:19.3815          | 37:51.4781           |
| Exp 03     | 50:10.4848     | 23.7223            | 49:40.5711   | 50:54.3457   | 49:53.5015          | 50:27.4680           |
| Exp 04     | 1:02:59.6786   | 42.4553            | 1:01:57.3587 | 1:04:06.2426 | 1:02:29.2840        | 1:03:30.0733         |
| Exp 05     | 1:15:25.0224   | 38.1774            | 1:14:03.4848 | 1:16:04.2124 | 1:14:57.6904        | 1:15:52.3544         |
| Exp 06     | 1:28:15.7322   | 38.6297            | 1:27:11.2592 | 1:28:56.5747 | 1:27:48.0764        | 1:28:43.3880         |
| Exp 07     | 1:40:38.7351   | 1:00.7532          | 1:39:17.4301 | 1:42:03.2031 | 1:39:55.2407        | 1:41:22.2296         |
| Exp 08     | 1:53:56.6570   | 1:20.4922          | 1:52:25.6182 | 1:56:04.3765 | 1:52:59.0310        | 1:54:54.2830         |
| Exp 09     | 2:06:13.1388   | 1:12.9379          | 2:04:56.7505 | 2:08:56.2825 | 2:05:20.9210        | 2:07:05.3565         |
| Exp 10     | 2:18:43.0757   | 55.7519            | 2:17:03.0363 | 2:20:05.3270 | 2:18:03.1618        | 2:19:22.9897         |
| Exp 11     | 2:31:51.1218   | 1:16.1605          | 2:29:37.9157 | 2:33:39.0101 | 2:30:56.5969        | 2:32:45.6467         |

Figure A.7: Evaluations of Lead time

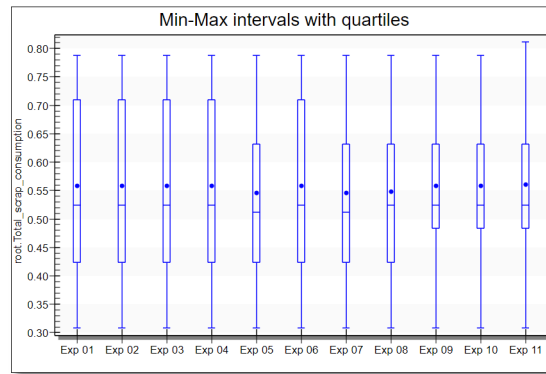
Evaluations of the output value 'root.Total\_Production\_Cost'



| Experiment | root.Total_Production_Cost | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|----------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 870949.223999999           | 5991.85687907067   | 864723.023999999 | 884923.763999999 | 866659.531547991    | 875238.916452007     |
| Exp 02     | 866617.223999998           | 7478.98991793677   | 855347.703999998 | 875328.273999998 | 861262.862698131    | 871971.585301864     |
| Exp 03     | 868821.223999997           | 5461.19870982542   | 860923.023999997 | 876632.023999997 | 864911.440546009    | 872731.007453985     |
| Exp 04     | 866921.223999996           | 8869.73230043501   | 851043.023999996 | 878225.853999996 | 860571.201883578    | 873271.246116414     |
| Exp 05     | 869498.026999995           | 7572.76204223018   | 860888.273999995 | 886443.763999995 | 864076.532323299    | 874919.521676692     |
| Exp 06     | 868593.223999994           | 5078.06114066685   | 860923.023999994 | 878573.073999995 | 864957.736539998    | 872228.711459991     |
| Exp 07     | 869118.026999994           | 7789.6673280371    | 853905.853999994 | 878912.023999994 | 863541.245408722    | 874694.808591266     |
| Exp 08     | 866997.039999994           | 5665.94074172288   | 858608.273999993 | 875945.853999994 | 862940.677552788    | 871053.402447199     |
| Exp 09     | 870341.223999994           | 4485.80932848117   | 861648.273999993 | 877323.763999993 | 867129.741682259    | 873552.706317729     |
| Exp 10     | 870721.223999996           | 4821.6295998956    | 864403.763999997 | 877793.373999997 | 867269.321106037    | 874173.126893955     |
| Exp 11     | 866928.237000001           | 6512.68509624632   | 854808.274000001 | 876563.764000001 | 862265.673012991    | 871590.800987012     |

Figure A.8: Evaluations of Production cost

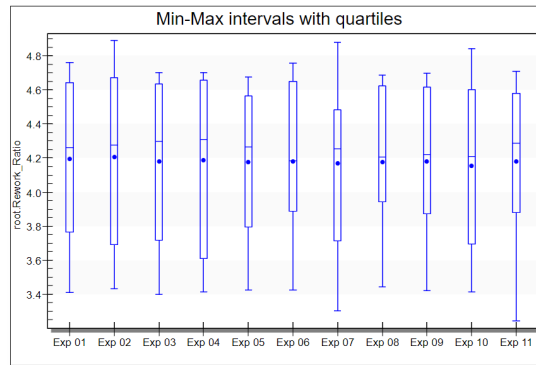
Evaluations of the output value 'root.Total\_scrap\_consumption'



| Experiment | root.Total_scrap_consumption [kg] | Standard Deviation [kg] | Minimum [kg] | Maximum [kg] | Left interval bound [kg] | Right interval bound [kg] |
|------------|-----------------------------------|-------------------------|--------------|--------------|--------------------------|---------------------------|
| Exp 01     | 0.5578                            | 0.166195199823715       | 0.308        | 0.788        | 0.438817469436892        | 0.676782530563108         |
| Exp 02     | 0.5578                            | 0.166195199823715       | 0.308        | 0.788        | 0.438817469436892        | 0.676782530563108         |
| Exp 03     | 0.5578                            | 0.166195199823715       | 0.308        | 0.788        | 0.438817469436892        | 0.676782530563108         |
| Exp 04     | 0.5578                            | 0.166195199823715       | 0.308        | 0.788        | 0.438817469436892        | 0.676782530563108         |
| Exp 05     | 0.5462                            | 0.159391760556603       | 0.308        | 0.788        | 0.43208819026031         | 0.66031180973969          |
| Exp 06     | 0.5578                            | 0.166195199823715       | 0.308        | 0.788        | 0.438817469436892        | 0.676782530563108         |
| Exp 07     | 0.5462                            | 0.159391760556603       | 0.308        | 0.788        | 0.43208819026031         | 0.66031180973969          |
| Exp 08     | 0.5486                            | 0.159234418389995       | 0.308        | 0.788        | 0.434600834723971        | 0.662599165276029         |
| Exp 09     | 0.5578                            | 0.151658827636244       | 0.308        | 0.788        | 0.449224354532894        | 0.666375645467106         |
| Exp 10     | 0.5578                            | 0.151658827636244       | 0.308        | 0.788        | 0.449224354532894        | 0.666375645467106         |
| Exp 11     | 0.5602                            | 0.155838805608017       | 0.308        | 0.812        | 0.448631823116179        | 0.671768176883821         |

Figure A.9: Evaluations of Scrap cost

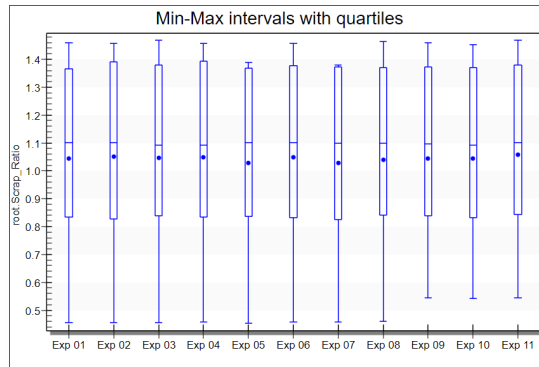
Evaluations of the output value 'root.Rework\_Ratio'



| Experiment | root.Rework_Ratio | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|-------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 4.19397809014661  | 0.493876758911743  | 3.41207349081365 | 4.76190476190476 | 3.84040165337855    | 4.54755452691467     |
| Exp 02     | 4.20573031259971  | 0.535317069266272  | 3.4330985915493  | 4.89082969432314 | 3.8224859131075     | 4.58897471209192     |
| Exp 03     | 4.17835913696176  | 0.497846908447694  | 3.4001743679163  | 4.70275066548358 | 3.82194038923043    | 4.53477788469309     |
| Exp 04     | 4.18571056636467  | 0.525316124453657  | 3.41506129597198 | 4.69973890339426 | 3.80962604708013    | 4.56179508564922     |
| Exp 05     | 4.17548428490864  | 0.452318842604111  | 3.42706502636204 | 4.67372134038801 | 3.85166000736333    | 4.49930856245395     |
| Exp 06     | 4.1796423530919   | 0.481490534164712  | 3.42706502636204 | 4.75770925110132 | 3.83493346704785    | 4.52435123913594     |
| Exp 07     | 4.16842611403505  | 0.515452262940835  | 3.30147697654214 | 4.8780487804878  | 3.7994033423013     | 4.53744889383996     |
| Exp 08     | 4.17766596611173  | 0.443441317532598  | 3.44218887908208 | 4.68611847922193 | 3.86019728968647    | 4.495134642537       |
| Exp 09     | 4.18099587764787  | 0.459385139466174  | 3.42105263157895 | 4.69858156028369 | 3.85211269416996    | 4.50987906112579     |
| Exp 10     | 4.15265498759069  | 0.504956925246284  | 3.41506129597198 | 4.84154929577465 | 3.7911460339332     | 4.51416394124819     |
| Exp 11     | 4.18126637739331  | 0.48717826772359   | 3.24276950043821 | 4.70692717584369 | 3.83248552698013    | 4.53004722780649     |

Figure A.10: Evaluations of Rework ratio

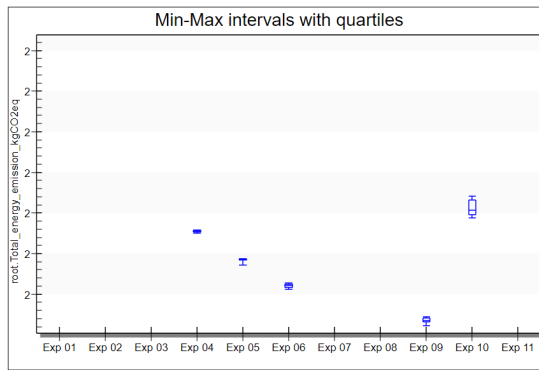
Evaluations of the output value 'root.Scrap\_Ratio'



| Experiment | root.Scrap_Ratio | Standard Deviation | Minimum           | Maximum           | Left interval bound | Right interval bound |
|------------|------------------|--------------------|-------------------|-------------------|---------------------|----------------------|
| Exp 01     | 1.04411630862554 | 0.353617919130209  | 0.45662100456621  | 1.45985401459854  | 0.790954033690993   | 1.29727858356008     |
| Exp 02     | 1.05015881557739 | 0.357404844808957  | 0.45662100456621  | 1.45719489981785  | 0.794285403372994   | 1.30603222778178     |
| Exp 03     | 1.04733034726464 | 0.356601375232237  | 0.456204379562044 | 1.46788990825688  | 0.792032155304694   | 1.30262853922458     |
| Exp 04     | 1.04944620438461 | 0.357013746153644  | 0.457038391224863 | 1.45719489981785  | 0.793852787678032   | 1.30503962109119     |
| Exp 05     | 1.02838894558013 | 0.339584778808929  | 0.452488687782805 | 1.388888888888889 | 0.785273281792861   | 1.27150460936739     |
| Exp 06     | 1.04778738389175 | 0.35649643841136   | 0.457038391224863 | 1.45719489981785  | 0.792564318340449   | 1.30301044944304     |
| Exp 07     | 1.02871575804076 | 0.340228416667706  | 0.457038391224863 | 1.37994480220791  | 0.785139300793249   | 1.27229221528828     |
| Exp 08     | 1.03948381786005 | 0.348373742579179  | 0.459136822773186 | 1.46386093321135  | 0.790075955793163   | 1.28889167992693     |
| Exp 09     | 1.04507815949831 | 0.332473461634518  | 0.544464609800363 | 1.45852324521422  | 0.807053632602755   | 1.28310268639386     |
| Exp 10     | 1.04377162502489 | 0.330201874990288  | 0.541516245487365 | 1.45322434150772  | 0.80733373302211    | 1.28016987674757     |
| Exp 11     | 1.05864603718429 | 0.345607910497261  | 0.544959128065395 | 1.4692378328742   | 0.811218290671696   | 1.30607378369689     |

Figure A.11: Evaluations of Scrap ratio

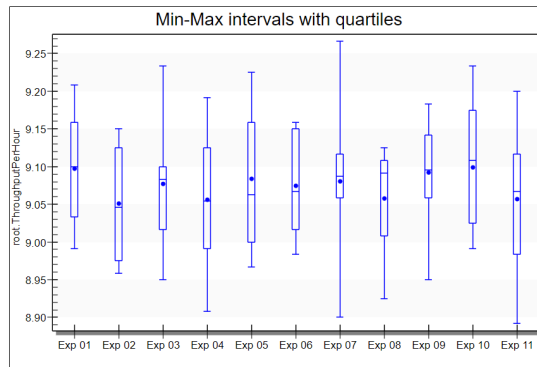
Evaluations of the output value 'root.Total\_energy\_emission\_kgCO2eq'



| Experiment | root.Total_energy_emission_kgCO2eq | Standard Deviation   | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|------------------------------------|----------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 1.92431999999943                   | 0                    |                  |                  |                     |                      |
| Exp 02     | 1.92431999999903                   | 0                    |                  |                  |                     |                      |
| Exp 03     | 1.92431999999863                   | 0                    |                  |                  |                     |                      |
| Exp 04     | 1.92431999999827                   | 2.80978990072627e-08 | 1.92431999999825 | 1.92431999999829 | 1.92431997988241    | 1.92432002011413     |
| Exp 05     | 1.92431999999792                   | 2.80978990072627e-08 | 1.92431999999786 | 1.92431999999794 | 1.92431997988206    | 1.92432002011378     |
| Exp 06     | 1.92431999999756                   | 2.80978990072627e-08 | 1.92431999999756 | 1.92431999999764 | 1.92431997988174    | 1.92432002011346     |
| Exp 07     | 1.92431999999733                   | 0                    |                  |                  |                     |                      |
| Exp 08     | 1.92431999999716                   | 0                    |                  |                  |                     |                      |
| Exp 09     | 1.92431999999718                   | 2.80978990072627e-08 | 1.92431999999711 | 1.92431999999722 | 1.92431997988132    | 1.92432002011303     |
| Exp 10     | 1.92431999999856                   | 2.80978990072627e-08 | 1.92431999999844 | 1.92431999999871 | 1.9243199798827     | 1.92432002011442     |
| Exp 11     | 1.92432000000061                   | 0                    |                  |                  |                     |                      |

Figure A.12: Evaluations of Total energy emissions

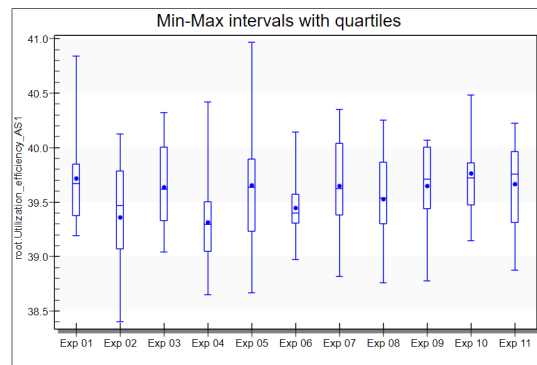
Evaluations of the output value 'root.ThroughputPerHour'



| Experiment | root.ThroughputPerHour | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 9.0975                 | 0.0789641659624559 | 8.99166666666667 | 9.20833333333333 | 9.04096794432099    | 9.15403205567901     |
| Exp 02     | 9.05083333333333       | 0.0776238556305508 | 8.95833333333333 | 9.15             | 8.99526083313607    | 9.1064058335306      |
| Exp 03     | 9.07666666666667       | 0.0758491029593201 | 8.95             | 9.23333333333333 | 9.02236474807567    | 9.13096858525766     |
| Exp 04     | 9.05583333333333       | 0.0899288127242679 | 8.90833333333333 | 9.19166666666667 | 8.99145146358127    | 9.1202152030854      |
| Exp 05     | 9.08416666666667       | 0.0921661476108429 | 8.96666666666667 | 9.225            | 9.01818304327307    | 9.15015029006026     |
| Exp 06     | 9.07416666666667       | 0.067637605509199  | 8.98333333333333 | 9.15833333333333 | 9.02574352644812    | 9.12258980688522     |
| Exp 07     | 9.08083333333333       | 0.0981346077312572 | 8.9              | 9.26666666666667 | 9.01057676770407    | 9.1510898989626      |
| Exp 08     | 9.0575                 | 0.0680923936581505 | 8.925            | 9.125            | 9.00875126767717    | 9.10624873232283     |
| Exp 09     | 9.0925                 | 0.0701024382730719 | 8.95             | 9.18333333333333 | 9.04231223577323    | 9.14268776422677     |
| Exp 10     | 9.09916666666667       | 0.0846607244928768 | 8.99166666666667 | 9.23333333333333 | 9.03855632864154    | 9.15977700469179     |
| Exp 11     | 9.05666666666667       | 0.0973253421376945 | 8.89166666666667 | 9.2              | 8.98698947076843    | 9.1263438625649      |

Figure A.13: Evaluations of Throughput Per Hour

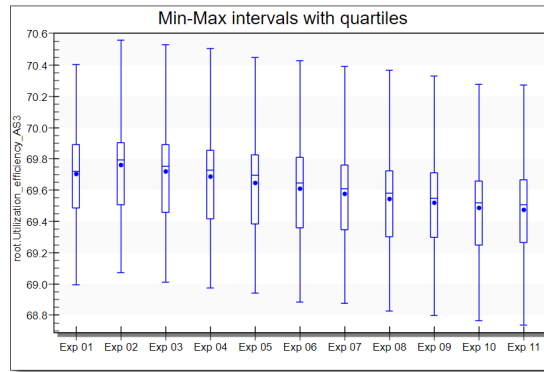
Evaluations of the output value 'root.Utilization\_efficiency\_AS1'



| Experiment | root.Utilization_efficiency_AS1 | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|---------------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 39.7188473134597                | 0.460063910377495  | 39.1918094570703 | 40.8392751523491 | 39.3894781840533    | 40.0482164428662     |
| Exp 02     | 39.3584861088808                | 0.547676906665676  | 38.400719320284  | 40.1238007507175 | 38.9663930499045    | 39.7505791678571     |
| Exp 03     | 39.6343419072094                | 0.429438436502372  | 39.0420276925471 | 40.3232271451689 | 39.3268981786883    | 39.9417856357306     |
| Exp 04     | 39.3157020409802                | 0.486485972512914  | 38.6503061611837 | 40.4217784515871 | 38.9674168188172    | 39.6639872631433     |
| Exp 05     | 39.6526696914939                | 0.664393776959442  | 38.670652627839  | 40.9687563089335 | 39.1770166464188    | 40.128322736569      |
| Exp 06     | 39.4483399090974                | 0.306158362140261  | 38.9738623053639 | 40.1413632507229 | 39.2291548982238    | 39.667524919971      |
| Exp 07     | 39.6499234439295                | 0.465062682715843  | 38.8149282239989 | 40.3513639079442 | 39.3169755915325    | 39.9828712963265     |
| Exp 08     | 39.5266413175887                | 0.418051836411739  | 38.7587324187638 | 40.2547968102675 | 39.2273494881281    | 39.8259331470494     |
| Exp 09     | 39.6496947877711                | 0.403713491154713  | 38.7784549116276 | 40.0679969585651 | 39.3606680718912    | 39.938721503651      |
| Exp 10     | 39.7623530410538                | 0.411267339371946  | 39.1459648517515 | 40.4800071525906 | 39.4679183712899    | 40.0567877108176     |
| Exp 11     | 39.6663117230124                | 0.423315409781013  | 38.8763445393676 | 40.225705807841  | 39.3632515941065    | 39.9693718519182     |

Figure A.14: Evaluations of Utilization efficiency of Station 1

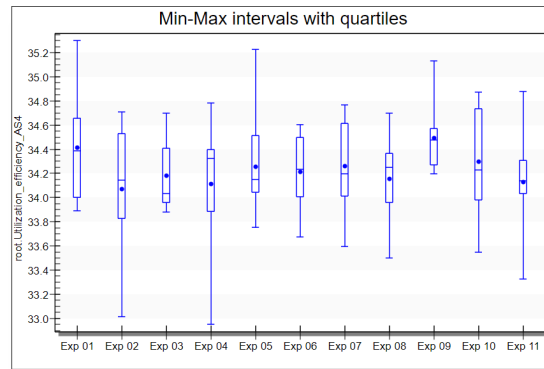
Evaluations of the output value 'root.Utilization\_efficiency\_AS3'



| Experiment | root.Utilization_efficiency_AS3 | Standard Deviation | Minimum           | Maximum          | Left interval bound | Right interval bound |
|------------|---------------------------------|--------------------|-------------------|------------------|---------------------|----------------------|
| Exp 01     | 69.7018020413252                | 0.38388555466317   | 68.9960354044261  | 70.4033949811301 | 69.4269705486921    | 69.9766335339583     |
| Exp 02     | 69.7603386024497                | 0.402412314837907  | 69.0718922887954  | 70.5610477800216 | 69.4722434252126    | 70.0484337796868     |
| Exp 03     | 69.7214462629803                | 0.408279852486061  | 69.01211102769915 | 70.5310767839992 | 69.4291503959622    | 70.0137421299984     |
| Exp 04     | 69.6857328329509                | 0.411952245176161  | 68.9746125638574  | 70.507730816879  | 69.3908078251636    | 69.9806578407381     |
| Exp 05     | 69.6467326294268                | 0.407437923588996  | 68.9406478473199  | 70.4492537022662 | 69.3550395164643    | 69.9384257423893     |
| Exp 06     | 69.6090027662025                | 0.4153479337995    | 68.8821638023578  | 70.4295615046143 | 69.3116467157267    | 69.9063588166784     |
| Exp 07     | 69.5776221890761                | 0.410435535695893  | 68.8772774178738  | 70.3912420963376 | 69.2837830245158    | 69.8714613536363     |
| Exp 08     | 69.5452776455001                | 0.412218266577247  | 68.8270879779963  | 70.3669714923517 | 69.2501621875704    | 69.8403931034298     |
| Exp 09     | 69.5200404084199                | 0.412430387236168  | 68.7968289000685  | 70.3283146387319 | 69.2247730889875    | 69.8153077278523     |
| Exp 10     | 69.4856670934456                | 0.41115132448716   | 68.7648016395135  | 70.2777267784728 | 69.1913154811022    | 69.7800187057891     |
| Exp 11     | 69.4741307080812                | 0.413772379235407  | 68.7348273696124  | 70.2733601402941 | 69.1779026292271    | 69.7703587869352     |

Figure A.15: Evaluations of Utilization efficiency of Station 3

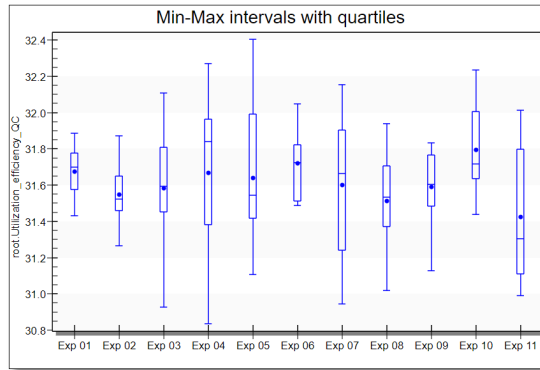
Evaluations of the output value 'root.Utilization\_efficiency\_AS4'



| Experiment | root.Utilization_efficiency_AS4 | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|---------------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 34.4115695785736                | 0.43340678777069   | 33.8891276786238 | 35.3024675306965 | 34.1012848265056    | 34.7218543306415     |
| Exp 02     | 34.0704045500371                | 0.502492773713691  | 33.0121134129125 | 34.7103489087402 | 33.7106597326805    | 34.4301493673938     |
| Exp 03     | 34.1830737795478                | 0.284683979275841  | 33.8807049420052 | 34.6989015859412 | 33.9792627170084    | 34.3868848420872     |
| Exp 04     | 34.1112175323637                | 0.548487938438994  | 32.9490115984577 | 34.7821942947363 | 33.7185438392123    | 34.5038912255151     |
| Exp 05     | 34.2560552270061                | 0.429787632236218  | 33.751443233841  | 35.2290570430105 | 33.9483615021426    | 34.5637489518696     |
| Exp 06     | 34.2139076789674                | 0.294162725766297  | 33.6761396168105 | 34.602328489842  | 34.0033105886414    | 34.4245047692933     |
| Exp 07     | 34.2619917146249                | 0.369526316684852  | 33.5957838236817 | 34.7687698427992 | 33.9974402936725    | 34.5265431355773     |
| Exp 08     | 34.1537993789134                | 0.372348927376609  | 33.5006451523441 | 34.6986152948697 | 33.8872271934428    | 34.420371564384      |
| Exp 09     | 34.4927992565162                | 0.265835898628747  | 34.1963251654179 | 35.1333981760075 | 34.3024819190305    | 34.683116594002      |
| Exp 10     | 34.2958620520935                | 0.448341390274629  | 33.5471311994833 | 34.8749193701301 | 33.9748853137302    | 34.6168387904569     |
| Exp 11     | 34.125989611463                 | 0.413993146433173  | 33.3264172628776 | 34.8805401941508 | 33.8296034808729    | 34.4223757420531     |

Figure A.16: Evaluations of Utilization efficiency of Station 4

Evaluations of the output value 'root.Utilization\_efficiency\_QC'



| Experiment | root.Utilization_efficiency_QC | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|--------------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 31.6747025241139               | 0.147546685160614  | 31.4297296885538 | 31.8863296761005 | 31.5690708452493    | 31.7803342029784     |
| Exp 02     | 31.545927150616                | 0.18511313149345   | 31.2657209290043 | 31.8724736924882 | 31.4134008872287    | 31.6784534140034     |
| Exp 03     | 31.58154509936                 | 0.353103942086434  | 30.9277179384605 | 32.1087870228261 | 31.3287507910658    | 31.8343394076542     |
| Exp 04     | 31.6678581496861               | 0.452118255504595  | 30.8339649087993 | 32.2698916230484 | 31.3441774765332    | 31.9915388228389     |
| Exp 05     | 31.6406208672339               | 0.414487764685616  | 31.1081452654437 | 32.4054313188027 | 31.3438806293567    | 31.9373611051111     |
| Exp 06     | 31.7194173923694               | 0.191330061039242  | 31.488821481436  | 32.0490388467903 | 31.582440302421     | 31.8563944823177     |
| Exp 07     | 31.6016546782961               | 0.391643837343195  | 30.943973819106  | 32.1530853039836 | 31.3212688735558    | 31.8820404830363     |
| Exp 08     | 31.5126573863723               | 0.278105112075611  | 31.0174048027538 | 31.9404063713683 | 31.3135562689369    | 31.7117585038076     |
| Exp 09     | 31.5899215302566               | 0.213760225171525  | 31.1262613566679 | 31.8321163165525 | 31.4368862286858    | 31.7429568318274     |
| Exp 10     | 31.7933615606476               | 0.239419792867634  | 31.4390143517911 | 32.2347125147581 | 31.6219560516287    | 31.9647670696666     |
| Exp 11     | 31.4252680509905               | 0.365042483076188  | 30.9902745701221 | 32.0132695756622 | 31.1639266978978    | 31.6866094040832     |

Figure A.17: Evaluations of Utilization efficiency of Quality check

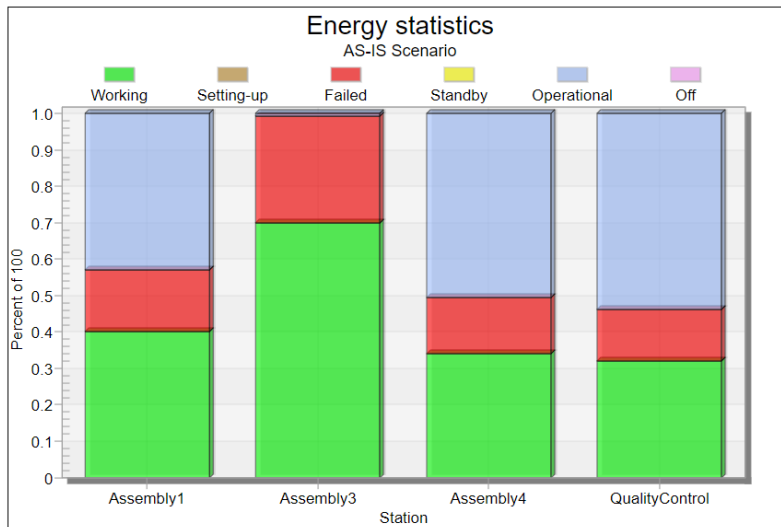


Figure A.18: Evaluations of Energy utilization at all the stations

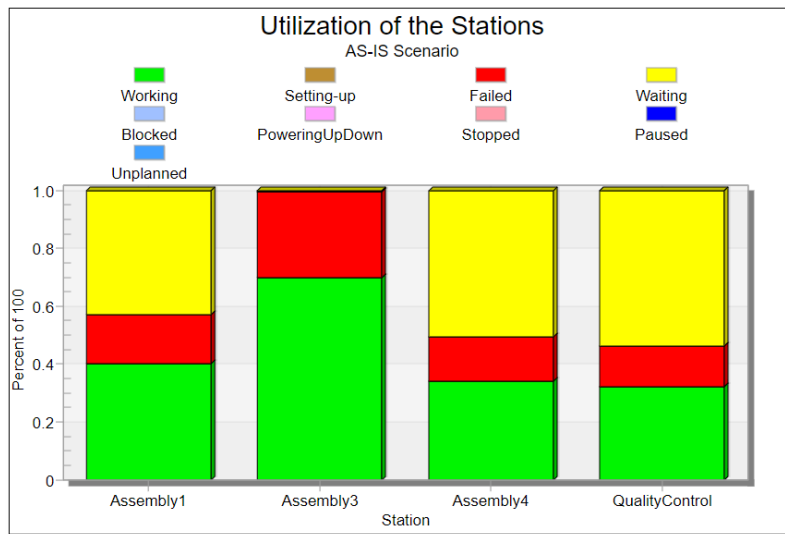
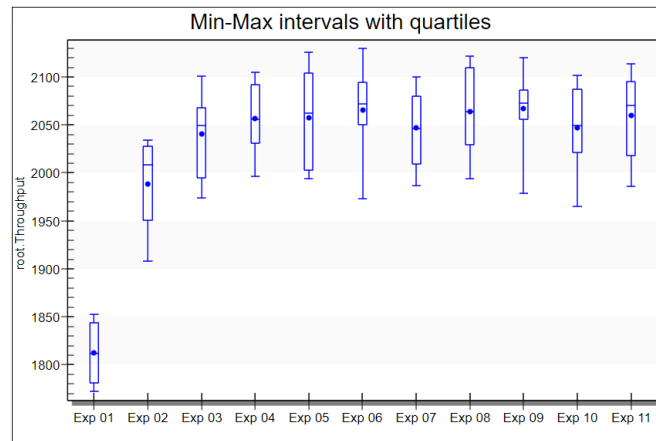


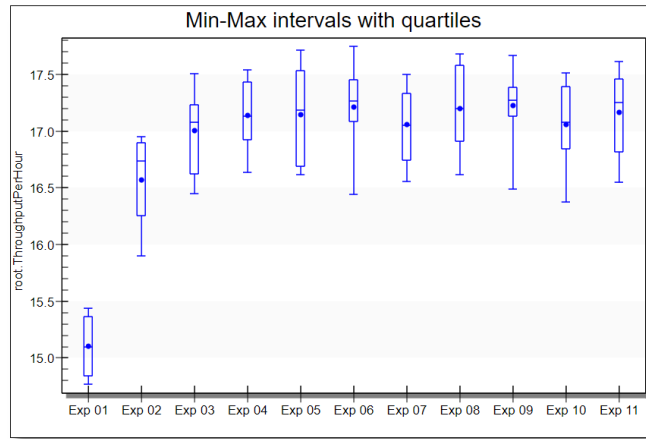
Figure A.19: Evaluations of Utilization efficiency at all the stations

## A.2 Results of Base scenario experiments



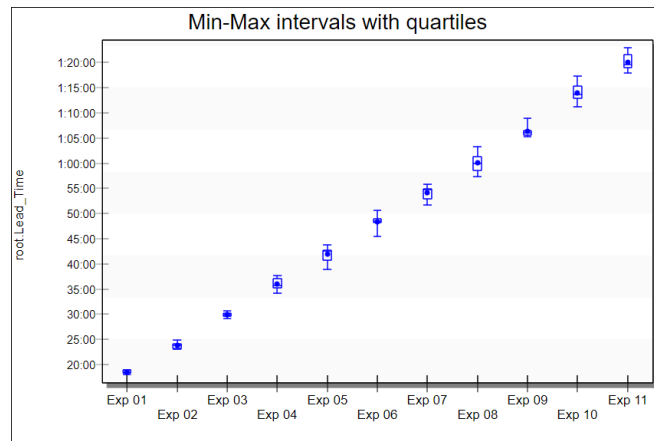
| Experiment | root.Throughput | Standard Deviation | Minimum | Maximum | Left interval bound | Right interval bound |
|------------|-----------------|--------------------|---------|---------|---------------------|----------------------|
| Exp 01     | 1812.6          | 32.8031163831227   | 1772    | 1853    | 1789.11558046345    | 1836.08441953655     |
| Exp 02     | 1988.6          | 45.7680140612428   | 1908    | 2034    | 1955.83374599489    | 2021.36625400511     |
| Exp 03     | 2040.6          | 41.5456910454436   | 1974    | 2101    | 2010.8565930916     | 2070.3434069084      |
| Exp 04     | 2056.6          | 37.1489494392971   | 1996    | 2105    | 2030.00431001174    | 2083.19568998826     |
| Exp 05     | 2057.7          | 51.3615723192977   | 1994    | 2126    | 2020.92920364287    | 2094.47079635713     |
| Exp 06     | 2065.8          | 47.3469463992417   | 1973    | 2130    | 2031.90335615594    | 2099.69664384406     |
| Exp 07     | 2046.9          | 40.3689925011188   | 1987    | 2100    | 2017.99901556025    | 2075.80098443975     |
| Exp 08     | 2063.8          | 47.9555349603429   | 1994    | 2122    | 2029.46765520219    | 2098.13234479781     |
| Exp 09     | 2066.9          | 39.2271164714729   | 1979    | 2120    | 2038.81650788097    | 2094.98349211903     |
| Exp 10     | 2046.9          | 43.7326473523417   | 1965    | 2102    | 2015.59090650196    | 2078.20909349804     |
| Exp 11     | 2059.8          | 43.4403805999211   | 1986    | 2114    | 2028.70014622633    | 2090.89985377367     |

Figure A.20: Evaluations of the 'Throughput' for 11 different number of pallet sizes



| Experiment | root.ThroughputPerHour | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 15.105                 | 0.273359303192654  | 14.7666666666667 | 15.4416666666667 | 14.9092965038621    | 15.3007034961379     |
| Exp 02     | 16.5716666666667       | 0.38140011717706   | 15.9             | 16.95            | 16.2986145499574    | 16.844718783376      |
| Exp 03     | 17.005                 | 0.346214092045533  | 16.45            | 17.5083333333333 | 16.7571382757632    | 17.2528617242368     |
| Exp 04     | 17.1383333333333       | 0.309574578660927  | 16.6333333333333 | 17.5416666666667 | 16.9167025834311    | 17.3599640832356     |
| Exp 05     | 17.1475                | 0.428013102660857  | 16.6166666666667 | 17.7166666666667 | 16.8410766970239    | 17.4539233029761     |
| Exp 06     | 17.215                 | 0.394557886660514  | 16.4416666666667 | 17.75            | 16.932527967966     | 17.497472032034      |
| Exp 07     | 17.0575                | 0.336408270842609  | 16.5583333333333 | 17.5             | 16.8166584630021    | 17.2983415369979     |
| Exp 08     | 17.1983333333333       | 0.399629458002784  | 16.6166666666667 | 17.6833333333333 | 16.9122304600183    | 17.4844362066484     |
| Exp 09     | 17.2241666666667       | 0.326892637262242  | 16.4916666666667 | 17.6666666666667 | 16.9901375656748    | 17.4581957676585     |
| Exp 10     | 17.0575                | 0.364438727936174  | 16.375           | 17.5166666666667 | 16.7965908875164    | 17.3184091124836     |
| Exp 11     | 17.165                 | 0.362003171666169  | 16.55            | 17.6166666666667 | 16.905834551886     | 17.424165448114      |

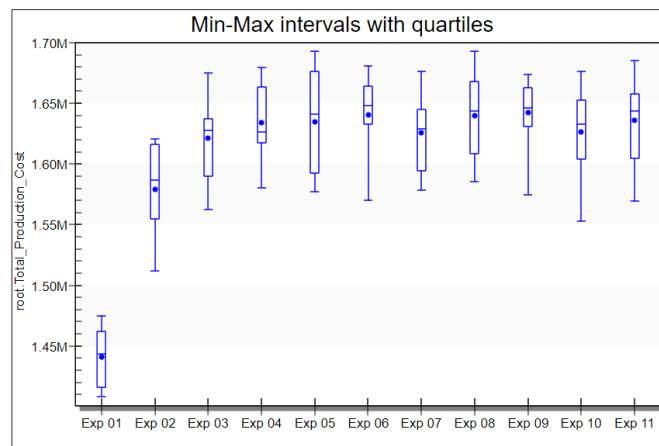
Figure A.21: Evaluations of the 'TPH' for 11 different number of pallet sizes



## A. Appendix 1

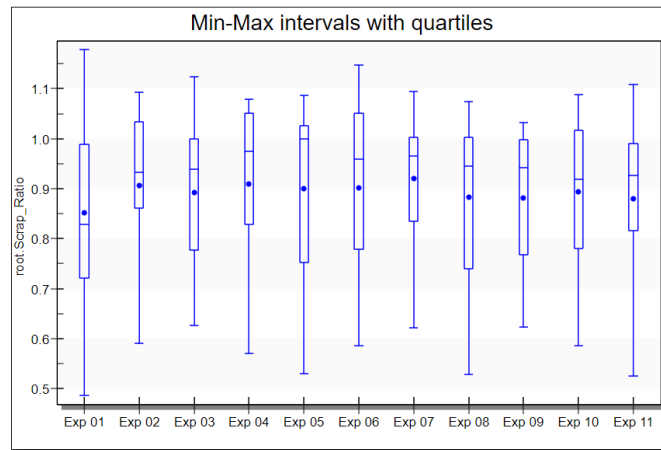
| Experiment | root.Lead_Time | Standard Deviation | Minimum      | Maximum      | Left interval bound | Right interval bound |
|------------|----------------|--------------------|--------------|--------------|---------------------|----------------------|
| Exp 01     | 18:32.1646     | 19.6275            | 18:03.3106   | 18:55.0826   | 18:18.1129          | 18:46.2164           |
| Exp 02     | 23:46.8849     | 36.1011            | 23:05.0588   | 24:51.7000   | 23:21.0394          | 24:12.7304           |
| Exp 03     | 29:57.5894     | 26.8000            | 29:11.5290   | 30:41.0120   | 29:38.4027          | 30:16.7761           |
| Exp 04     | 35:58.9424     | 1:04.0024          | 34:13.0245   | 37:38.7844   | 35:13.1217          | 36:44.7630           |
| Exp 05     | 41:53.1665     | 1:29.8653          | 38:54.6665   | 43:49.4800   | 40:48.8301          | 42:57.5029           |
| Exp 06     | 48:17.3898     | 1:21.9935          | 45:28.6007   | 50:37.8216   | 47:18.6890          | 49:16.0907           |
| Exp 07     | 54:05.2550     | 1:19.4346          | 51:45.3273   | 55:46.5585   | 53:08.3861          | 55:02.1239           |
| Exp 08     | 1:00:03.2913   | 1:48.4054          | 57:22.0986   | 1:03:13.8290 | 58:45.6817          | 1:01:20.9010         |
| Exp 09     | 1:06:21.8391   | 1:14.7714          | 1:05:14.2253 | 1:08:52.6592 | 1:05:28.3087        | 1:07:15.3694         |
| Exp 10     | 1:13:56.3555   | 1:43.6194          | 1:11:15.1090 | 1:17:14.6381 | 1:12:42.1723        | 1:15:10.5387         |
| Exp 11     | 1:20:01.6611   | 1:38.9756          | 1:17:51.9510 | 1:22:55.9973 | 1:18:50.8025        | 1:21:12.5197         |

Figure A.22: Evaluations of the 'Lead Time' for 11 different number of pallet sizes



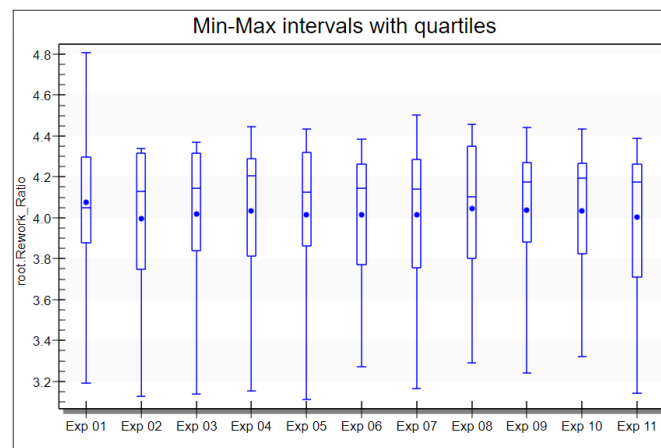
| Experiment | root.Total_Production_Cost | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|----------------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 1441092.195                | 25602.2197575671   | 1408019.234      | 1474796.244      | 1422763.04410984    | 1459421.34589015     |
| Exp 02     | 1579362.917                | 36941.5273898549   | 1511667.424      | 1620503.644      | 1552915.72468413    | 1605810.10931586     |
| Exp 03     | 1620961.47                 | 34032.9820178187   | 1562668.904      | 1674912.934      | 1596596.56459127    | 1645326.37540872     |
| Exp 04     | 1633861.161                | 31746.7030597519   | 1580214.614      | 1679226.724      | 1611133.04929105    | 1656589.27270895     |
| Exp 05     | 1634516.869                | 44460.3617597975   | 1577151.244      | 1692933.414      | 1602686.78992706    | 1666346.94807294     |
| Exp 06     | 1640768.397                | 36632.1237024945   | 1569825.45399999 | 1680675.964      | 1614542.71308947    | 1666994.08091052     |
| Exp 07     | 1625926.91399999           | 33476.7446106806   | 1578138.43399999 | 1676427.42399999 | 1601960.230287      | 1649893.59771299     |
| Exp 08     | 1639700.41199999           | 38242.6923308524   | 1585680.34399999 | 1693136.11399999 | 1612321.68918551    | 1667079.13481448     |
| Exp 09     | 1642101.07599999           | 29839.8778711187   | 1574310.90399999 | 1673918.82399999 | 1620738.09930412    | 1663464.05269587     |
| Exp 10     | 1626203.10099999           | 35783.2560798452   | 1552879.07399999 | 1676294.49399999 | 1600585.13872019    | 1651821.06327979     |
| Exp 11     | 1635852.452                | 36085.9129990355   | 1569493.164      | 1685455.004      | 1610017.81146369    | 1661687.0925363      |

Figure A.23: Evaluations of the 'Production Cost' for 11 different number of pallet sizes



| Experiment | root.Scrap_Ratio  | Standard Deviation | Minimum           | Maximum          | Left interval bound | Right interval bound |
|------------|-------------------|--------------------|-------------------|------------------|---------------------|----------------------|
| Exp 01     | 0.852275339648765 | 0.214737081926288  | 0.485698866702644 | 1.17911285794497 | 0.698540686419139   | 1.00600999287839     |
| Exp 02     | 0.906051959659247 | 0.159344680894925  | 0.589970501474926 | 1.09289617486339 | 0.791973855208822   | 1.02013006410967     |
| Exp 03     | 0.89290608691645  | 0.164825698736964  | 0.625902744342802 | 1.12469437652812 | 0.774904010091376   | 1.01090816374152     |
| Exp 04     | 0.910004314877463 | 0.180666299089012  | 0.570071258907363 | 1.07843137254902 | 0.780661629433581   | 1.03934700032135     |
| Exp 05     | 0.899829346698324 | 0.191307223984479  | 0.529355149181906 | 1.08747044917258 | 0.762868606262856   | 1.03679008713379     |
| Exp 06     | 0.901397752240539 | 0.190342734418073  | 0.585365853658537 | 1.1472275334608  | 0.765127509541675   | 1.0376679949394      |
| Exp 07     | 0.919785554936743 | 0.142973623077317  | 0.621712099473936 | 1.09507217521155 | 0.817427824415288   | 1.0221432854582      |
| Exp 08     | 0.882626894784968 | 0.17996589573034   | 0.528592023065834 | 1.07474352711285 | 0.753785642379573   | 1.01146814719036     |
| Exp 09     | 0.881968661712438 | 0.142940442842575  | 0.62320230105465  | 1.03194103194103 | 0.779634685597238   | 0.984302637827637    |
| Exp 10     | 0.894614606496274 | 0.158174954830182  | 0.586223742061553 | 1.08857001484414 | 0.781373932774271   | 1.00785528021828     |
| Exp 11     | 0.879830916934589 | 0.180719688528392  | 0.525059665871122 | 1.10789980732177 | 0.750450008902994   | 1.00921182496619     |

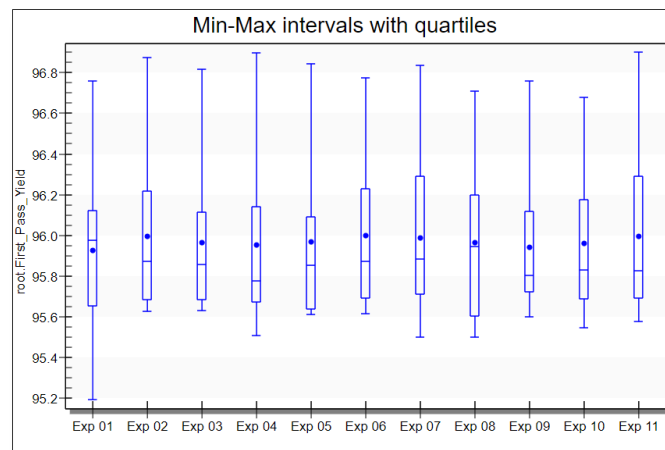
Figure A.24: Evaluations of the 'Scrap Ratio' for 11 different number of pallet sizes



## A. Appendix 1

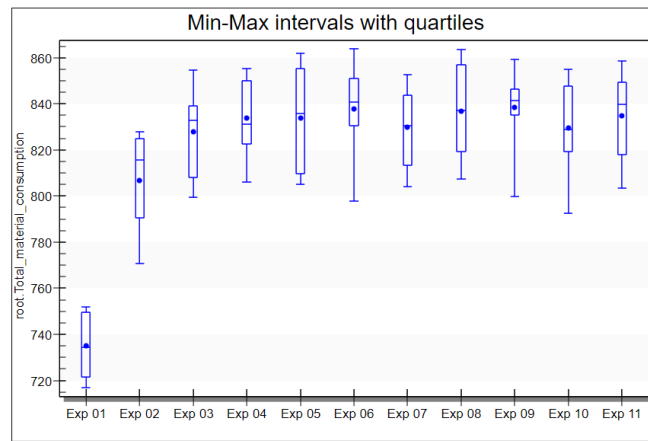
| Experiment | root.Rework_Ratio | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|-------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 4.07440763567121  | 0.432954006881072  | 3.19037656903766 | 4.80868665977249 | 3.76444703866968    | 4.38436823267274     |
| Exp 02     | 3.99516603205073  | 0.380298070822114  | 3.125            | 4.33962264150943 | 3.7229028927863     | 4.26742917131515     |
| Exp 03     | 4.01867090460547  | 0.389476853829484  | 3.13670411985019 | 4.36959490213928 | 3.73983648752517    | 4.29750532168577     |
| Exp 04     | 4.03236033345     | 0.406020509725153  | 3.15145813734713 | 4.4464609800363  | 3.74168197595914    | 4.32303869094085     |
| Exp 05     | 4.0137504702512   | 0.424312185015213  | 3.11004784688995 | 4.43529949702789 | 3.70997672964123    | 4.31752421086117     |
| Exp 06     | 4.01528568296236  | 0.366819521294213  | 3.27124034529759 | 4.38432835820895 | 3.75267211199384    | 4.27789925393089     |
| Exp 07     | 4.01624538907901  | 0.416846071406265  | 3.1657355679702  | 4.50204638472033 | 3.71781679135888    | 4.31467398679913     |
| Exp 08     | 4.0442761165313   | 0.378157458606833  | 3.29067641681901 | 4.45567294441893 | 3.77354548517684    | 4.31500674788575     |
| Exp 09     | 4.03904281911717  | 0.369767793751253  | 3.24052943861251 | 4.44033302497687 | 3.77431851981173    | 4.30376711842262     |
| Exp 10     | 4.03414331690296  | 0.383629761426684  | 3.3210332103321  | 4.43510737628385 | 3.75949495243585    | 4.30879168137008     |
| Exp 11     | 4.00484129291434  | 0.415697869696026  | 3.14378178455848 | 4.38715513342379 | 3.70723471619858    | 4.30244786963009     |

Figure A.25: Evaluations of the 'Rework Ratio' for 11 different number of pallet sizes



| Experiment | root.First_Pass_Yield | Standard Deviation | Minimum          | Maximum          | Left interval bound | Right interval bound |
|------------|-----------------------|--------------------|------------------|------------------|---------------------|----------------------|
| Exp 01     | 95.9259983327398      | 0.426069993328351  | 95.1913133402275 | 96.7573221757322 | 95.6209661413348    | 96.2310305241448     |
| Exp 02     | 95.9950896461505      | 0.381505653268425  | 95.6276445698166 | 96.875           | 95.7219619740026    | 96.2682173182984     |
| Exp 03     | 95.9625613217912      | 0.370080689777334  | 95.6304050978607 | 96.8164794007491 | 95.697613013844     | 96.2275096297385     |
| Exp 04     | 95.9538829759063      | 0.426431601423847  | 95.508166969147  | 96.89557855127   | 95.6485919018963    | 96.2591740499163     |
| Exp 05     | 95.9673328170036      | 0.405684982938495  | 95.6104252400549 | 96.8421052631579 | 95.6768946699773    | 96.25777096403       |
| Exp 06     | 95.9987853587088      | 0.382037624164084  | 95.615671641791  | 96.7741935483871 | 95.7252768377553    | 96.2722938796624     |
| Exp 07     | 95.9882313494495      | 0.416946883672982  | 95.4979536152797 | 96.8342644320298 | 95.6897305781731    | 96.2867321207259     |
| Exp 08     | 95.9655145575404      | 0.381762569422089  | 95.4995499549955 | 96.709323583181  | 95.6922029538822    | 96.2388261611986     |
| Exp 09     | 95.942448088738       | 0.368279311280574  | 95.6003666361137 | 96.7594705613875 | 95.6787894243682    | 96.2061067531079     |
| Exp 10     | 95.9613810422907      | 0.391040003217842  | 95.5454545454545 | 96.6789667896679 | 95.6814275347067    | 96.2413345498747     |
| Exp 11     | 95.9953410632453      | 0.433792031664251  | 95.5748175182482 | 96.9024503005085 | 95.6847805072228    | 96.3059016192678     |

Figure A.26: Evaluations of the 'Rework Ratio' for 11 different number of pallet sizes



| Experiment | root.Total_material_consumption [kg] | Standard Deviation [kg] | Minimum [kg] | Maximum [kg] | Left interval bound [kg] | Right interval bound [kg] |
|------------|--------------------------------------|-------------------------|--------------|--------------|--------------------------|---------------------------|
| Exp 01     | 734.9576                             | 14.7975175035014        | 716.772      | 751.966      | 724.363755650187         | 745.551444349813          |
| Exp 02     | 806.7324                             | 20.9151802563452        | 770.862      | 827.876      | 791.758796209258         | 821.706003790742          |
| Exp 03     | 827.937                              | 18.1301058463614        | 799.36       | 854.722      | 814.957287738363         | 840.916712261637          |
| Exp 04     | 833.717                              | 16.7936672521999        | 806.046      | 855.308      | 821.694071364149         | 845.739928635851          |
| Exp 05     | 833.8068                             | 22.6515065223816        | 805.148      | 861.808      | 817.590124849584         | 850.023475150416          |
| Exp 06     | 837.7752                             | 20.5031708593766        | 797.94       | 863.964      | 823.096562133178         | 852.453837866822          |
| Exp 07     | 829.6826                             | 17.6392447822708        | 804.172      | 852.626      | 817.05430517775          | 842.31089482225           |
| Exp 08     | 836.7118                             | 20.9025907899765        | 807.324      | 863.406      | 821.747209264801         | 851.676390735199          |
| Exp 09     | 838.4842                             | 16.9258530577766        | 799.88       | 859.324      | 826.366636852029         | 850.601763147971          |
| Exp 10     | 829.4032                             | 19.284416211594         | 792.64       | 854.814      | 815.597093423387         | 843.209306576613          |
| Exp 11     | 834.8634                             | 18.2076226052006        | 803.402      | 858.714      | 821.828191910941         | 847.898608089059          |

Figure A.27: Evaluations of the 'Total Material Consumption' for 11 different number of pallet sizes

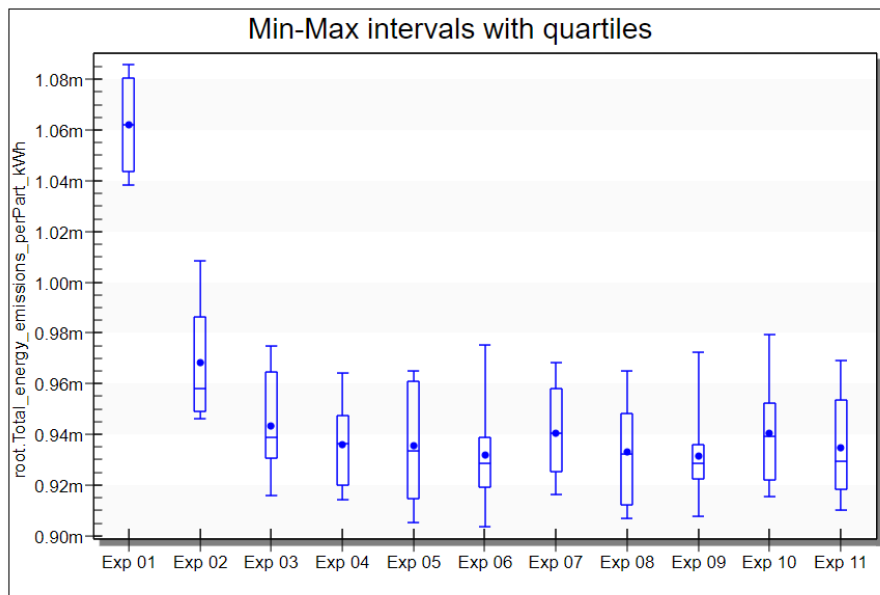
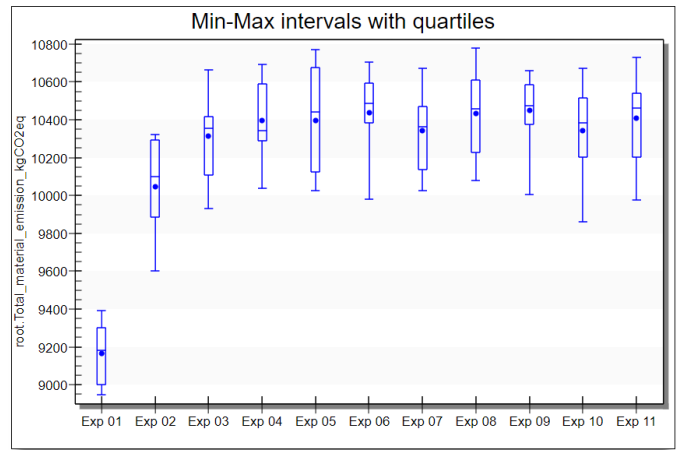
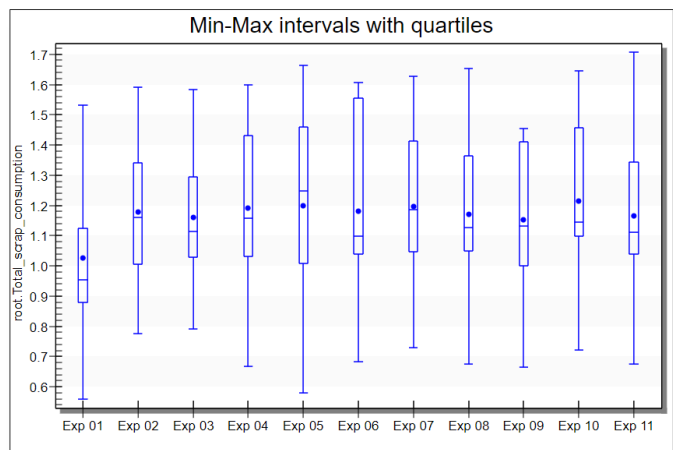


Figure A.28: Evaluations of the 'Energy Emission per Part' for 11 different number of pallet sizes



| Experiment | root.Total_material_emission_kgCO2eq | Standard Deviation | Minimum   | Maximum   | Left interval bound | Right interval bound |
|------------|--------------------------------------|--------------------|-----------|-----------|---------------------|----------------------|
| Exp 01     | 9164.9556                            | 169.598633309014   | 8945.912  | 9389.838  | 9043.53648204379    | 9286.37471795621     |
| Exp 02     | 10047.7984                           | 244.547146201673   | 9602.782  | 10322.376 | 9872.72211423528    | 10222.8746857647     |
| Exp 03     | 10313.301                            | 223.097910792978   | 9932.56   | 10664.862 | 10153.5806589935    | 10473.0213410065     |
| Exp 04     | 10394.4                              | 209.590808133901   | 10039.186 | 10691.668 | 10244.3496690579    | 10544.4503309421     |
| Exp 05     | 10397.5688                           | 289.907672509287   | 10024.808 | 10772.328 | 10190.0179890175    | 10605.1196109825     |
| Exp 06     | 10439.1702                           | 238.876470704772   | 9978.68   | 10702.854 | 10268.1536663902    | 10610.1867336098     |
| Exp 07     | 10341.9366                           | 218.949111916491   | 10024.048 | 10671.746 | 10185.1864686605    | 10498.6867313395     |
| Exp 08     | 10432.0998                           | 249.520621171324   | 10078.794 | 10780.316 | 10253.4629021465    | 10610.7366978535     |
| Exp 09     | 10448.4512                           | 194.372036745722   | 10006.15  | 10659.842 | 10309.2962976488    | 10587.6061023512     |
| Exp 10     | 10344.0142                           | 233.869268335089   | 9862.79   | 10673.754 | 10176.582424612     | 10511.445975388      |
| Exp 11     | 10406.9764                           | 233.968743747017   | 9974.642  | 10731.294 | 10239.4734081373    | 10574.4793918627     |

Figure A.29: Evaluations of the 'Total Material Emissions' for 11 different number of pallet sizes



| Experiment | root.Total_scrap_consumption [kg] | Standard Deviation [kg] | Minimum [kg] | Maximum [kg] | Left interval bound [kg] | Right interval bound [kg] |
|------------|-----------------------------------|-------------------------|--------------|--------------|--------------------------|---------------------------|
| Exp 01     | 1.0256                            | 0.289240845432776       | 0.558        | 1.532        | 0.818526584111284        | 1.23267341588872          |
| Exp 02     | 1.1784                            | 0.255211981606578       | 0.776        | 1.59         | 0.995688541222699        | 1.3611114587773           |
| Exp 03     | 1.161                             | 0.25214678264852        | 0.792        | 1.584        | 0.980482979624626        | 1.34151702037537          |
| Exp 04     | 1.19                              | 0.281086779799012       | 0.668        | 1.6          | 0.988764245875956        | 1.39123575412404          |
| Exp 05     | 1.1988                            | 0.319467890926982       | 0.58         | 1.662        | 0.970086426223682        | 1.42751357377632          |
| Exp 06     | 1.1802                            | 0.310137532215773       | 0.682        | 1.606        | 0.958166220175003        | 1.402233779825            |
| Exp 07     | 1.1966                            | 0.257457741947856       | 0.73         | 1.626        | 1.01228075562644         | 1.38091924437356          |
| Exp 08     | 1.1698                            | 0.275517210593701       | 0.676        | 1.654        | 0.972551613976221        | 1.36704838602378          |
| Exp 09     | 1.1512                            | 0.251753318415734       | 0.664        | 1.454        | 0.970964668687563        | 1.33143533131244          |
| Exp 10     | 1.2142                            | 0.259581629207891       | 0.722        | 1.644        | 1.02836022145279         | 1.40003977854721          |
| Exp 11     | 1.1664                            | 0.283575269255508       | 0.674        | 1.708        | 0.963382685559367        | 1.36941731444063          |

Figure A.30: Evaluations of the 'Scrap Consumption' for 11 different number of pallet sizes

### A.2.1 Results for 75-25 demand scenario

## A.3 Results of Base scenario experiments

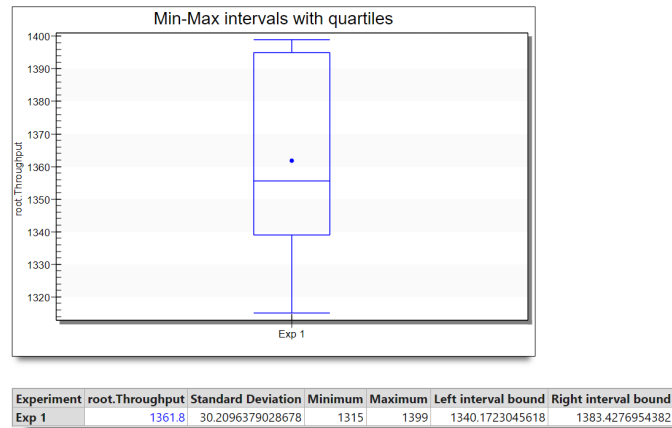


Figure A.31: Evaluation of Throughput

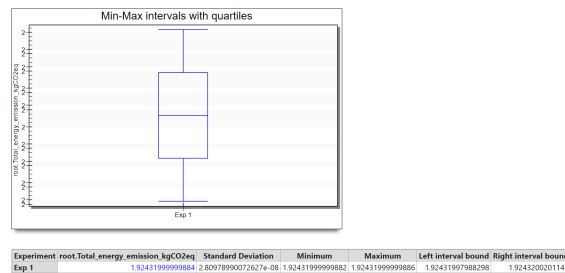


Figure A.32: Evaluation of Energy emissions

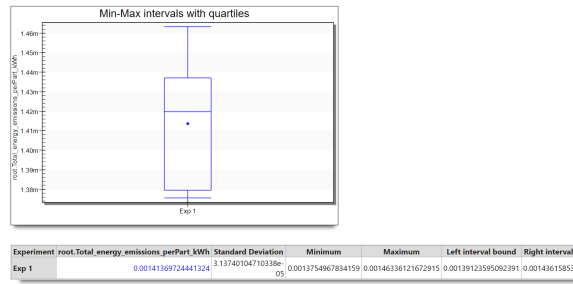


Figure A.33: Evaluation of Energy emissions per part

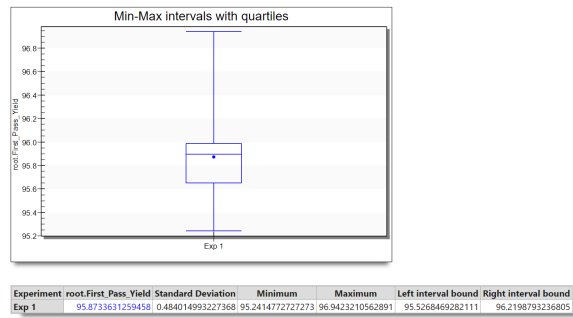


Figure A.34: Evaluation of First Pass Yield

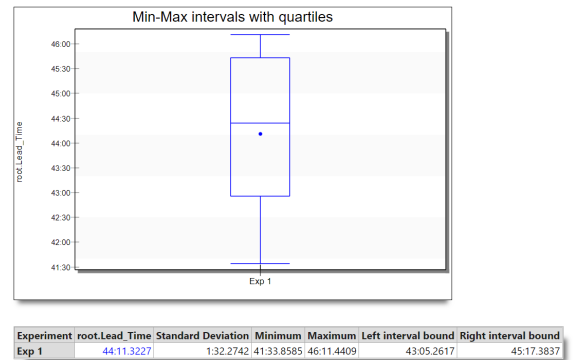


Figure A.35: Evaluation of Lead time

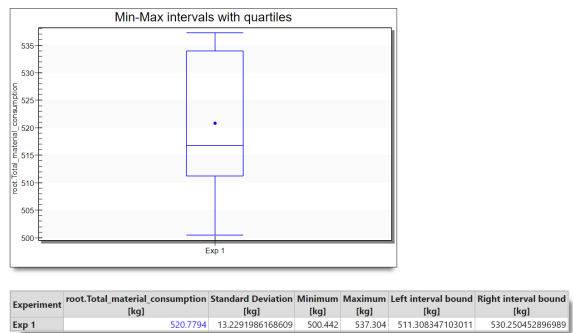


Figure A.36: Evaluation of Material consumption

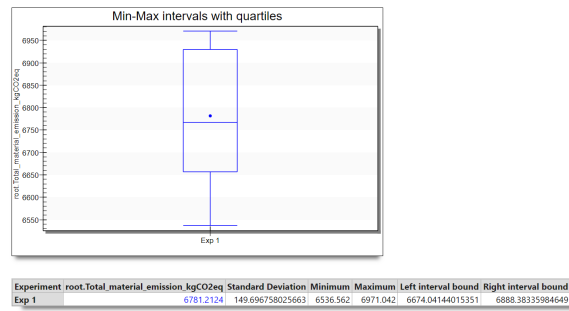


Figure A.37: Evaluation of Total material emissions

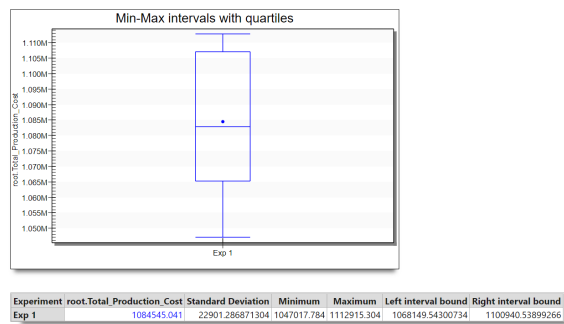


Figure A.38: Evaluation of Production cost

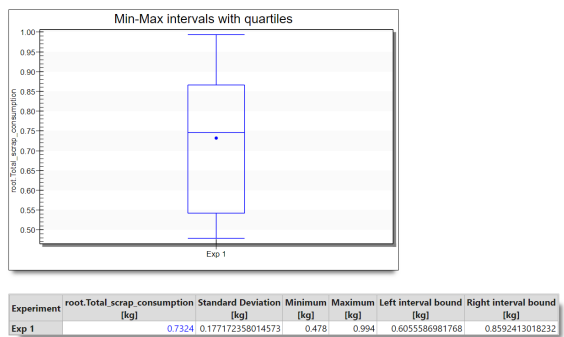


Figure A.39: Evaluation of Scrap cost

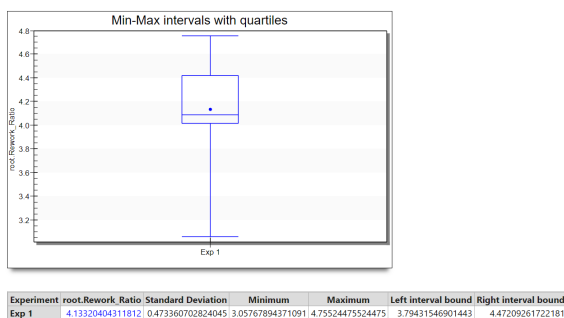


Figure A.40: Evaluation of Rework ratio

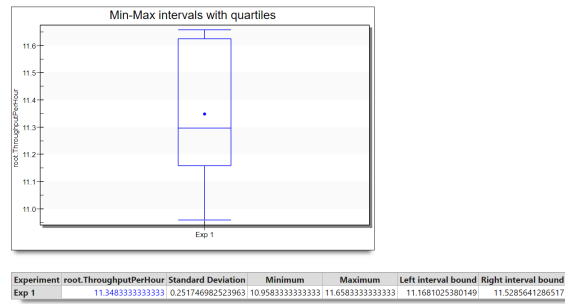


Figure A.41: Evaluation of Throughput per hour

### A.3.1 Results for 25-75 demand scenario

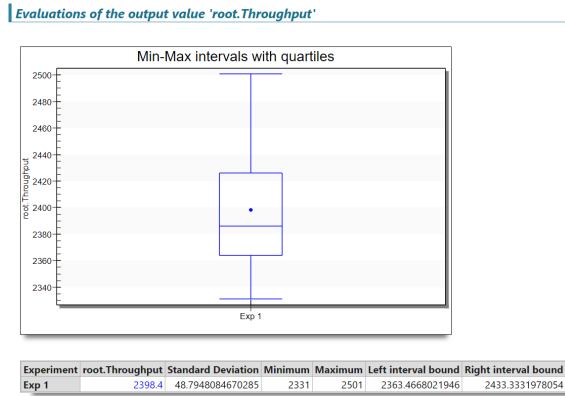


Figure A.42: Evaluation of Throughput

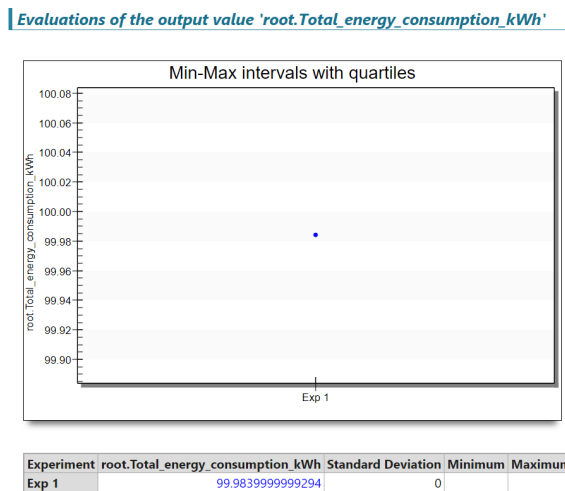


Figure A.43: Evaluation of Energy consumption

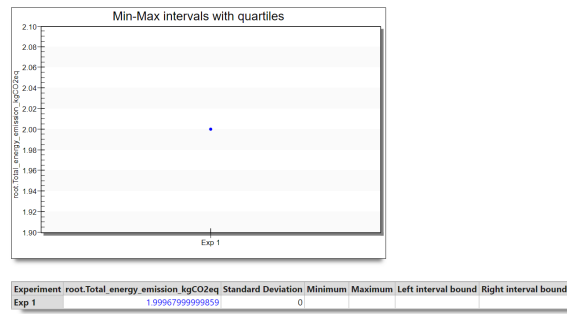


Figure A.44: Evaluation of Energy consumption

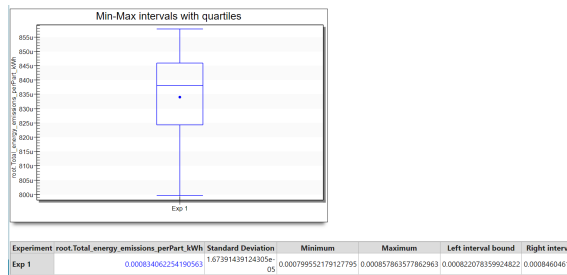


Figure A.45: Evaluation of Energy emissions per part

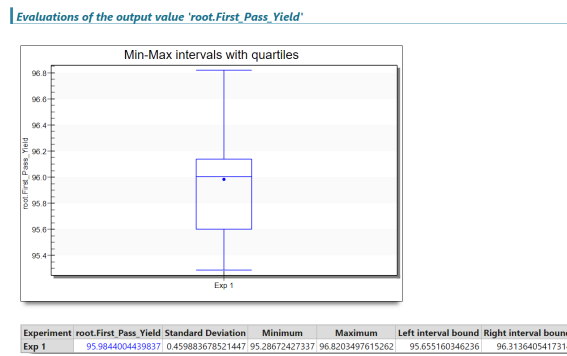


Figure A.46: Evaluation of First Pass Yield

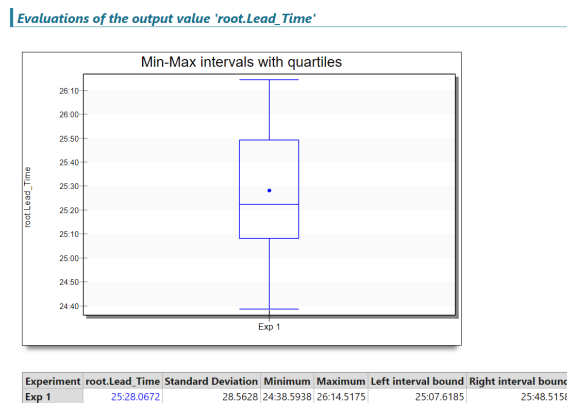


Figure A.47: Evaluation of Lead time

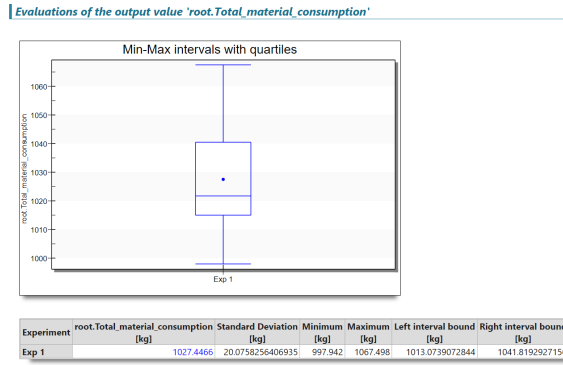


Figure A.48: Evaluation of Material consumption

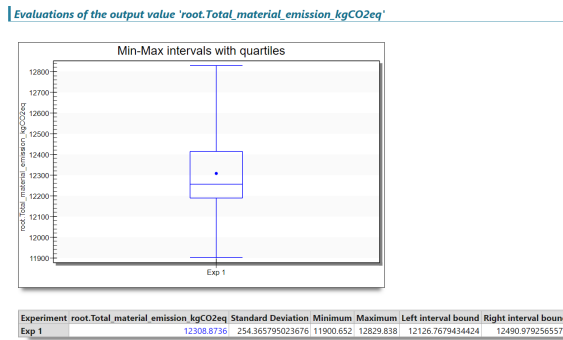


Figure A.49: Evaluation of First Pass Yield

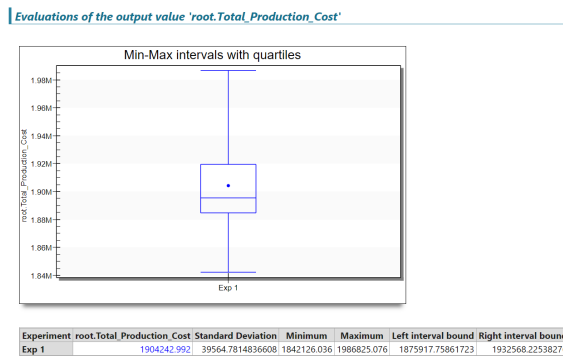


Figure A.50: Evaluation of Production cost

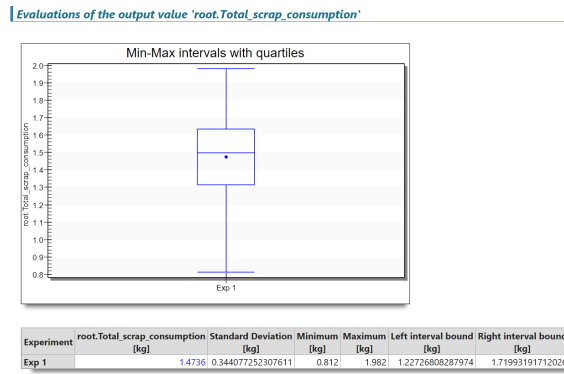


Figure A.51: Evaluation of Scrap cost

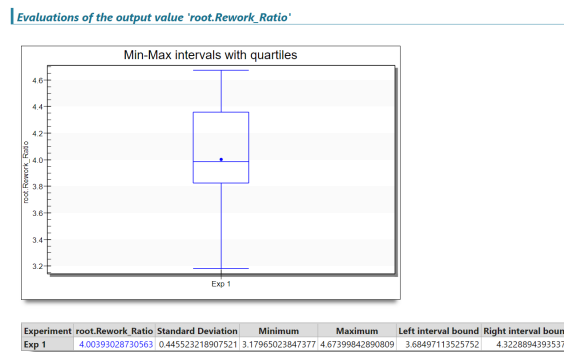


Figure A.52: Evaluation of Rework ratio

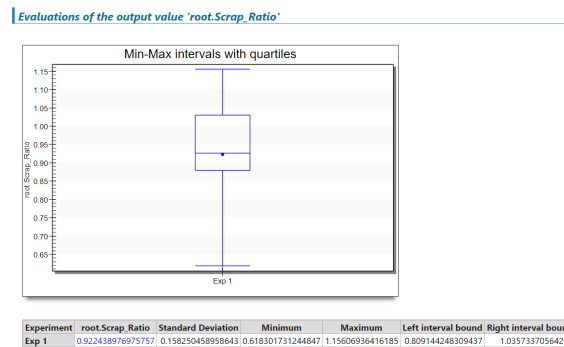


Figure A.53: Evaluation of Scrap ratio

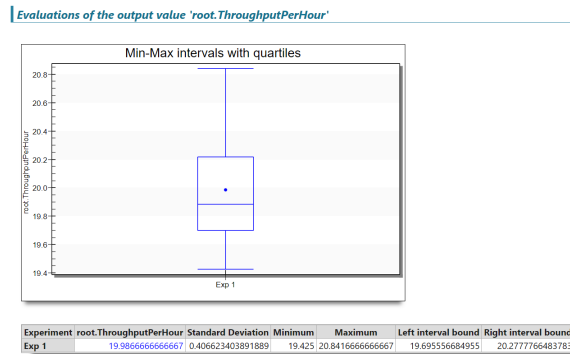


Figure A.54: Evaluation of Throughput per hour

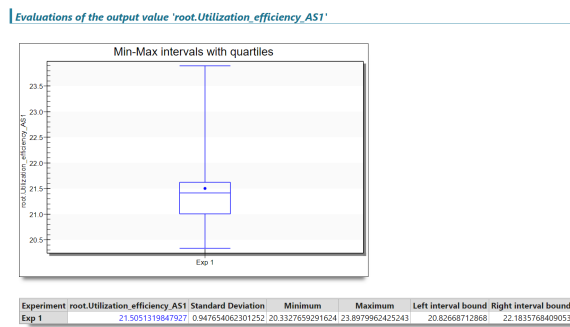


Figure A.55: Evaluation of Utilization efficiency of station 1

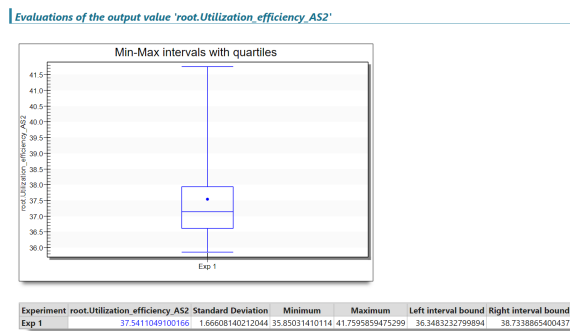


Figure A.56: Evaluation of Utilization efficiency of station 2

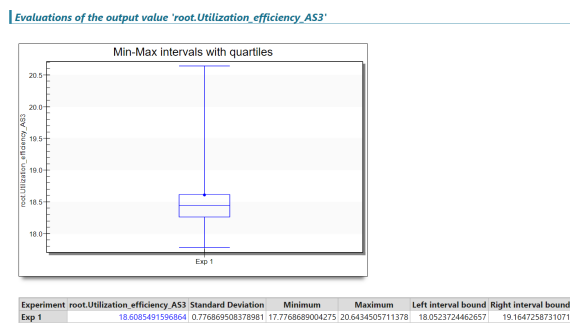


Figure A.57: Evaluation of Utilization efficiency of station 3

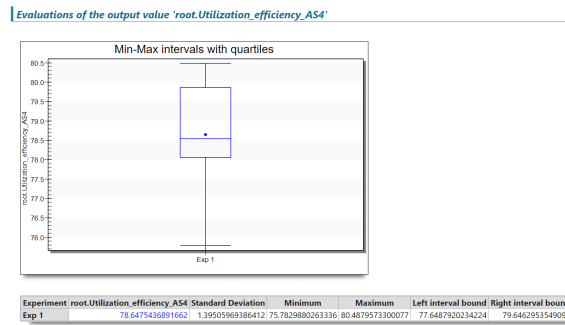


Figure A.58: Evaluation of Utilization efficiency of station 4

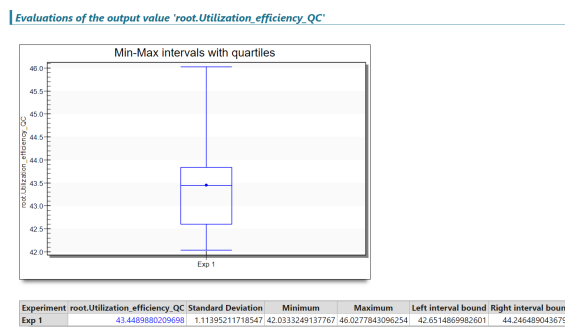


Figure A.59: Evaluation of Utilization efficiency of Quality check

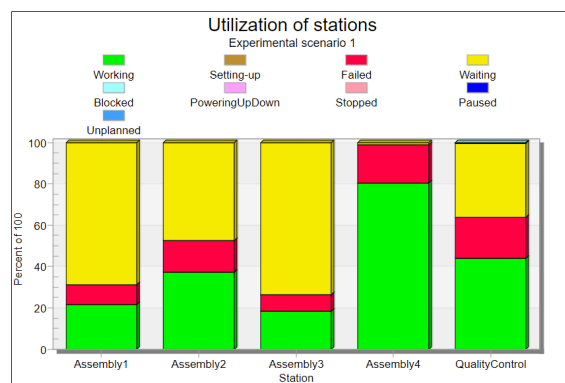


Figure A.60: Evaluation of Utilization efficiency of all the stations

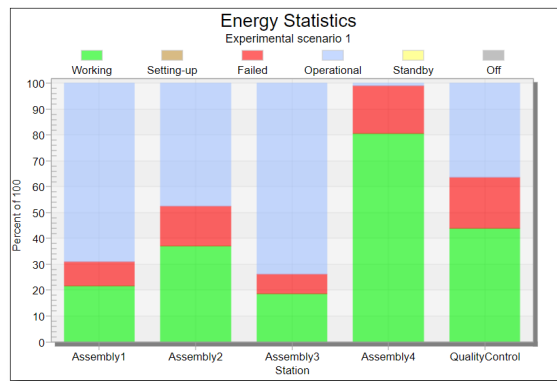


Figure A.61: Evaluation of Energy utilization at all the stations

### A.3.2 Results for 75-25 demand scenario

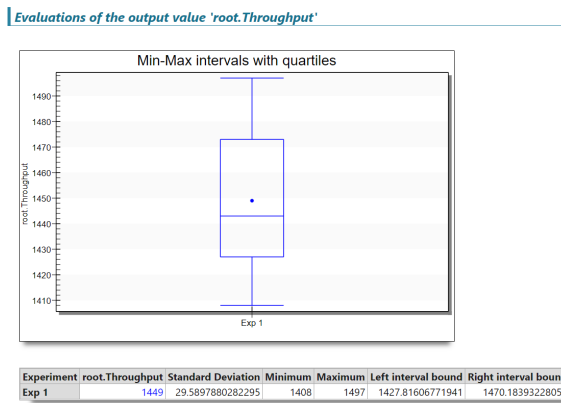


Figure A.62: Evaluation of Throughput

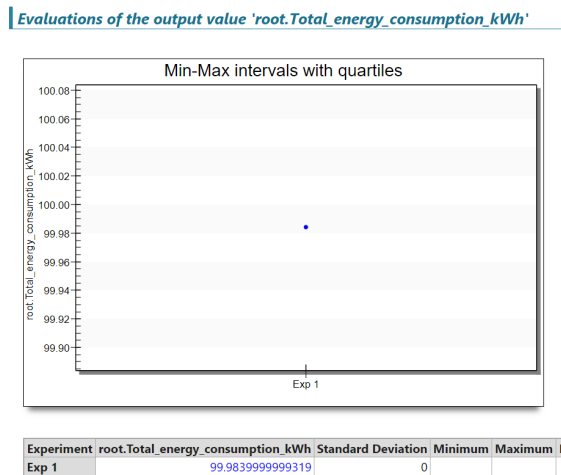


Figure A.63: Evaluation of Energy consumption

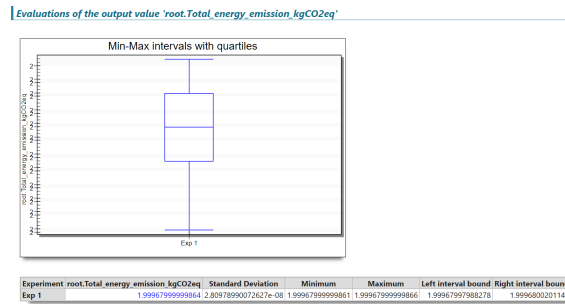


Figure A.64: Evaluation of Energy emissions

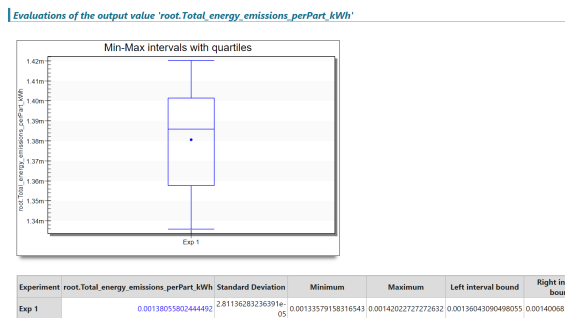


Figure A.65: Evaluation of Energy emissions per part

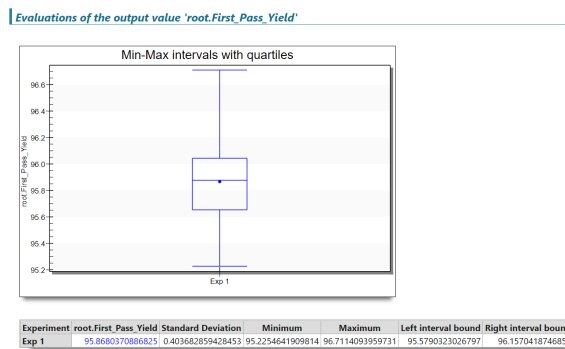


Figure A.66: Evaluation of First Pass Yield

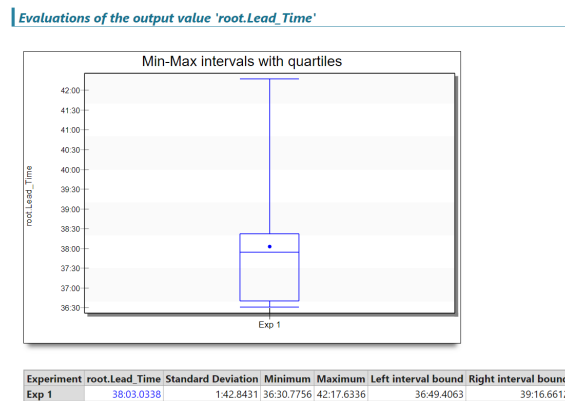


Figure A.67: Evaluation of Lead time

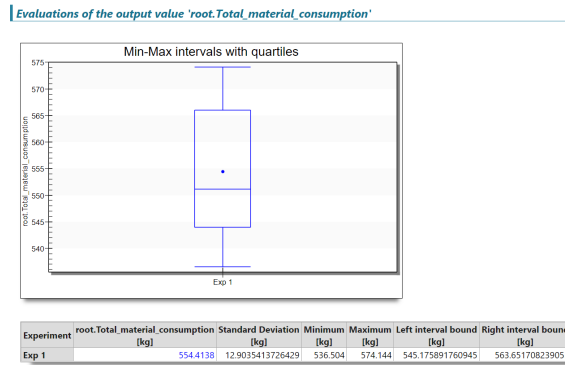


Figure A.68: Evaluation of Material consumption

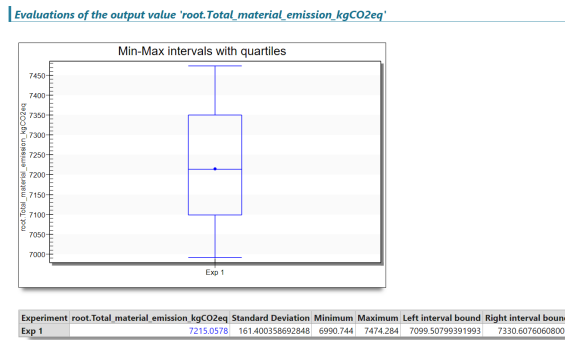


Figure A.69: Evaluation of Total material emissions

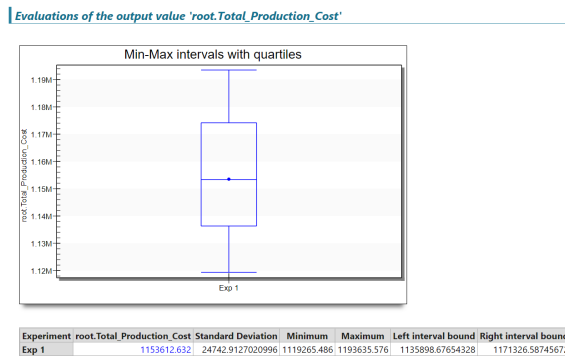


Figure A.70: Evaluation of Production cost

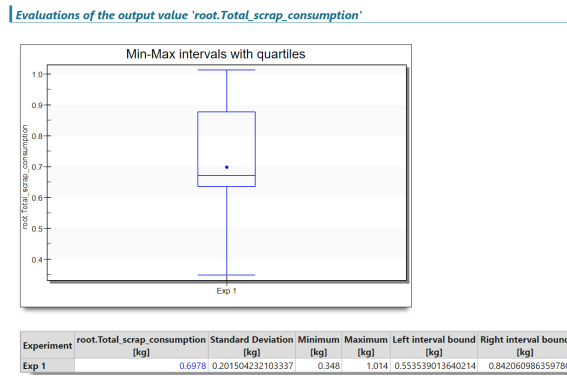


Figure A.71: Evaluation of Scrap cost

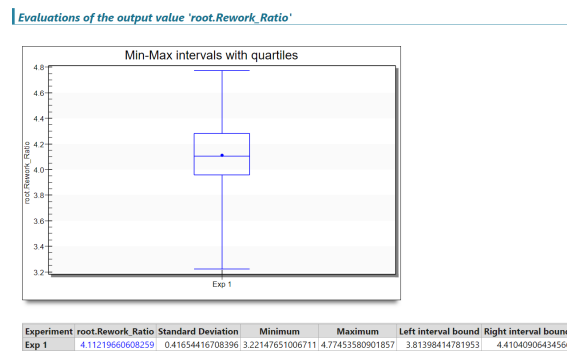


Figure A.72: Evaluation of Rework ratio

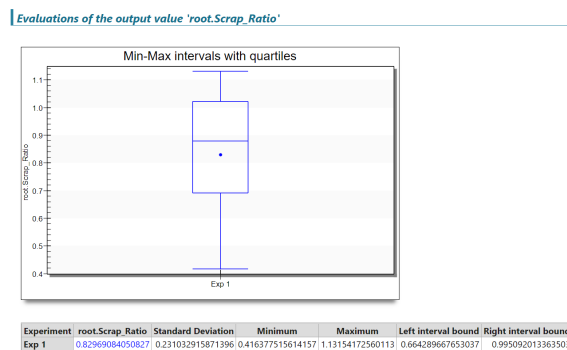


Figure A.73: Evaluation of Scrap ratio

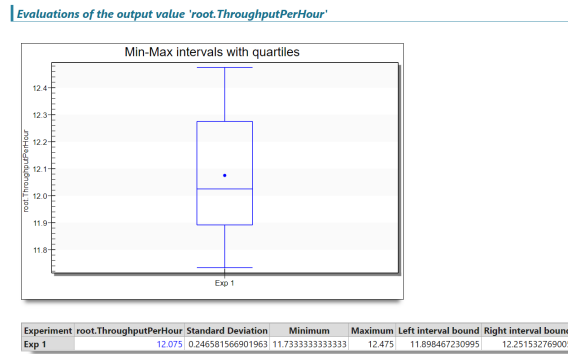


Figure A.74: Evaluation of Throughput per hour

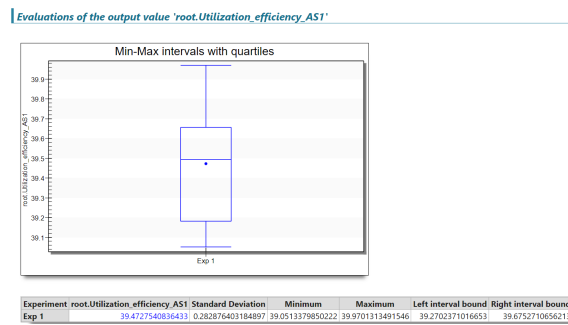


Figure A.75: Evaluation of Utilization efficiency of station 1

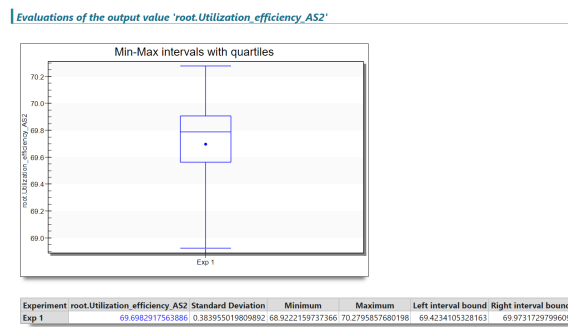


Figure A.76: Evaluation of Utilization efficiency of station 2

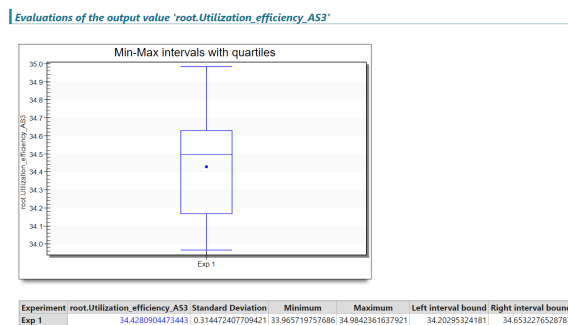


Figure A.77: Evaluation of Utilization efficiency of station 3

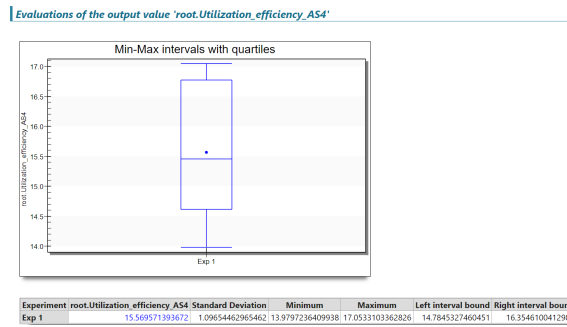


Figure A.78: Evaluation of Utilization efficiency of station 4

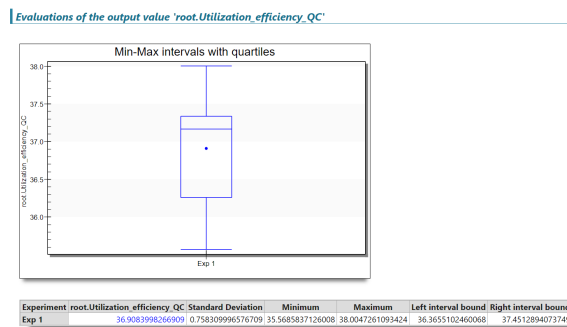


Figure A.79: Evaluation of Utilization efficiency of Quality check

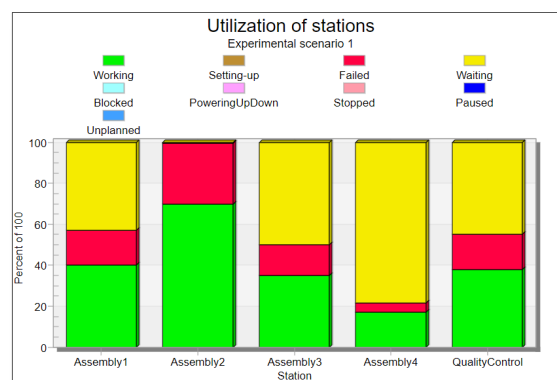


Figure A.80: Evaluation of Utilization efficiency of all the stations

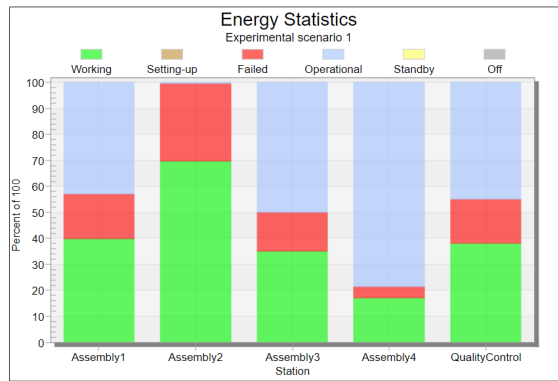


Figure A.81: Evaluation of Energy utilization at all the stations

## A.4 Results of Experimental scenario 1

### A.4.1 Results for 50-50 demand scenario

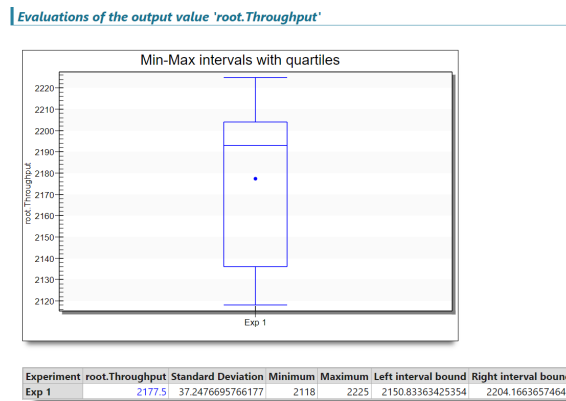


Figure A.82: Evaluation of Throughput

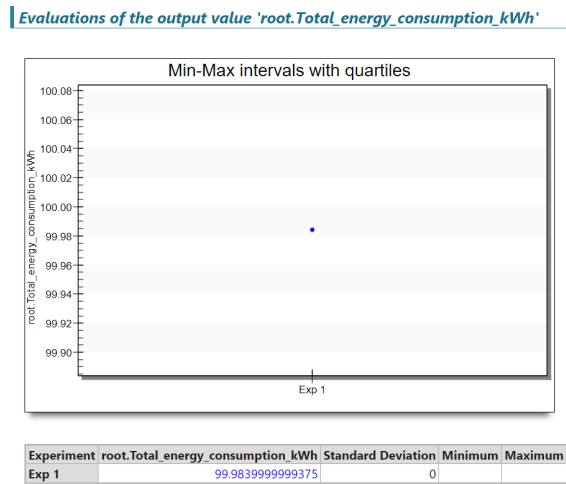


Figure A.83: Evaluation of Energy consumption

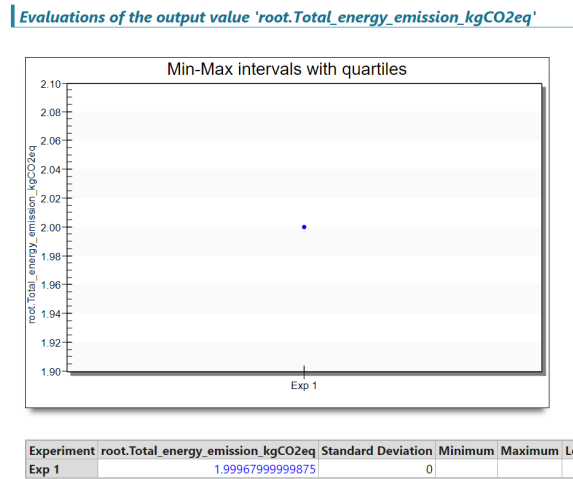


Figure A.84: Evaluation of Energy emissions

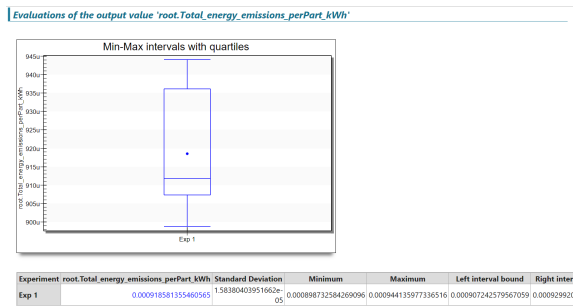


Figure A.85: Evaluation of Energy emissions per part

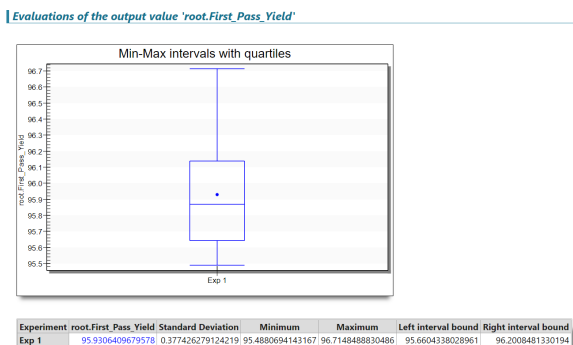


Figure A.86: Evaluation of First Pass Yield

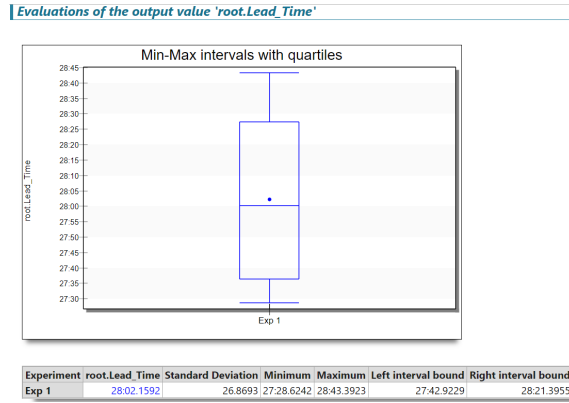


Figure A.87: Evaluation of Lead time

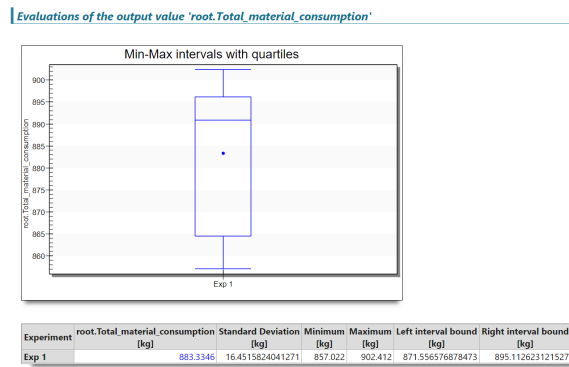


Figure A.88: Evaluation of Material consumption

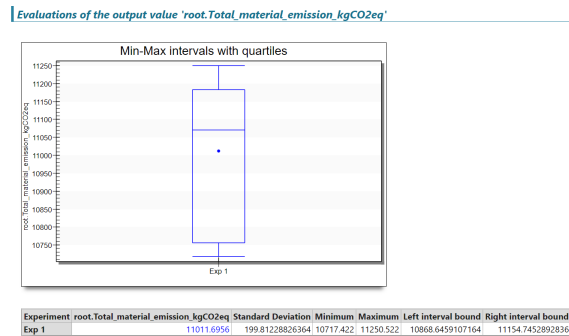


Figure A.89: Evaluation of Total material emissions

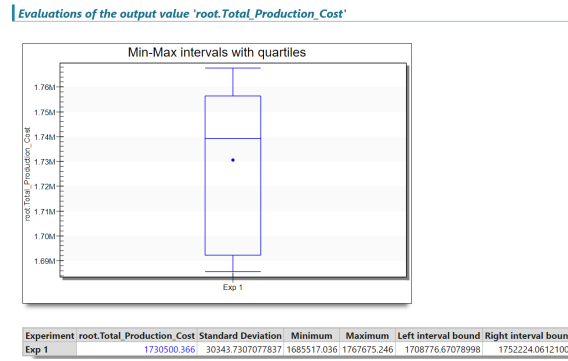


Figure A.90: Evaluation of Production cost

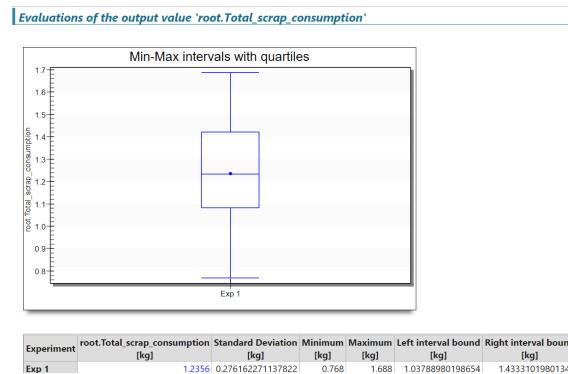


Figure A.91: Evaluation of Scrap cost

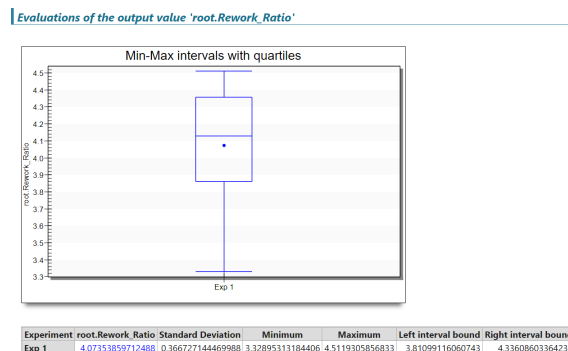


Figure A.92: Evaluation of Rework ratio

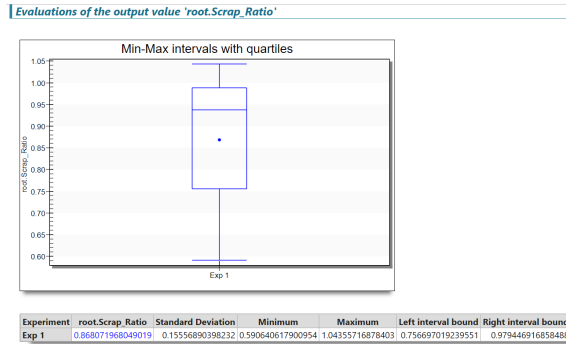


Figure A.93: Evaluation of Scrap ratio

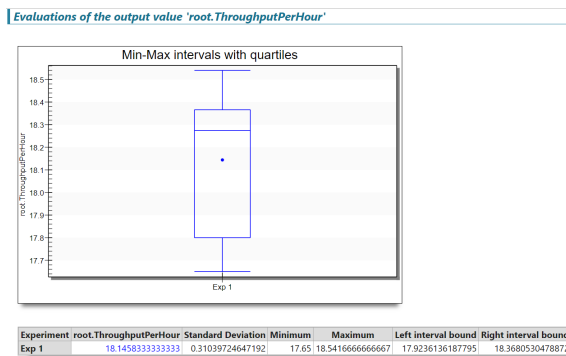


Figure A.94: Evaluation of Throughput per hour

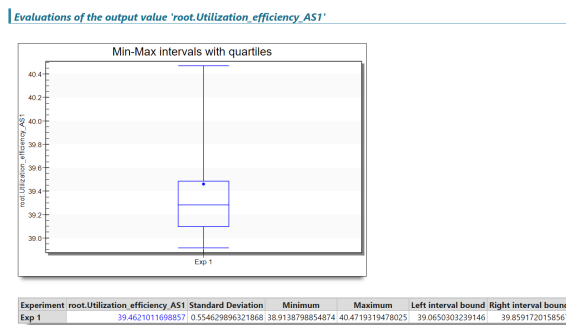


Figure A.95: Evaluation of Utilization efficiency of station 1

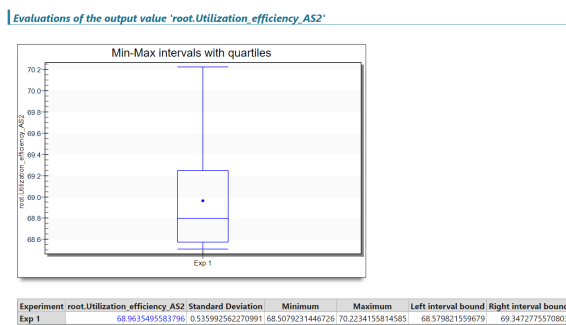


Figure A.96: Evaluation of Utilization efficiency of station 2

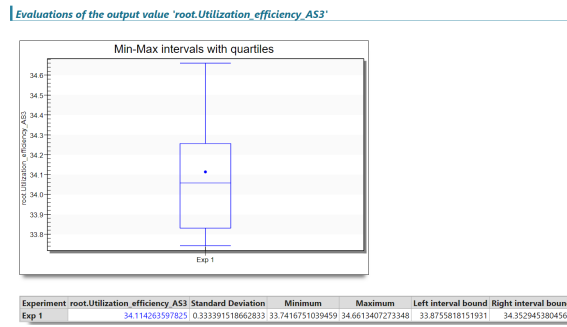


Figure A.97: Evaluation of Utilization efficiency of station 3

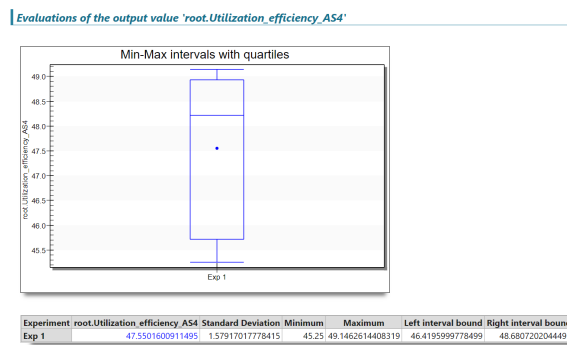


Figure A.98: Evaluation of Utilization efficiency of station 4

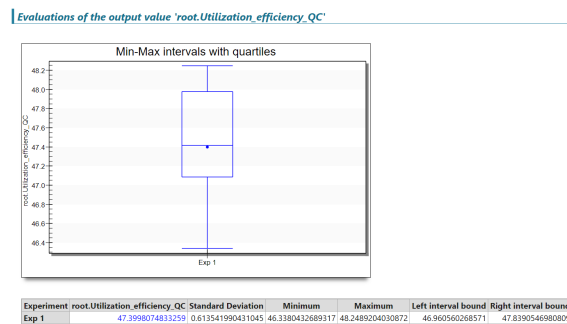


Figure A.99: Evaluation of Utilization efficiency of Quality check

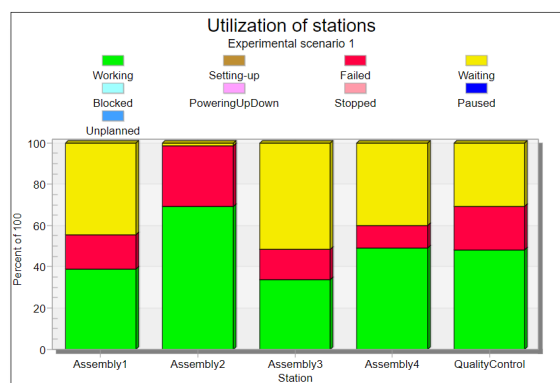


Figure A.100: Evaluation of Utilization efficiency of all the stations

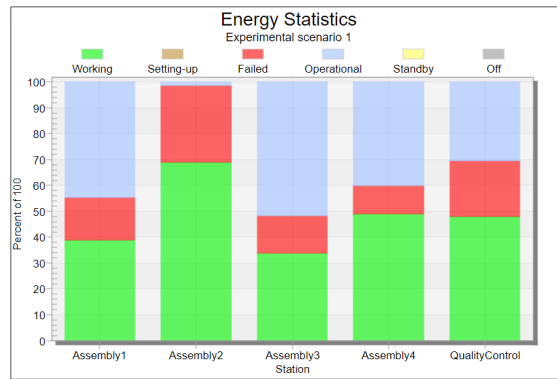


Figure A.101: Evaluation of Energy utilization at all the stations

### A.4.2 Results for 25-75 demand scenario

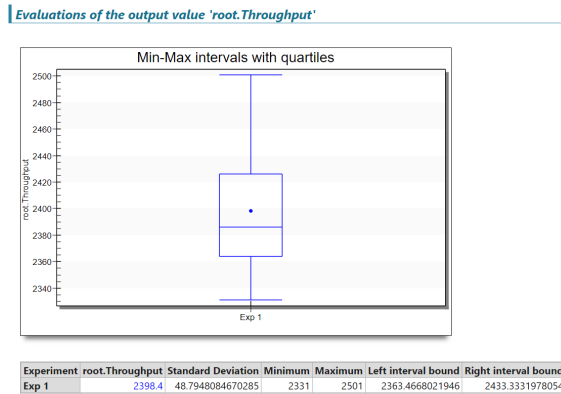


Figure A.102: Evaluation of Throughput

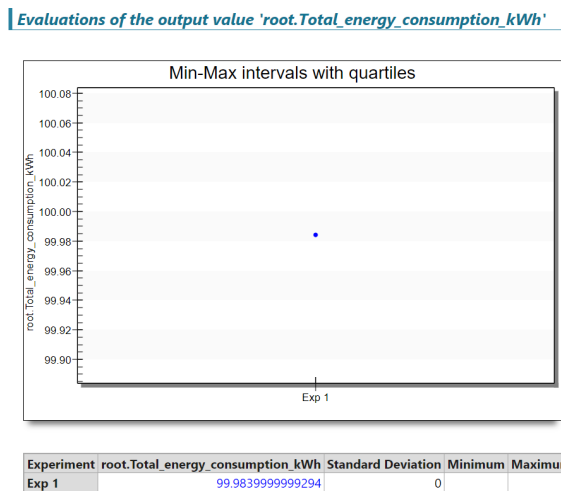


Figure A.103: Evaluation of Energy consumption

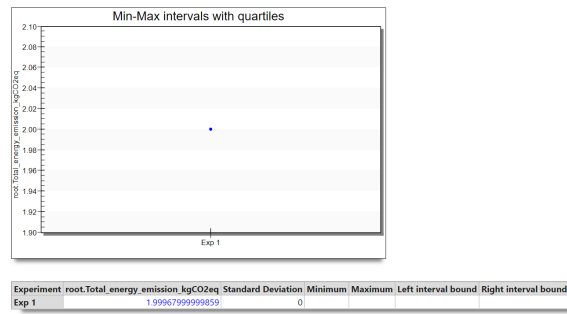


Figure A.104: Evaluation of Energy consumption

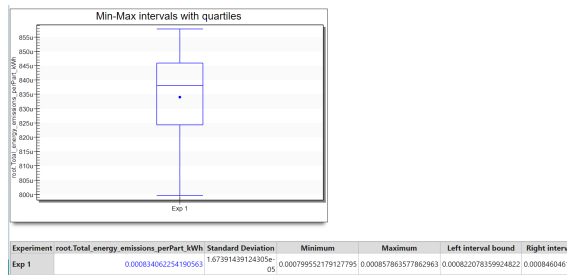


Figure A.105: Evaluation of Energy emissions per part

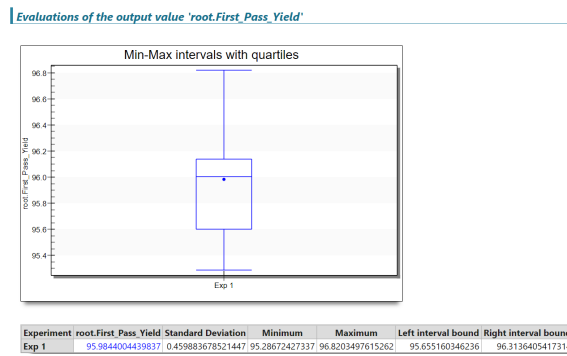


Figure A.106: Evaluation of First Pass Yield

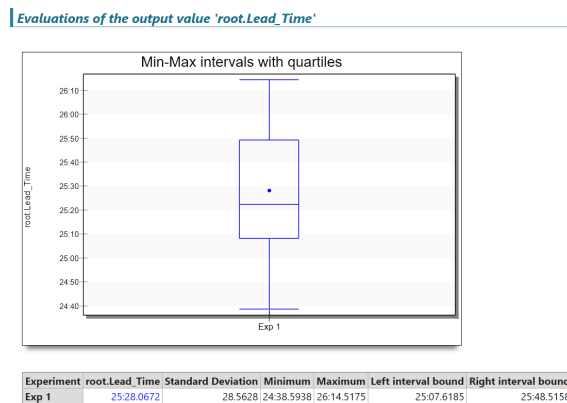


Figure A.107: Evaluation of Lead time

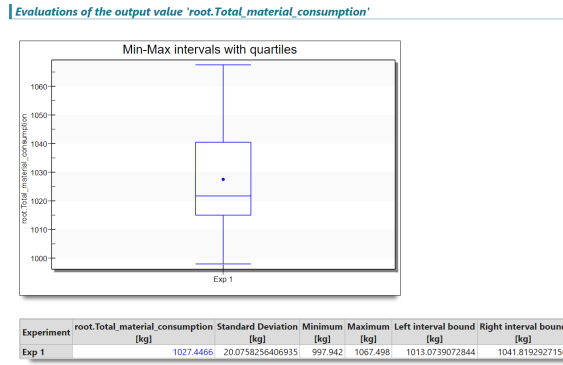


Figure A.108: Evaluation of Material consumption

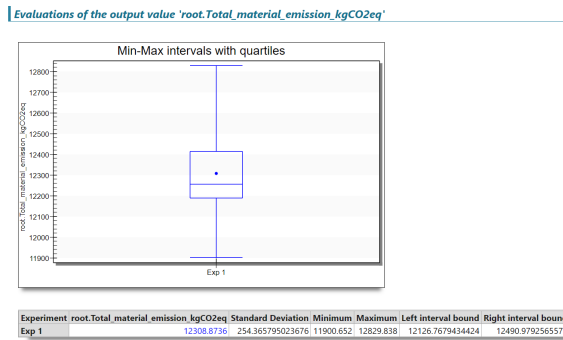


Figure A.109: Evaluation of First Pass Yield

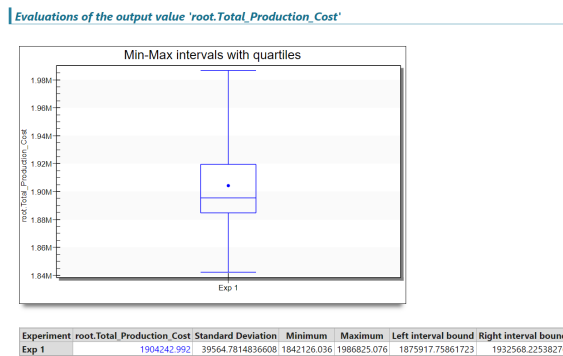


Figure A.110: Evaluation of Production cost

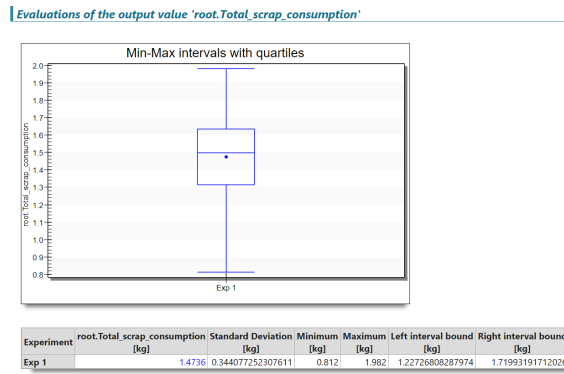


Figure A.111: Evaluation of Scrap cost

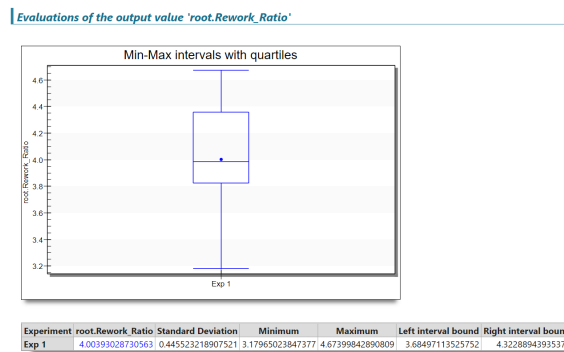


Figure A.112: Evaluation of Rework ratio

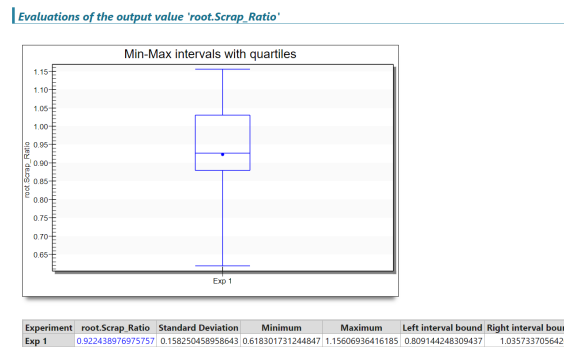


Figure A.113: Evaluation of Scrap ratio

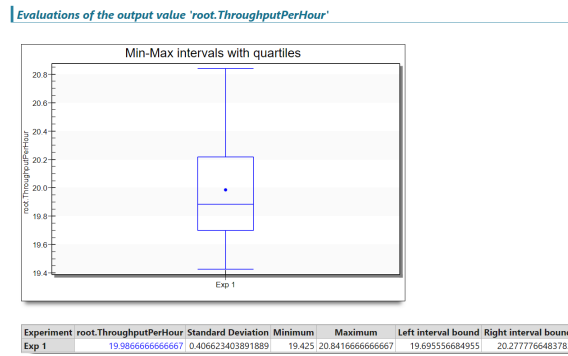


Figure A.114: Evaluation of Throughput per hour

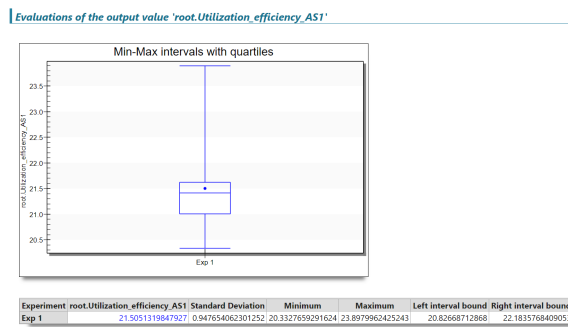


Figure A.115: Evaluation of Utilization efficiency of station 1

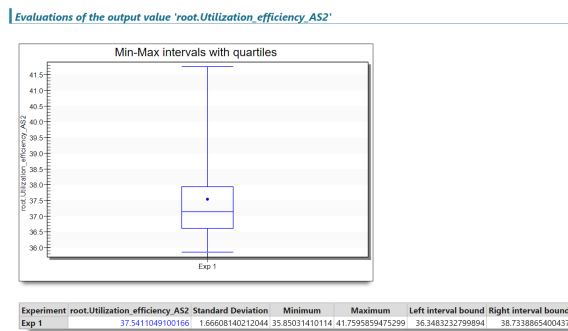


Figure A.116: Evaluation of Utilization efficiency of station 2

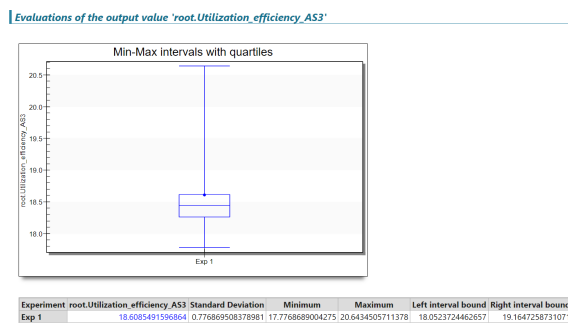


Figure A.117: Evaluation of Utilization efficiency of station 3

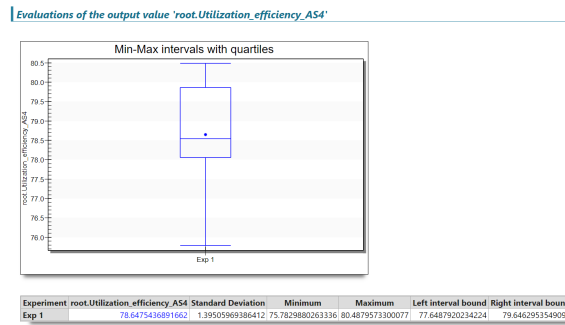


Figure A.118: Evaluation of Utilization efficiency of station 4

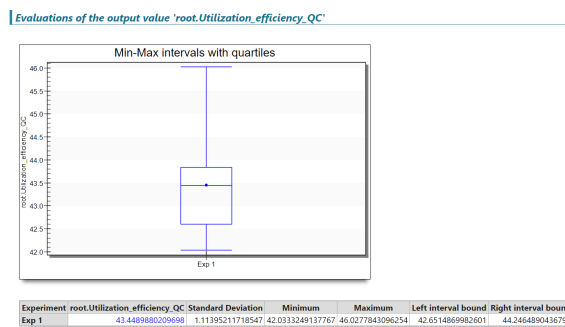


Figure A.119: Evaluation of Utilization efficiency of Quality check

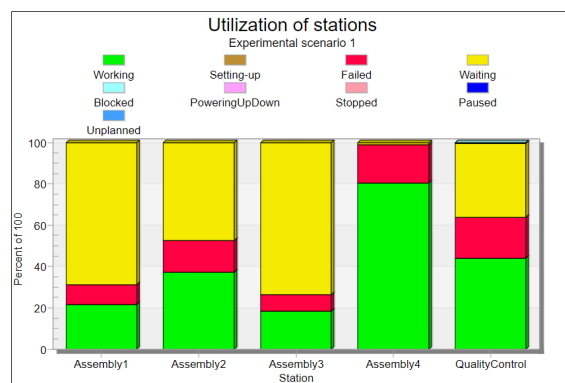


Figure A.120: Evaluation of Utilization efficiency of all the stations

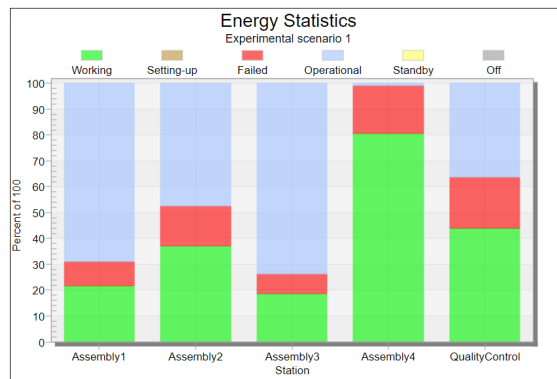


Figure A.121: Evaluation of Energy utilization at all the stations

### A.4.3 Results for 75-25 demand scenario

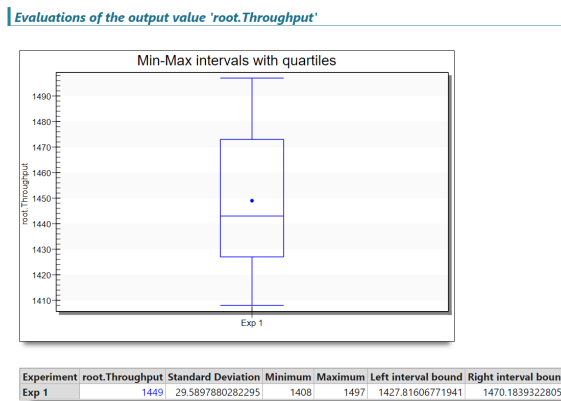


Figure A.122: Evaluation of Throughput

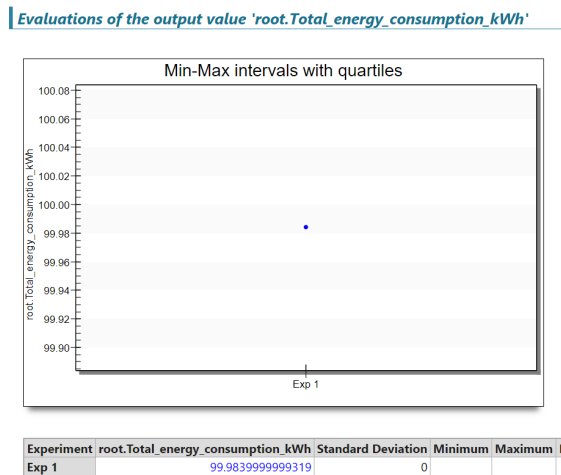


Figure A.123: Evaluation of Energy consumption

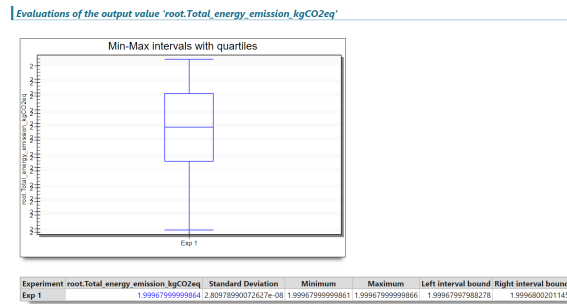


Figure A.124: Evaluation of Energy emissions

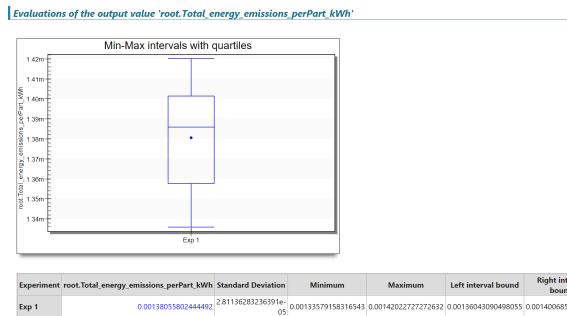


Figure A.125: Evaluation of Energy emissions per part

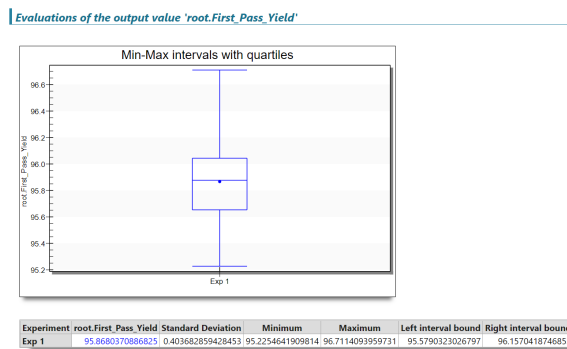


Figure A.126: Evaluation of First Pass Yield

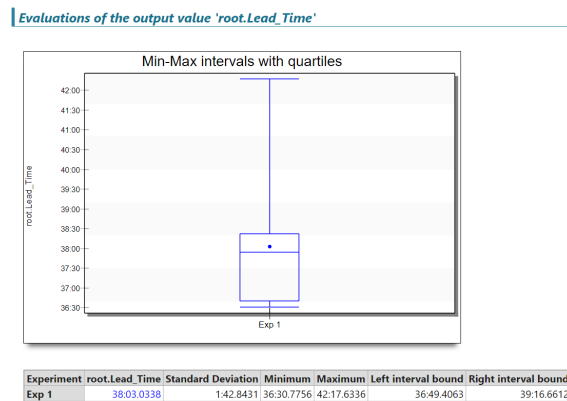


Figure A.127: Evaluation of Lead time

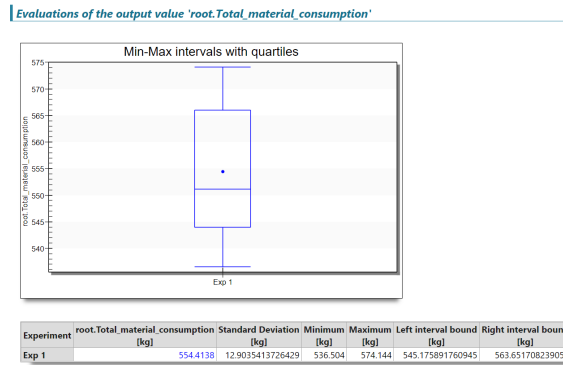


Figure A.128: Evaluation of Material consumption

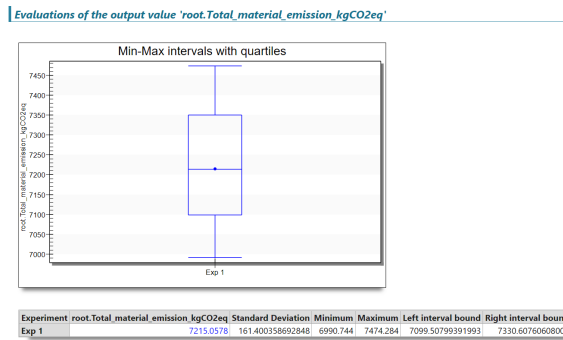


Figure A.129: Evaluation of Total material emissions

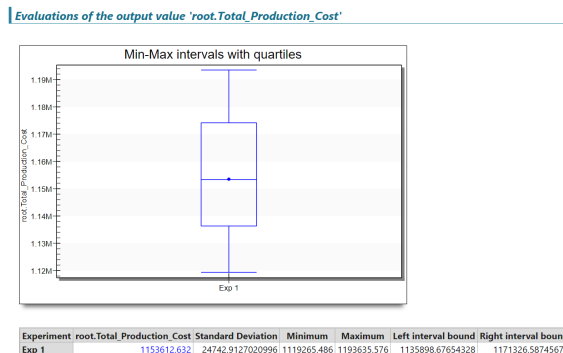


Figure A.130: Evaluation of Production cost

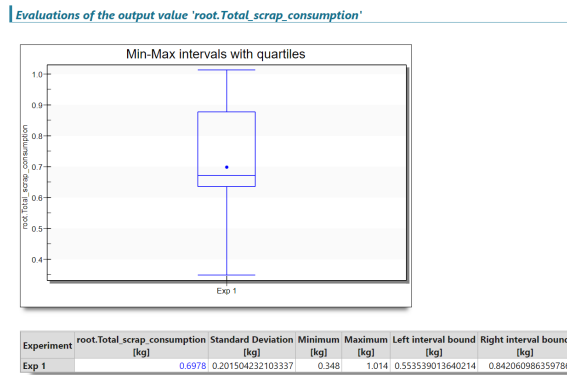


Figure A.131: Evaluation of Scrap cost

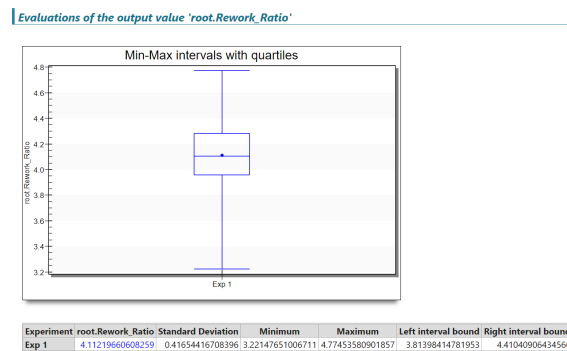


Figure A.132: Evaluation of Rework ratio

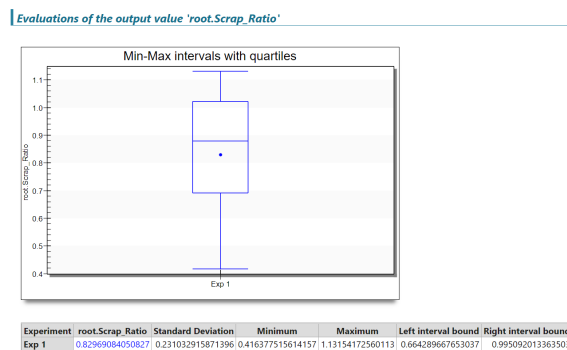


Figure A.133: Evaluation of Scrap ratio

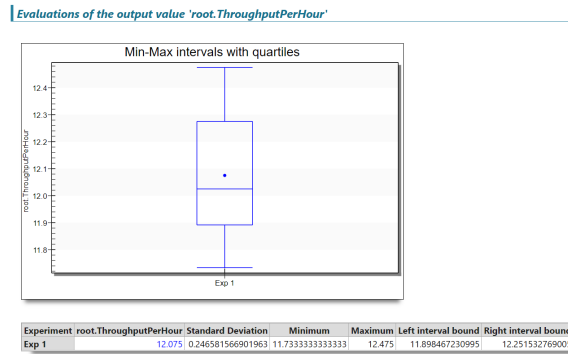


Figure A.134: Evaluation of Throughput per hour

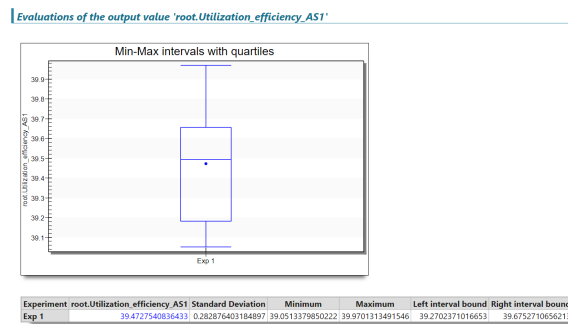


Figure A.135: Evaluation of Utilization efficiency of station 1

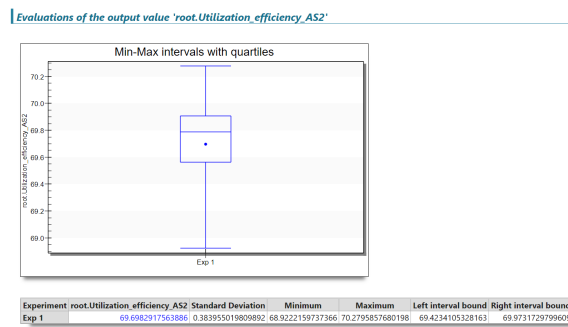


Figure A.136: Evaluation of Utilization efficiency of station 2

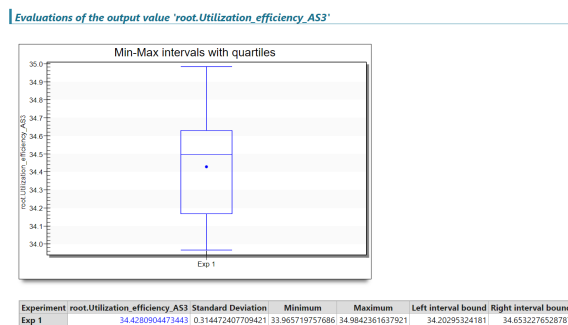


Figure A.137: Evaluation of Utilization efficiency of station 3

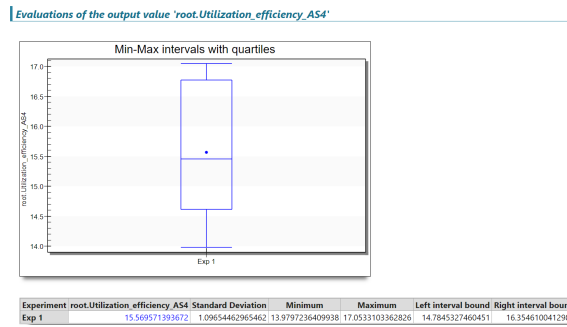


Figure A.138: Evaluation of Utilization efficiency of station 4

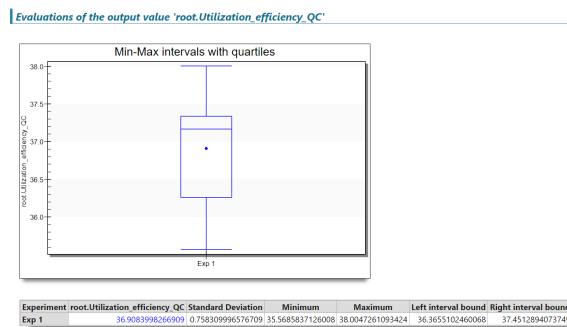


Figure A.139: Evaluation of Utilization efficiency of Quality check

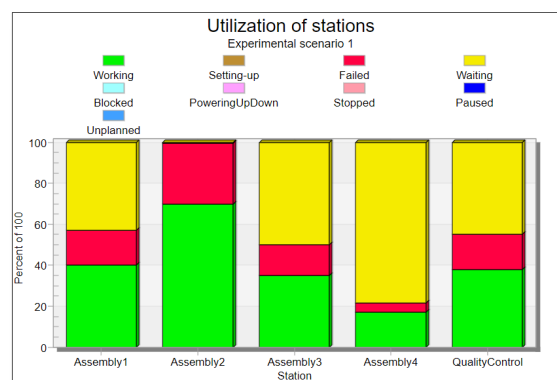


Figure A.140: Evaluation of Utilization efficiency of all the stations

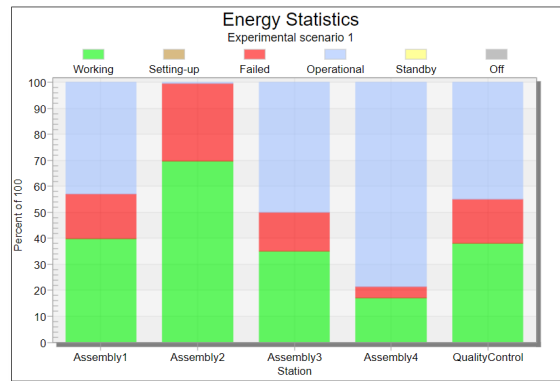


Figure A.141: Evaluation of Energy utilization at all the stations

# B

## Appendix 2

### B.1 Methods for Programming Model Behaviour

This section provides insights on how the DES model was created on Plant simulation using the programming language SimTalk2.0 for modelling the production system's behaviour. Although all the methods are not explained in detail due to confidentiality reasons, the methods for creating a base model frame has been explained in detail in this section. The following Figure B.1 depicts the code used in plat simulation for creating the MU's or as in this case the drones. The two different drone variants are distinguished by colour coding the MU's using vector graphics in the simulation model.

```
var tempPartType, tempSum, nextCall, tempValue: real
var i, j : integer
var myPart, myTable : object

--To begin with this table "ProductionPlan" represents the distribution of different product variants.
--Parts are created randomly from this list.

myTable := .InputData.InputData.ProductionPlan
--while true
  nextCall := z_negexp(3,.InputData.InputData.interArrvialTime) --Randomize IAT
  --print ""
  tempPartType := z_uniform(4,0,1) --Randomize a number between 0 and 1
  tempSum := 0
  If .Models.Model.BufferIncoming.numMU < .Models.Model.BufferIncoming.capacity --Is there room for more parts?
    for i := 1 to myTable.yDim --Go through every row in the table
      tempSum := tempSum + myTable["Percentage", i] --Add percentage for comparison
      if tempPartType < tempSum --Is there a match of product variant?
        myPart := .UserObjects.myPartMain.create(.Models.Model.BufferIncoming)--Produce part and add in the buffer
        myPart.variantName := myTable[0,i] --Add variant name
        ---tempValue := tempValue + myTable["Scrap_rate" , i]---add percentage for scrap comparison
        .InputData.InputData.ProductionStages.copyRangeTo({1,myPart.variantName}..{*},myPart.variantName), myPart.production
        .InputData.InputData.ProductionStages.copyRangeTo({1,0}..{*},0), myPart.productionStages, 1,0) --Add production stag
      For j:= 1 To myPart.productionStages.xDim --Set first production stage
        If (myPart.productionStages[j,1] = "YES")
          myPart.nextMachine := myPart.productionStages[j,0]
          exitloop
        End
    End
```

Figure B.1: Program for creating parts or MU's

The following Figure B.2 depicts the code used in Plant simulation for creating the individual components that have to be assembled on top of each other to make a drone. Both the creation of the MU's and its respective components are randomized in this case.

```

For i:= 1 To .InputData.InputData.componentsinfoV1.yDim --Set first production stage
tempPartType := .InputData.InputData.componentsinfoV1[0,i]
If @.cont.Scrap = true and scrapSet = false
tempValue := tempValue + .InputData.InputData.componentsinfoV1["Scrap",i]
If (randomValue <= tempValue) --change
partQuality := .InputData.InputData.componentsinfoV1[0,i]
End
end

If @.cont.Rework = true and scrapSet = false
tempValue := tempValue + .InputData.InputData.componentsinfoV1["Rework",i]
If (randomValue <= tempValue) --change
partQuality := .InputData.InputData.componentsinfoV1[0,i]
End
end

For j:= 1 To .InputData.InputData.componentsinfoV1["Quantity",i]
myPart := tempPartType.create(@.cont)
myPart.partWeight := .InputData.InputData.componentsinfoV1["Material weight",i]
@.cont.partWeight := @.cont.partWeight + myPart.partWeight
myPart.PartCost := .InputData.InputData.componentsinfoV1["Material cost",i]
@.cont.PartCost := @.cont.PartCost + myPart.PartCost
If @.cont.Scrap = true and scrapSet = false and partQuality = myPart.class
myPart.Scrap := true
@.cont.failedcomponent := myPart
scrapSet := true
End

```

**Figure B.2:** Program for creating components

The following Figure B.3 is called within the methods for creating components. This was done so that the quality of the parts which was assumed to have a scrap rate of 1% from the supplier could be set prior to simulation start as in real-world situations. The rework rate was set to 4% so that the model could conform with the 5% defected quality products as in case of the real world production system's.

```

if @.cont.variantName = "VarA"

randomValue := z_uniform(33,0,1)
If (randomValue <= 0.01) --Scrap
@.cont.Scrap := true
Else
randomValue := z_uniform(33,0,1)
If (randomValue <= 0.05 and randomValue > 0.01) --Rework
@.cont.Rework := true
End
End
If @.cont.Scrap = true or @.cont.Rework = true
randomValue := z_uniform(33,0,1)
End

For i:= 1 To .InputData.InputData.componentsinfoV1.yDim --Set first production stage
tempPartType := .InputData.InputData.componentsinfoV1[0,i]
If @.cont.Scrap = true and scrapSet = false
tempValue := tempValue + .InputData.InputData.componentsinfoV1["Scrap",i]
If (randomValue <= tempValue) --change

```

**Figure B.3:** Program for setting the Quality of Production System

The following Figure B.4 depicts the program used to set-up the assembly stations.

The program is flexible and can be easily modified. The assembly stations can either be set as a manual station using normal distributions or as an automated station by using a constant distribution. Depending on the scenario and the production stages the individual components of the drone variants are set to the corresponding assembly stations where they shall be assembled one top of the other.

```

myTable :=.InputData.InputData.ProductionParameters
If @.cont.variantName = "VarA" Then
    myComponentsInfo := .InputData.InputData.componentsinfoV1
    myVariant := "Processing_TimeVarA"
Else
    myComponentsInfo := .InputData.InputData.componentsinfoV2
    myVariant := "Processing_TimeVarB"
End

If (@.cont.Scrap = true and @.cont.failedcomponent /= VOID) Then
    If myComponentsInfo["Assembly_Stage", @.cont.failedcomponent.class] = ?.name Then
        myPart := @.cont.failedcomponent.class.create(@.cont)
        @.cont.failedcomponent.move(.Models.Model.Buffer_Scrap)
        scrapTime := myTable["Scrap_Processing", ?]
    end
end

If @.cont.variantName = "VarA" Then
    temp_time := scrapTime + z_normal(5, myTable[myVariant, ?], myTable[myVariant, ?]*0.3, myTable[myVariant, ?]*0.3,
    myTable[myVariant, ?]*1.7)
    Result := temp_time
else
    Result := scrapTime + myTable[myVariant, ?]
end

```

**Figure B.4:** Program for setting up the Assembly Stations

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