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**Concurrent design of product and production service system strategies:  
A case study on transportation solution for a health innovation center**

**Master's thesis in Product Development and Production Engineering**

**ROBEL BESRAT  
TESLEEM OYELAKIN**



**MASTER'S THESIS 2020**

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*Division of Product Development and Production System*  
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Master's thesis 2020

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Gothenburg, Sweden, 2020

# Concurrent design of product and production service system strategies: A case study on transportation solution for a health innovation center

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## **ABSTRACT**

Today, many manufacturing companies are searching for ways to improve on their market strength and to provide better service that fulfills the demand of the customer with the Product Service System (PSS) model. Since PSS business model focuses on motivating and satisfying the customers' needs, it also helps company to innovative solution, strengthen competitiveness which in turn assure the desired profit. In developing a design of a product, the main stakeholders such as the product design and production system should search for a way that could add more value to the product, company and customers.

In this paper, a methodology approach that enables a support decision in PSS design is presented with regards to land mode of transportation in form of micro-mobility. A substantial knowledge is basis to a well designed and developed Product Service System (PSS) but however cross information does not always exist during product development. Therefore, use of micro-mobility is on the rise and it is imperative to avoid more process iteration and design conflict that may hinder functionality of the product and delivery to market.

The proposed model of Product & Production Service System (PPSS) has shown a lack in the literature of PSS design and proffer relevant information for companies using the PSS design business model where improvement can be done through cross boundary integration.

Key words: PPS design, Product development, Production system, Communication, Integration, Micro-mobility, PPSS, Product Service System, Improvement.

## **ACKNOWLEDGEMENT**

The author would like to express our sincere gratitude to the Department of Product and Production Development for the opportunity and privilege to conduct this master thesis. In this regard, we would like to say big thanks to our Examiner Torbjörn Ylipää for his kindful gesture and guidance throughout the project. On the hand, we are also thankful for the tutoring help and constructive feedback from indomitable supervisor, Massimo Panarotto. This master's thesis could not have been completed without your extensive cooperation and professionalism which ensure that the project is channeled in the right direction to obtain the desired results.

Furthermore, we would like to thank the GoCo Health Innovation Center, Mölndal for their cooperation that prompted the establishment of the important requirements to satisfy the demand of the customer.

Lastly, our appreciation also goes to individuals who have contributed in one way or the other to the completion of this project. All efforts, supports and advices are well appreciated.

Robel Besrat & Tesleem Oyelakin

Göteborg, 2020.

## **ABBREVIATIONS**

PSS	Product Service System
B2B	Business to Business
B2C	Business to Customer
PSL	Production System Layout
NPV	Net Present Value
DES	Discrete Event System
CES	Cambridge Engineering Selector
MSD	Musculoskeletal Disorders
RCM	Reliability Centered Maintenance
TQM	Total Quality Management
DFM	Design for Manufacturing
NPD	New Product Development
PPSS	Product & Production Service System
CE	Concurrent Engineering
TPS	Toyota Production System
MTTR	Mean Time To Repair
MTBF	Mean Time Between Failure
CAD	Computer Aided Design
CAE	Computer Aided Engineering
FEM	Finite Element Method
SBCE	Set-Based Concurrent Engineering
LCC	Life Cycle Cost



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## **PREFACE**

In this study, the basis for the research work stemmed from passion to support business model of PSS design decision in development of a product. The support has been conducted between the multifunctional team of production system and product design. The work is part of what the project focuses on regarding to the study case. It is so stimulated to not only support the PSS design, but rather to see the impact of the cross-function as result of knowledge sharing. This project is carried out at the Department of Industrial and Material Science, Chalmers University of Technology, Sweden.

In truth, the success of this project could not have been achieved with the notion of Production & Product Service System (PPSS) design without the help of our outstanding mentors: supervisor in person of Massimo Panarotto and Torbjörn Ylipää as examiner. My co-partners Robel Besrat and Tesleem Oyelakin your efforts are highly appreciated. I would also like to thank GoCo Health Innovation Centre AB for their co-operation and involvement and others whose name are not mentioned.

Thank you all for your staunch support.

Göteborg, April 2020

Robel Besrat & Tesleem Oyelakin.

## NOTATIONS

Casting time

$$t = C_m (V/A)^n$$

Cutting time

$$t_c = \frac{WL}{f * S * N}; \quad f = Ft / S * N; \quad S = V_c * 1000 / \pi * \emptyset$$

### Capital variables

*A* Surface area of the casting that contacts the mold

*C<sub>m</sub>* Mold constant

*D* Distance

*F<sub>m</sub>* Minimum power for propulsion

*Fr* Friction

*G* Force of gravity

*G* Electricity cost

*M* Mass of object

*N* Number of teeth

*N* Normal force

*R* Revenue

*S* Spindle speed

*S* Population density

*V* Volume of the cast

*V<sub>c</sub>* Cutting speed

*W* Watt

*X* Usage of hours per month

*Ft* Feed transverse

*HI* Amount of power input needed

*WL* Workpiece length

### Small variables

*f* Feed per tooth

*g* Gravitational constant

*h* Presumed highest mean weight of users

*n* constant value

*t* cast solidification time

$t_c$	Cutting time
$\emptyset$	Diameter of object
$\pi$	3.14
$\mu$	Friction coefficient



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# 1 Chapter One: Introduction

*The introductory chapter has six sections (background, purpose, project aims, research questions, scope, problem statement and delimitations) introducing and describing the steps of this thesis work.*

## 1.1 Project background

Product service system (PSS) business model is becoming a more popular trend adopted within most of the producing sector (Bhamra et al, 2018). A business model that provide a cohesive product and service delivery prior implementation. Today, no business model is emphasizing the integration, parallel or concurrent of functions within an organization in the product development process (Andreasen & Hein, 1987). The activities product design and production systems in PSS design often take place simultaneously in a product development. According to Isaksson et al (2011), integration and cooperation is not always well coordinated between the two stakeholders due to no or very low co-development of PSS resulting into late market delivery. This gap as result of communication barrier between them has direct impact on product and services of PSS design (Tukker & Berg, 2004). In order to establish a communication across multi-functional team, sharing of knowledge need to be facilitated (Bertoni et al, 2016). Since PSS design involves a lot of investments and activities, there is a need for a model-based approach that will enable to simulate the process (Borshchev & Filippov, 2004). According to Durugbo et al (2010); Fuchs et al (2015) and Wallin et al (2013), it is essential to develop an overall approach of PSS design with other areas such as Business-to-business (B2B) and Business-to-customer (B2C) to get a fully optimized PSS-system.

This report focuses on a case study which will be used to evaluate transportation mode for a health innovation center. Through means of micro-mobility of land transport mode, multiple people can share the same product. Due to the sharing potential, it has been regarded as an alternative transportation paradigm and increasingly becoming popular in many countries (Alfian et al, 2014). A sustainable PSS that is well developed add economical value and social-being while minimizing the negative environmental and social impact (Tukker & Berg, 2004). According to Forrester (1989) and Bertoni (2019), transportation system is regarded as a symbiosis area where multiple objects is active and together form an ecosystem. Thus, different tools of modelling are used to study the various systems. These tools allow the possibility to make a simulation of real-time occurrences with an input of different data and to be able to evaluate these data (Bonabeau, 2002); (Jim Hight, 1995) and (Macal et al, 2005).

## 1.2 Purpose

The purpose of this study is to examine the significant impact of information sharing i.e communication between product & production development (PPD) in PSS design. This will be achieved by early knowledge of stakeholder's inputs during the conceptual phase. The materializing of PSS-design is done by evaluating transportation modes that is best suited to the study which is GoCo Health innovation center.

### **1.3 Aims**

The aim of this project is to model a decision support approach enabling early integration between production and product development in a business model of PSS design.

### **1.4 Research question**

Today's sharing transportation modes e.g bike share has emerged as a rapidly growing mode of transport in more than 800 cities all over the world (Fishman & Schepers, 2016). Due to the high degree of safety in bike sharing recorded where 'Safety in Number' had showed that cyclist is less likely prone to be harm (Schepers et al, 2015) paved way for design of micro-mobility. In the design of such product development, multifunctional disciplines, experts and company divisions with own end-objectives are involved and the process usually leads to design conflicts at the end. Since the case of micro-mobility is drastically increasing as a form of transport mode that is shaking up urban transport worldwide. Hence, need to support the system process with a potential model to prevent unwanted flaws which could affects the efficiency of the design process negatively.

The joined collaboration of Product & Production Service System (PPSS) will be applied on the study case of GoCo for determining the land mode of transportation. In this case, the research question will be presented as follow:

*RQ How can a PSS model-based approach be developed to enhance design integrations between product and production service system development?*

### **1.5 Scope**

The scope of this project is to simulate a PSS design process of Product and Production service system. This will be done by analyzing the possible factors and challenges with respect to the case study in order to evaluate and determine the optimal transportation mode for GoCo health innovation center.

### **1.6 Problem statement**

Many literatures have re-emphasized that there is a lack of a common PSS design due to scarce collaboration between product and production service system development. This inadequacy has led both disciplines to have their own PSS business model which is not working as an entity. Thus, research is needed to enable collaboration between the two stakeholders.

### **1.7 Delimitations**

Delimitations have been set to increase the quality of the project and make a clear understanding which marks the limits of the report. The research will be focusing only on the land-transport sharing mode. Moreover, this paper will not focus on the juridical aspect of the product in terms of production and usability, software interface, internal electrical circuit and none other materials than metals for the construction of the frame. Finally, no end life investigation of the PSS life-cycle evaluation phase will

be examined since we want to evaluate a product and not mechanic structure of the product design.

## 2 Chapter Two: Literature review

*This chapter contain the content and structure regarding the design of a product in order to understand the need for shift in PSS context from the product development and production system perspective.*

### 2.1 Product Development Process

Current International concern and company(s) manufacturers regarding the process of product development is to be cost effective, good quality and high productivity (Ullman, 2008). In this process, activities are characterized by significant events and this significant event requires a broad knowledge of the designer in order to fully understand decisions to be taken at the proper time (Dorst & Cross, 2001).

#### 2.1.1 Design knowledge and learning curve

In a design process, problems and solutions are inversely proportional because it is process that requires knowledge about decision making which is more challenging especially when designing a new project (Ullman, 2008) Therefore, a general knowledge is needed by the product designer and production system to be able to save time in product development. As the design process progresses, alternative solutions pop-up based on the designer's knowledge about the methods involved that could reduce time and cost so that the degree of design freedom is increased (Ullman, 2008).

The learning curve is the curve that represents knowledge about the problem to let gain more knowledge per unit time (Ullman, 1997). The New Product Development (NPD) in *Figure 1* explains the degree of freedom, product knowledge and incurred cost in the stages of design process. Making early decision will fasten the cost of modifications and reconstructing amplifies resulting to smaller exponential freedom of choice.

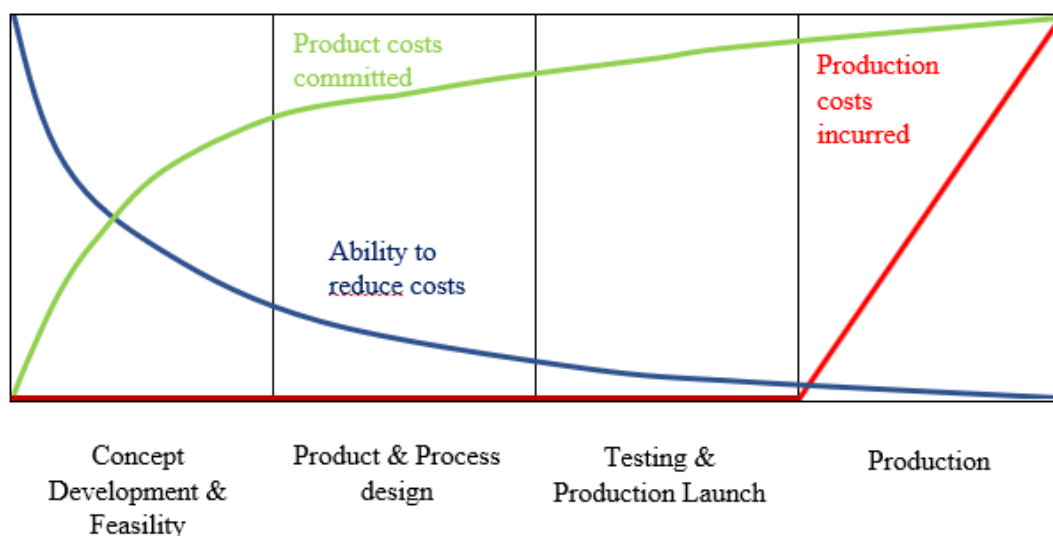


Figure 1 New Product Development

According to the NPD methodology, freedom of choice can be increased at the initial stage with proper solution to the design problem based on the designer's knowledge. The most effective cost reduction or improvement on profitability need to start early in the development cycle as proposed by the NPD.

## 2.2 PSS design business model

The term Product Service System (PSS) is defined as a wanted set of products and services capable of fulfilling the demands of customer (Mont, 2002). It is a system of products, services, supporting networks and infrastructure designed to be competitive and enhancing customers' satisfaction (Wallin et al, 2013). According to Wallin et al, (2013), PSS design has a lower environmental impact over the traditional business model. This is because it is a business model approach focusing more on product servitization rather than the physical products as in the case for traditional.

The process of PSS design focuses on products, service and communication integration in addressing changes in terms of technology and social & customer attitudes (Manzini, 1996). Through this integration, Goedkoop et al, (1999) pointed that key value (customer satisfaction) is the core purpose behind the development of PSS design to have strong market share around a product beyond the tangible product. PSS design generates environmental significance (Mont, 2002); an excellent vehicle to enhance competitiveness and to foster sustainability simultaneously (Tukker, 2004).

### 2.2.1 PSS Categories

PSS design became a well performing commodity in various markets (Tukker, 2004). In *Figure 2*, the three categories and sub-categories of PSS approach is illustrated.

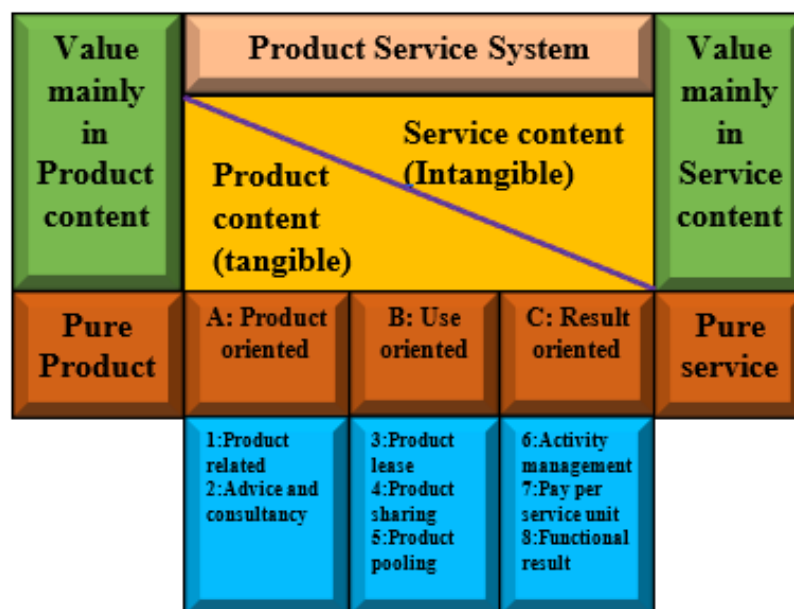


Figure 2 PSS main and sub-categories

The business model of PSS design has eight archetypical strategies comprising its main and sub-categories. The strategy shows the relationship between the PSS and its sustainability in the conceptual model. It can be deduced from the model that to the right in *Figure 2* is the pure service where more services are added to the product while to the left is more of a pure product. This movement means that significant service attention is given on the PSS with transition from left to right. Further service integration will lead to PSS result oriented where services is the core target. Business improvement would be ensured on the company scale level with integration of product service, thereby creating value adding service content (Goedkoop et al, 1999). In a case where there is no value adding on the product, there will be no shift and the customers only appears mainly on the product as purely product-oriented content (Tukker, 2004).

### **2.2.1.1 Product Oriented PSS**

PSS Product Oriented methodology is a strategy practice by companies that sells tangible products to customers. It is a product related service that does not only focus on the product but also offered services upon entire product usage period. This simply means that the ownership of the product is transferred to the customer while some additional services is included in the original act of sale (Tukker, 2004). Some of the services offer includes maintenance package, renewal of outdated products, consultancy and training and could be in the form of organizational structure like waste and recycling programs (Tukker, 2004).

### **2.2.1.2 Use Oriented PSS**

The Use Oriented PSS is about the methodology of manufacturer owing the product and the customer only use the product. The strategy value is that as more users uses same product, the owning company gets paid for each user (Tukker, 2004). Moreso, the owning company gets regular customer feedback on the state of the product in order to enable better improvement and allocate where maintenance should be more concentrated (Konrad et al, 2017).

### **2.2.1.3 Result Oriented PSS**

For Results-Oriented PSS methodology, the focus is purely about the service and not the product provided. Its' strategy is usually a third party that uses the product for another reason (Tukker 2004). For intances, AirBnb, Trivago etc service has two main stakeholders, the owners of the apartment and the rentals. The owners use a platform for posting and rental possibilities of accommodations for low fees. In this case, the medium gets set percentage of the rental value from two places for each booking (Razli et al, 2017).

## **2.3 Product servitization**

The design of product and servitization are two distinct production processes. The end means of a product is to be consumed which makes servitization recognised when planning the development of a product. According to Jonsson & Mattsson (2009), the production of product development in most cases are not relevant unless it combined with the production of services.

### **2.3.1 Servitization and its purpose**

Perona et al (2017) has described servitization as a transitional change from selling products to enable customized means to end a client's difficulties. This shows the merging between the idea of servitization and the idea of integrated solutions characterized as “ground-breaking” merging of services and products that gives the path for combined answer to clients' needs.

According Anderson & Narus (1999), servitization of a product is viewed from two different perspectives. The first point of view on servitization is categorized into four distinct trait which are:

1. Intangibility: These are services that are rather experienced but can't be touched.
2. Inseparability of production and consumption: Services were absorbed as they have been produced.
3. Perishability: Services can't be saved or stored for later use since they have already been absorbed.
4. Heterogeneity: Services have the potential for high variance in their performance because the provider dependency is huge.

The second point of view is the understanding of the dissimilarity between products and services. This perspective depends on the level of services and tangible products where very few or none is totally a product or a service.

## **2.4 Why PSS?**

PSS design is developed for today's demand with focus in fulfilling the needs of the customer (Mont & Tukker, 2006). Many manufacturing companies using PSS design has increased in their product competitiveness while the intended and desired profit on the product and service are assured (Scherer et al, 2016). With PSS design, manufactured products maximize the people social-being and economic value while minimizes environmental pollution and social impact (Tukker & Berg, 2004). A well-designed PSS is a solid alternative to achieve goal with value creation between the customer and company perspective supporting the innovativeness of the company (Pezzotta et al, 2014).

## **2.5 Challenges with PSS design**

Major company's challenges in PSS design is the aftermarket phase of the product development (Cohen et al, 2006). Organizations are still struggling with PSS design due to lack technical know-how and across-boundary discussion (Pezzotta et al, 2014). This is because the link between the stakeholders in the development of a product and service is not negotiated (Martin & D'Acunto, 2003). This thus creates design flaw which impacts long term profitability and quality (Lee & Kim, 2010). According to Ullman (2008), a substantial domain knowledge is required to produce any reasonably realistic product. In most case developers are unable to identify events that are significant during the process until key concept begins to emerge and eventually affects the product life cycle cost (Dorst & Cross, 2001). Furthermore, since the PSS involves many stakeholders, there are diverse opinions and perspectives

especially in the case of the end-user to be able to analyze the environment for their projected design (Isaksson et al, 2009).

## **2.6 Concurrent Engineering (CE) design**

Today's process in the development of a product design, large numbers of different activities of product designer and production engineer is been performed separately rather than simultaneously (Gunasekaran, 1998). Some techniques used in the design of CE such as Toyota Quality Maintenance (TQM) is developed to tackle the challenges facing product design. This is with consideration of multi-attributes to improve product development in terms of waste, customers' satisfaction and company's return on investment (Belay, 2010).

Exchange of information and knowledge as a result of integration between product and production system development in the early design processes facilitates high quality degree, low cost, flexibility and short delivery times (Ullman, 1997). According to Belay (2010), successfully implemented time-to-market strategy by company reduces development waste and likewise improve the success of new product aimed at satisfying the customer needs.

## **2.7 Integrated product & production system development**

The process of integration between product and production system development is divided into four modes. Each of these modes describe the time when the interaction or communication takes place as shown in *Figure 3*.

### **Serial/Batch**

The serial/batch is the traditional way of design process. The collaboration between team of downstream and upstream only starts when the upstream team signifies that its design is completed. The entire design is processed all in single data. This "batch" of information don't contain all the process steps and versions of the end design. Therefore, the assimilation process doesn't take notice of downstream strengths and opportunity.

### **Early start in the dark**

The collaboration between upstream and downstream teams is promptly but one "batch" knowledge sharing is still dominant. Communication often happens when the downstream team are unsure of the time to finish if not starting early enough. However, the upstream team interchanges information at the end of their project which could lead to rework for the downstream team because their preparations are not customized by the upstream team's design resulting into process prolongation.

### **Early involvement mode**

In this mode, it is a process of two-sided stream of information. The structure of upstream and downstream team has a bilateral collaboration where they work closely and exchange data inputs. Despite this bilateral collaboration, the downstream team

still needs to wait for the upstream teams to finish its design. The bilateral collaboration is to enable changes needed in respective areas before implementation due to knowledge gained from the exchange of data.

### Integrated problem solving

The integrated problem-solving mode ensure that the exchange of information happens in the initial stages of the project. All levels of the teams are synchronized, and stakeholders involved have full access to information. The downstream are a vital part of the product development and their input are used by upstream team to design a product in an optimized way.

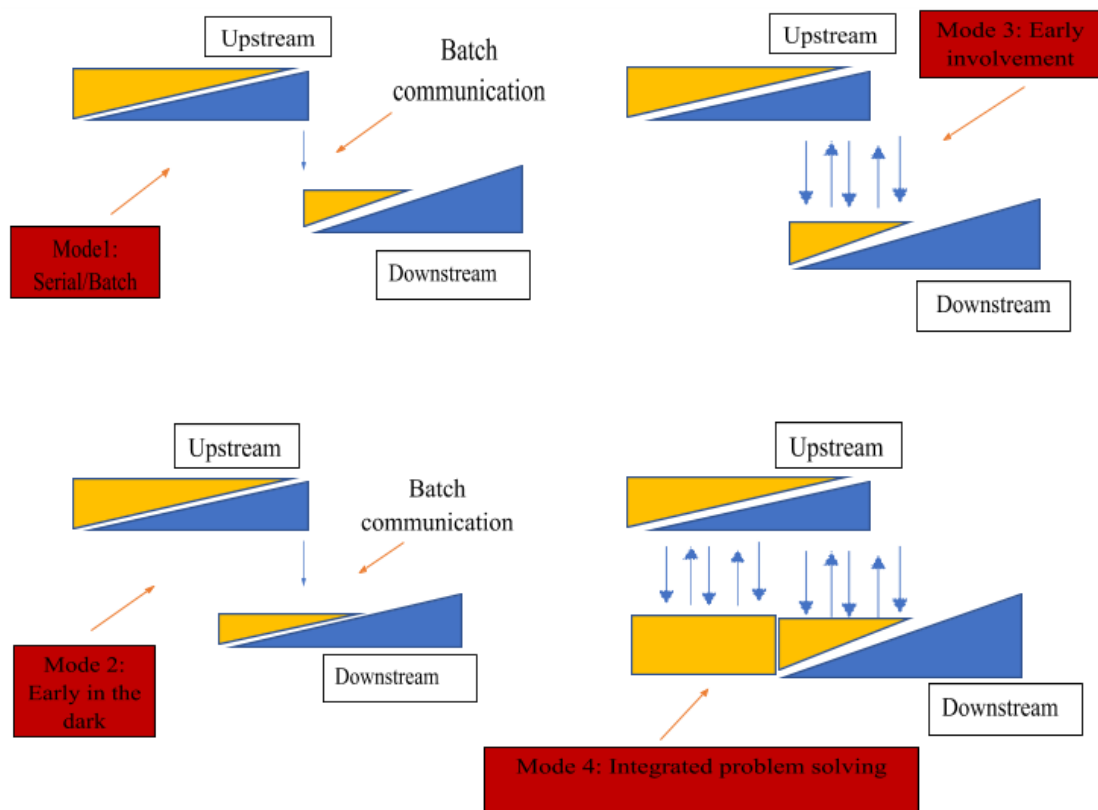


Figure 3 Stages of Product & Production System Development

### 2.7.1 Set-based Concurrent Engineering (SBCE)

The Set-Based Concurrent Engineering (SBCE) is a design process with a structure to keep multiple of different concepts viable. It is a design methodology used in many manufacturing or producing companies e.g Toyota. SBCE is based on three principles with framework for design implementation where product developers can work in parallel with parts of the project (Liker, 2009).

According to Dag Raudberget (2010), practical application of SBCE is based on three principles. These principles are:

- Principle 1 (Map the design space)

1. Determine profitable domain
  2. Examine comprise between stakeholders
  3. Disseminate variety of possibilities
- Principle 2 (Integrate by intersection)
    1. Observe for junction of profitable possibilities
    2. Establish minimal restraint
    3. Search for visionary robustness
  - Principle 3 (Establish feasibility before commitment)
    1. Minimize choice of possibilities successively while escalating product design
    2. Be in the accepted region of final product design
    3. Supervise by managing uncertainties at process gates

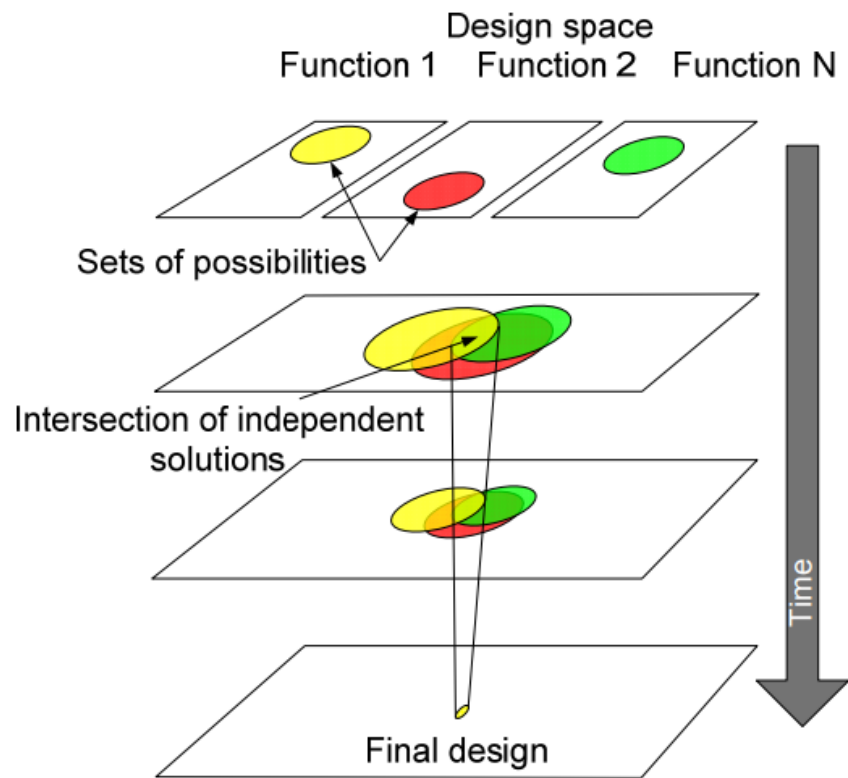


Figure 4 The principles of Set-based Concurrent Engineering (extracted from Bhushan & Mishra, 2016)

## 2.8 Model-based Product Development

Model-based product development demonstrates approaches of simulation and modelling as a tool for data gathering and broader understanding in shorter time. It is an agile way to adapt to customer needs and market changes (Panarotto et al, 2019). With this design approach, stakeholders have tendency to interact in the early stage of the project to allow transparent discussion. Moreso, modeling and simulation

increases the possibilities to cut down the iterations loops and stimulate learning (Wall, 2007).

Prior to model based-product development physical prototyping was the conventional way of data gathering. But this is no longer an applicable choice because of time and economical limitations. Artificial prototypes make it possible for product development companies to have multiple ongoing projects parallel by using small resources (Panarotto et al 2019) & (Wall, 2007). When final prototype has been decided, the total investment cost is generally not higher in comparison to producing a physical prototype. Hence, artificial prototype makes it possible to procure data in the concept development phase and make design adjustment while it is still economically feasible as described by NPD in *Figure 1*.

### **2.8.1 Criteria for the Model-based Product Development**

The input parameters used as a criterion for the model-based product development are reliability, maintenance, maintainability, ergonomics, material type and cost. According to “Swedish Standards Institute” (2017), these parameters are defined as;

#### **Reliability**

Reliability is defined as the ability of an item to perform a required function with a given time interval under a given condition.

#### **Maintenance**

The maintenance is the combination of all technical, managerial and administrative actions during an item life cycle intended to retain it in, or restore it to, in such a state that the item can perform the required function.

#### **Maintainability**

This is the ability of an item to be retained in, or restored to, under given conditions of use, after maintenance is performed using stated procedures and resources to perform a required function.

#### **Ergonomics**

Ergonomics is the collective word for adapting work for the labourer in order to prevent hazards caused by work environment. Ergonomics in its high degree depends on the planning and the conduct of an organized system.

#### **Material type**

Material is basically defined as the primary building element which a tangible product is made of.

#### **Cost**

Cost is the expenditure during a period, an expenditure reported during the period it is consumed. Also, it is the total value of consumed resources during a period.

## **2.9 Model-based Product design supports**

In product design, support system enables users to control and confirm the expected ability and production friendliness. Today, it is a general standard in industry to use virtual modeling (simulation) to be able to support the design project. However, the

virtual modeling is known as computer-aided engineering (CAE). The CAE as a supporting tool in its approach is divided into three generic phase which are pre-operation, simulation and post-operation.

A support system contains different elements that aids model-based engineering in every field of application and the most notably one is:

**Optimization:** The design structure is rearranged by an algorithm to optimize objectives and constraints.

**Kinematics and multibody dynamics:** Study of motion without considering environmental factors.

**Finite Element Method (FEM):** The FEM is used to solve partial differential equations approximately.

*(Simscale, 2020)*

## **2.10 Model-based Production systems design supports**

The concept of Toyota Production System (TPS) is one of the most established methods used in the manufacturing industries for supporting production system design. According to Ohno T. (1998), TPS is widely used in companies producing tangible goods as a result of its ability to cope with the market pressure under turbulent market conditions. Moreso, its framework is made up of process for producing marketable goods in production system both in of designing and organizing (Schweitzer & Aurich, 2012). Many European countries that are into manufacturing process applies TPS concept to suite their workplace in order to improve productivity (Herrmann et al., 2008). Maintenance technique is a support strategy used in production system to evaluates various subcomponents of manufacturing process mitigate unwanted disturbances such as equipment failure, stoppages, reduced speed and quality defects (Nakajima, 1998). According to Ylipää et al (2017), the substantial ripping effects in production system process due to machine blockage and idleness is a direct result of machine failure.

### **2.10.1 Modern Maintenance Methodology**

The definition of maintenance by the European Standard WI 319-003 is given as a combination of all technical, managerial and administrative actions during the lifecycle of a product. Many manufacturing companies are using predictive maintenance concepts i.e. preventive and proactive to eliminates failures (Ylipää et al, 2017). According to Mckinsey (2016), concept of predictive maintenance help to improve failure prediction and asset uptime. Also, Reliability Centered Maintenance (RCM) is a tool used for analyzing risk associated with the process of production system.

### **2.10.2 Automod Modelling Software**

A model is a representation of an events (Sokolowski & Banks, 2011); a way to solve problems in the real situation to enable optimization of a system prior to its implementation (Borshchev & Filippov, 2004). Automod is a modelling software designed for detailed analysis of operation and flow to simulate discrete event system

of manufacturing process. It is only the 3-D modelling software with discrete event simulation to construct any size of models, operations analysis and to control development and testing (Yilmaz et al., 2015).

#### **2.10.2.1 Discrete Event Simulation (DES)**

DES is a modelling system where events occur at discrete instances in time (Vagar A., 2005); simulation of systems that evolves through time (Matloff N., 2008); a process of modelling time dependent activities of a system in a real-world representation (Sung et al, 2005). DES is used for solving queueing-oriented service scheduling problems such as resources, distribution & selection of workload and system tasks (Malin et al, 1990). According to Pidd (2004), DES system's operation is represented as a chronological sequence of events where each event occurs at a point in time to mark a change of state in the system.

### **3 Chapter Three: Methodology Research**

*This chapter presents and described the framework approach of how the research questions will be answered. The research answer is based on the description of different method adopted for the data collection. The overview of the framework will enable the reader to understand the theoretical background behind the study and how the research is conducted.*

#### **3.1 Case study research**

A case study is a term which means that a research is done on a collection of individuals. A "case" can be express as an agent e.g person, people or an organization. In a case study, it is usually a collection of various kinds of data to be collected to provide a wider spectrum of the current case. (Patel & Davidson, 2011).

#### **3.2 Research Design Method**

The method of research design is to elaborate the need to establish cross communication network between product design stakeholders. Exchanging of product information is paramount between the product developer and production engineer to allow design specification integration at early stage. To strengthen the link, Automod simulation software is used to model the process of activities within these two areas. However, this project design method is based on the proposed framework in *Figure 5*.

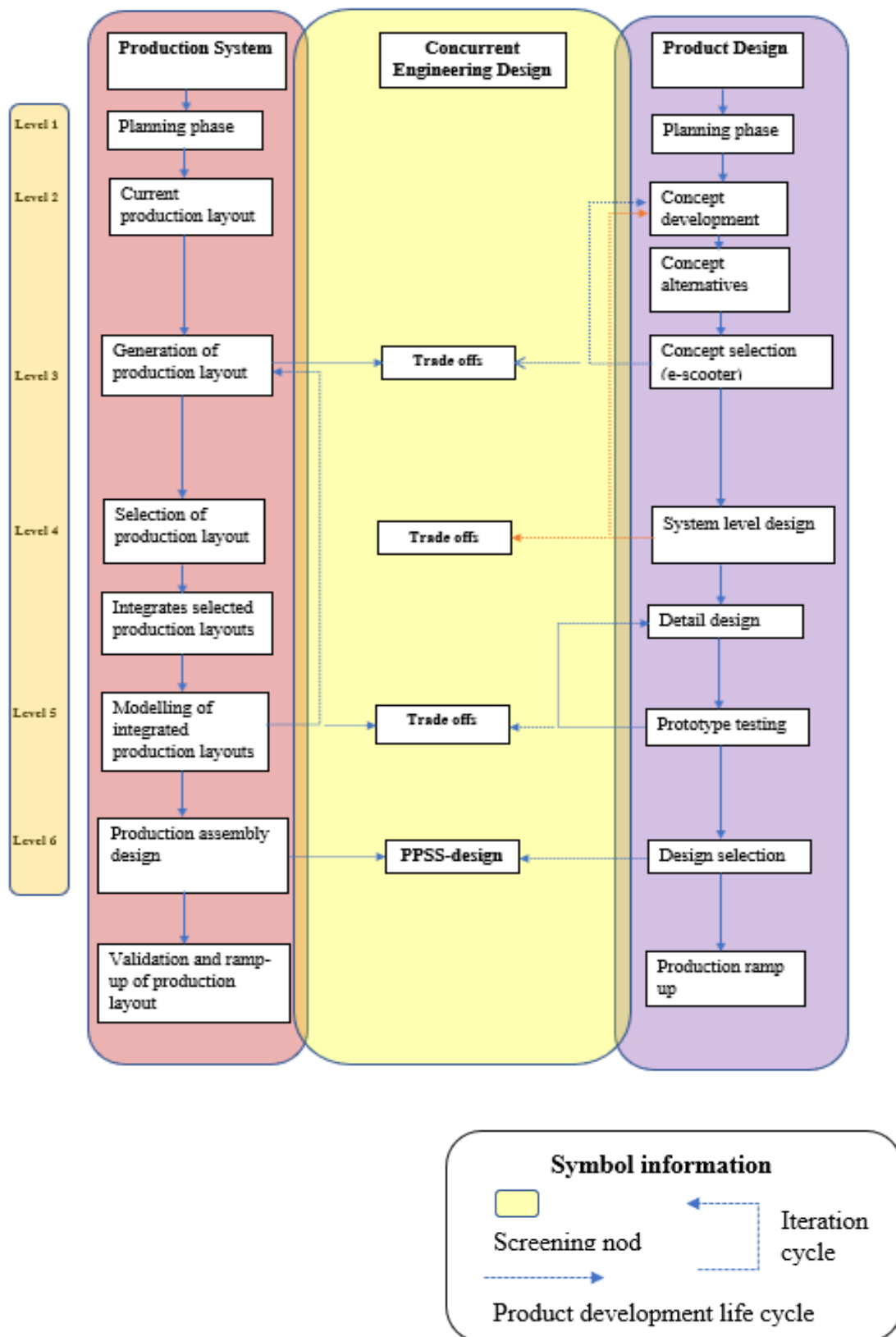


Figure 5 Design Chain Process

The flow of processes within the proposed framework between product design and production systems has three phases and each phase involves the activities of the stakeholder.

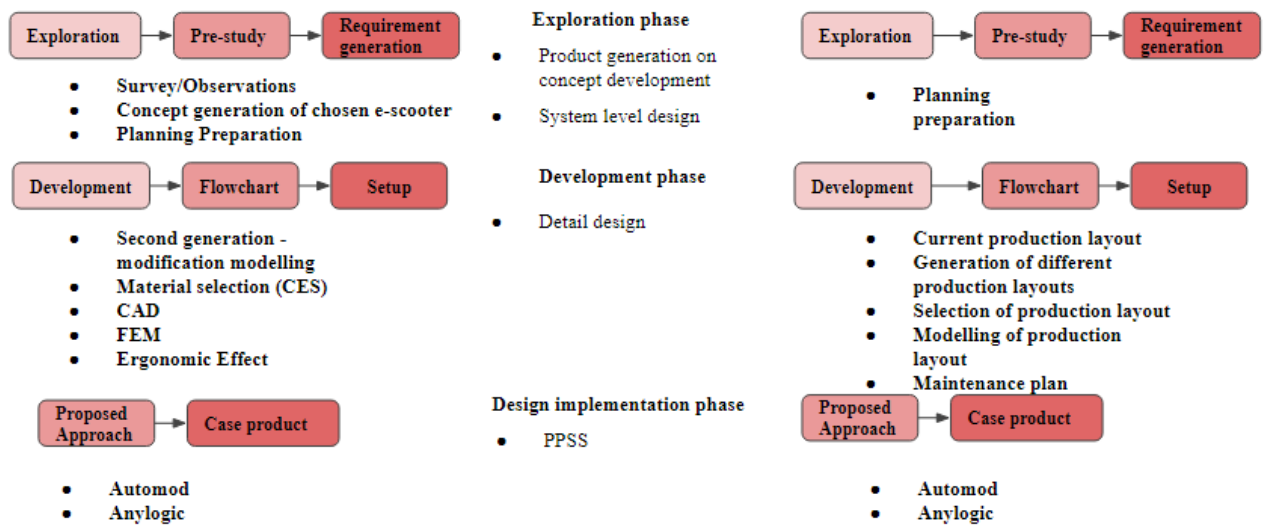


Figure 6 Flow process of product design and production systems integration

### 3.3 Product Development

The process of a product development comprises of six different stage activities. These activities define and interprets effectively the need of the customers starting with market possibilities to the sales production and product delivery at the end. The main task behind each of these stages is to responsively produce products that will meet up the demand of the end user.

#### 3.3.1 Hierarchy structure of Product development

The stages within hierarchical structure of product development is set of criteria required to streamline the possibilities in term values that the end user would probably prefer. According to Ulrich & Eppinger (2012), product development hierarchical structure is described as shown in *Table 1*:

Table 1 Description of product development process

No	Stages	Possibilities
1	Planning phase	Identification of opportunity that states the needs of the user. Defining the market segment for commodity, aims, core assumptions and limitations
2	Concept development	Establishment of product alternatives that guaranteed requirement specification with better improvement
3	System level design	Product segments disintegration and sub-structure of components
4	Detail design	Dimension and technical specification of product data. Covers essential areas of robust performance, material selection and production cost
5	Testing and refinement	Evaluation of prototype product to determine if the customer specifications is met
6	Implementation	Market introduction of the product and then be assessed based on economical, mechanical impacts to enable upgrading.

### 3.4 Production Systems Development

The word production and manufacturing in engineering practice are used interchangeably. However, the planning of an overall set of an element and the aggregation of the system events is the term production or manufacturing (Groover, 2011). In *Figure 7*, the activities of production system in a process of product realization is displayed.

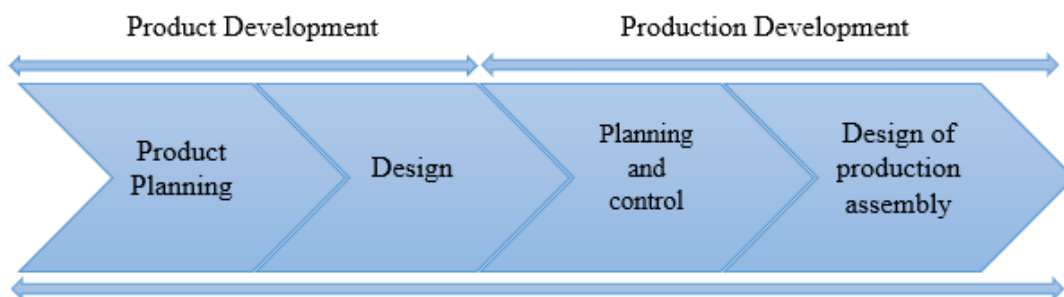


Figure 7 Product Realization Process (adapted from Bellgran & Säfsten, 2010)

#### 3.4.1 Methodology of Production Systems development

In the development of production systems, different activities are linked together and involves problems common to a variety of situations, regardless of the technology and process being used (Bennett D, 1985). The activities of both product design and

production systems are embedded in the development of product realization (Bellgran, 1998). In manufacturing context, the realization of a product depends on production volume and product variants; function of type of production flows and layouts (Bellgran & Säfsten, 2010). In production systems, product flows are classified into four processes as illustrated in *Figure 8*.

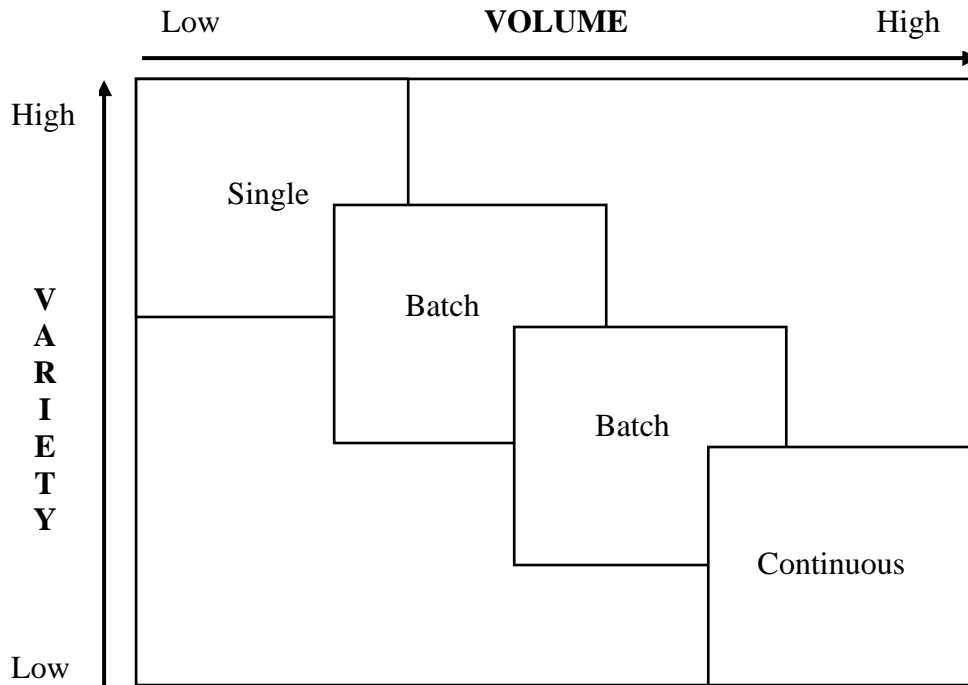


Figure 8 Types of production flow

Furthermore, production flow in discrete manufacturing context influences the choice of production layout. Tompkins (1996), suggested that it is imperative for a production layout to supports the visions of an organization. The reason is that each production flow is best suited one or more layouts. Four common types of layout are fixed position, cellular, process oriented and product oriented.

Table 2 Description of production layout types

No	Production layout	Production flow	Descriptions
1	Fixed position	Single	Addresses and deals with the requirements of large bulky projects e.g aircraft
2	Job shop	Batch	Deals with low-volume and high-variety production. Sometime called process-oriented e.g ship building
3	Work cell oriented	Batch	Arrangement of machinery that focus on production group of related products or of a single product e.g electronics
4	Product oriented	Continuous	Utilization of machine in a repetitive or continuous production e.g automobile

### 3.5 Process of data screening methodology

In the very beginning of a product development project, a lot of different ideas are generated and developed which makes the process more difficult to handle due to the numerous options. In order to predict a failure or success of any idea, development funnel is used to screen the process as the screening method. The ideas are screened through three phases within the development funnel to determine the best concept. An illustration of development funnel screening process is given in *Figure 8*.

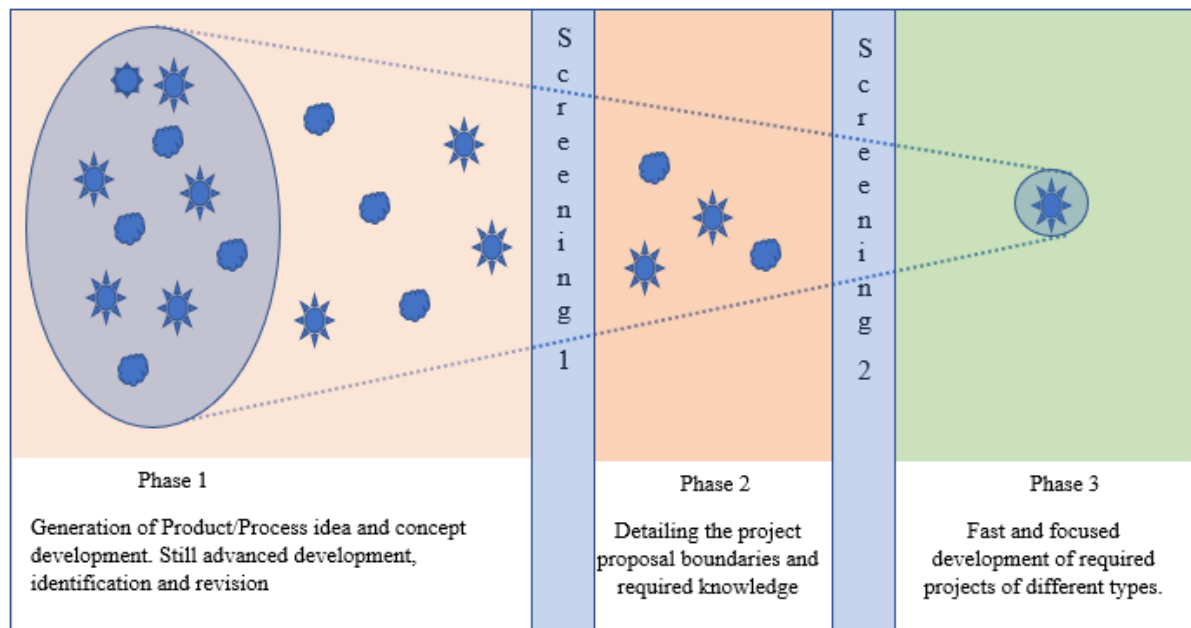


Figure 9 Development funnel screening process (Wheelwright, 1992)

For the case study research, the development funnel methodology is used to evaluate the various land transport modes. The micro-mobility modes of land transportation screened are:

- Bicycle
- E-bicycle
- Scooter
- E-scooter
- Mini car
- E-mini car

The set of land transport modes are chosen due to their level of usability and sustainability. In addition, they have a higher degree of accessibility and environmentally friendliness. These attributes of the selected modes required the user's opinions to be able to predict the market demand and customer expectations.

#### 3.5.1 Survey & Observation process (Questionnaire)

The questions are written in such a way to deduce user's comprehensive views as well as what we as product developer and production engineer perceived to be good in design perspective. The intention behind this act is to capture the "voice of the user"

and to narrow down the factors that are more essential to the users. The questionnaire was done in the city of Gothenburg, same city as for the case study. There are twelve number of questions covering the basic need for the users. The number of participants were 30 people, 18 males and 12 females between the ages of 16 – 45.

## 4 Results

This chapter describes the result of the model-based product development criteria used during the integration of design chain process in selecting the optimal land transport mode.

### 4.1 Product Generation on Concept Development

In this section, customer needs are identified and conducted different screening methods to find the best solution in relation to user specifications.

#### 4.1.1 First screening generation – Customer needs specification

The requirement specifications are focused on the highlighted modes above which is the background for the survey & observation conducted with literature-study to derive the needs. These needs are categorized into wish or demand which forms the questionnaire (see Appendix A).

The specification list is based on the client, the manufacturer, designer and the end users demand. 19 requirements are established. These are derived from current product development knowledge

1. User friendliness
2. Power/capacity
3. Accessibility
4. Comfortable
5. Maneuverability
6. Attractiveness
7. Safety
8. Mobility
9. Environmental effect
10. Cost
11. Size
12. Speed
13. Adjustability
14. Maintainability
15. Weight
16. Material
17. Reliability
18. Standardized material
19. Power efficiency

The demand stands for the needs which the customer really wants to be fulfilled and wish stands for the needs that should be fulfilled in the best possible way. These needs are ranked from 1 to 5, where 5 is of the highest importance.

#### 4.1.2 Survey and Observation

**Assumption:** The user wants to have a transportation mode with easy manoeuvrability, attractiveness and speed.

From the 19 requirements, the first 13 specifications are chosen as the primary input to conduct the survey because they are end user oriented.

The result in *Figure 10* shows that two out of the thirteen questions are more important to the average-user as a function of demand derived from the needs. The two parameters with the highest scores are accessibility (D) and maneuverability (H). However, other important parameters are user friendliness (B), safety (F), comfort (C), ergonomics (L) and high mobility (I).

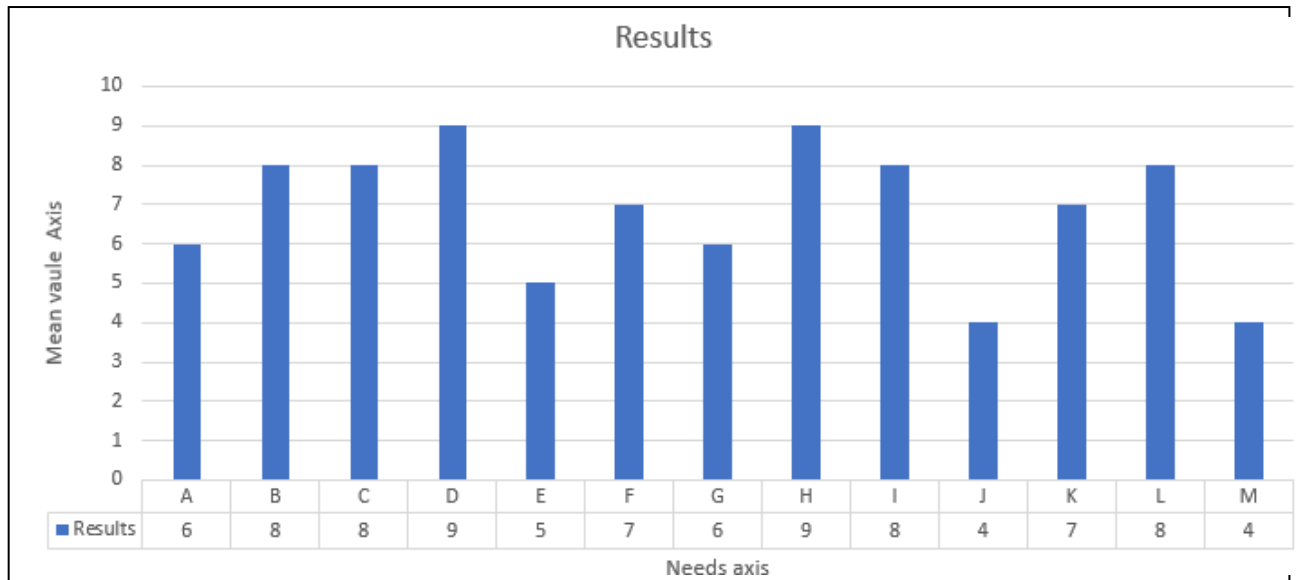


Figure 10 Customer Priority Needs

#### 4.1.2.1 Description of categories

The specification requirements that formed the derived needs is divided into four categories namely production, availability, process and footprint.

Table 3 Description of categories

<b>Production</b>	The aspect of decision making for the entire production process. Adam & Ebert (1978), pointed out that all inputs for production of a product ought to be produced with minimum cost regarding the demand planning and specification requirement.
<b>Availability</b>	Guarantee that a product will be available when needed do triggers the customer or user involvement. Product availability has always been considered to enhance levels of involvement that further prompt intention for the product purchase (Nakajima, 1998).
<b>Process</b>	According to "ISO 9001" (2015), a process is a set of interrelated or interacting activities that use inputs to deliver an intended result. It is a structured system with recurring linked activities that is executed by an organization to fulfill customer needs.
<b>Footprint</b>	An ecological footprint is a tool for measuring sustainable development as a result of amount of resources consumed by human. A multi-criteria measure of the environmental performance of a product or services of an organisation ("JRC European commission", 2011).

### 4.1.3 Selection process of the transportation mode

All the six micro-mobility modes of land transportation are evaluated through benchmarking process with literature studies and live observations of current market stakeholders as shown in *Table 4*.

Table 4 Customer Specification Requirements

Needs	Bicycle	E-bicycle	Mini car	E-mini car	Scooter	E-scooter	Stakeholder	Category	source
User friendly	3	4	1	2	4	5	User	Availability	S/O
Power/capacity	3	4	5	5	2	4	Manufacturing	Production	Lit.
Accessibility	2	2	1	1	5	5	User	Availability	S/O
Comfortability	3	4	5	5	2	2	User	Design	S/O
Safety	2	2	5	5	3	3	Customer	Production	S/O
cost	4	3	2	1	5	4	Customer	Production	Survey
Mobility	3	3	2	2	5	5	User	Production	S/O
Ergonomic	3	3	5	5	2	2	User	Design	S/O
Speed	2	3	5	4	1	3	User	Production	S/O
Pollution	5	4	1	2	5	4	Customer	Design	Survey
Standardized part	4	3	2	1	4	3	Customer	Design	Lit.
Power efficiency	2	3	4	5	1	4	Customer	Footprint	Lit.
Attractiveness	2	3	4	4	5	5	Customer/user	Design	S/O
Maneuverability	3	3	5	5	1	3	Manufacturing	Production	S/O
Maintenance	3	2	1	1	5	4	Manufacturing	Production	Lit.
Weight	5	3	1	1	4	3	Customer	Production	Lit.
Material	5	4	1	1	5	4	Manufacturing	Production	Lit.
Size	3	3	1	1	5	5	User	Design	S/O
Reliability	5	4	3	3	5	4	Customer	Production	Lit.
Throughput	4	3	2	1	5	4	Manufacturing	Production	Lit.
<b>Sum</b>	<b>66</b>	<b>63</b>	<b>56</b>	<b>55</b>	<b>75</b>	<b>75</b>			

The summation of needs for each of the design is expressed graphically as shown in *Figure 11*.

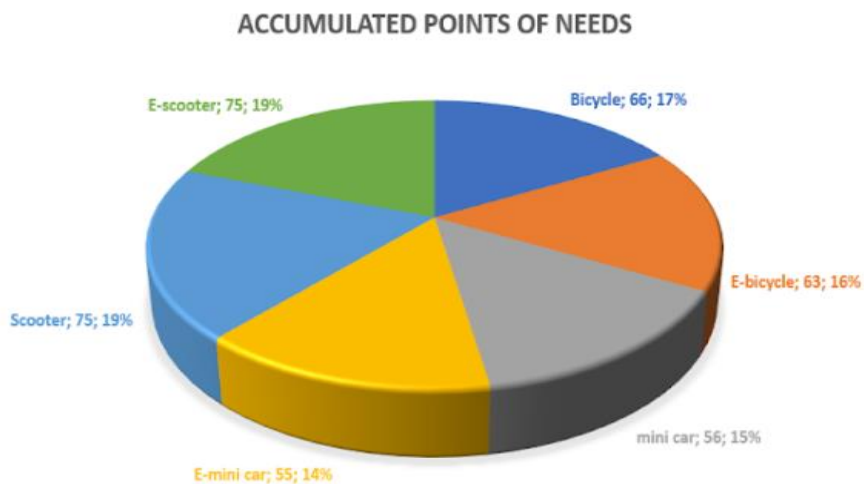


Figure 11 Design Accumulated Points

The result of the survey in *Table 4* is ranked based on the perspective of the customer who are the end users. The accumulated point for each of the micro-mobility shows which mode of land transportation the customers most prefer. Two of these types of micro-mobility has highest shared points which are scooter and electric scooter. This indicates that the scooter and electric scooter transportation mode is the customers wishes. However, the customer survey has already showed that user’s friendliness is one of the major customer demands. Thus, the tipping point to choose the electric scooter becomes the final choice due to its higher user’s friendliness ranking.

## 4.2 System Level Design

The design of system level focus on the numbers of design alternatives for the electric scooter. Main product designs are described with sub-structures and combinations.

### 4.2.1 Concept generation of the chosen E-scooter

After the selection of the E-scooter, multiple design types are developed to meet the customer’s demands and wishes.

The three design types are:

1. Sitting E-scooter: This type of E-scooter is not as common as the Standing design. Its design components consist of deck, handlebar, pole bar and seat pole.
2. Standing E-scooter: The Standing E-scooter is the most common type of electric scooter used in the society today with design components such as deck, handlebar and pole bar.
3. Skate E-scooter: The deck is only the design component for the Skate E-scooter.

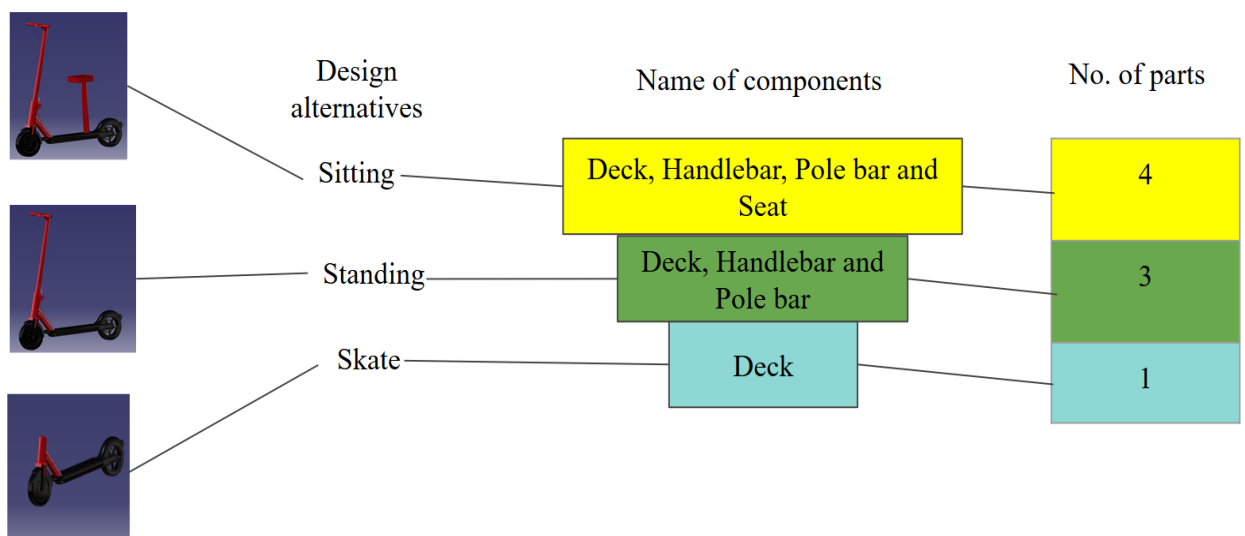


Figure 12 System level design of alternative types

### 4.3 Detail Design

This section describes the different dimensions used for the E-scooter's variance with consideration of using different materials. Data for different loads on the E-scooter designs are also depicted using the CES and Catia as the modelling software.

#### 4.3.1 Second screening generation – Frame modification

There are two geometric variants for each part of the developed E-scooter concepts. This is to compare and assess which geometric design will best suit the operating circumstances.

Table 5 Components Technical Specification

Frame parts	Original geometry (mm)	Modified geometry (mm)
Deck	1000x400x100, 10 th.	950x300x150, 11.11 th.
Handlebar	25 rad., 400 H, 10 th.	20 rad., 410 H, 11,2 th.
Pole bar	50 rad., 870 H, 13,5 th.	65 rad., 550 H, 15 th.
Seat pole	50 rad., 600 H, 15 th.	65 rad., 700 H, 13,5 th.

#### 4.3.2 Material selection

A software program called Cambridge Engineering Selector (CES) EduPack is used for the material screening process. It is a digital material library that works as a tool for screening best suited materials in relation to the design demands. The screening of materials with CES has three levels. The levels are:

1. To convert design demands as priorities and minimal acceptable limits within the requirement frame
2. Screen the material universe and eliminate those who do not fulfill the design requirements
3. Hierarchical classing of the optimal material in relation to the design

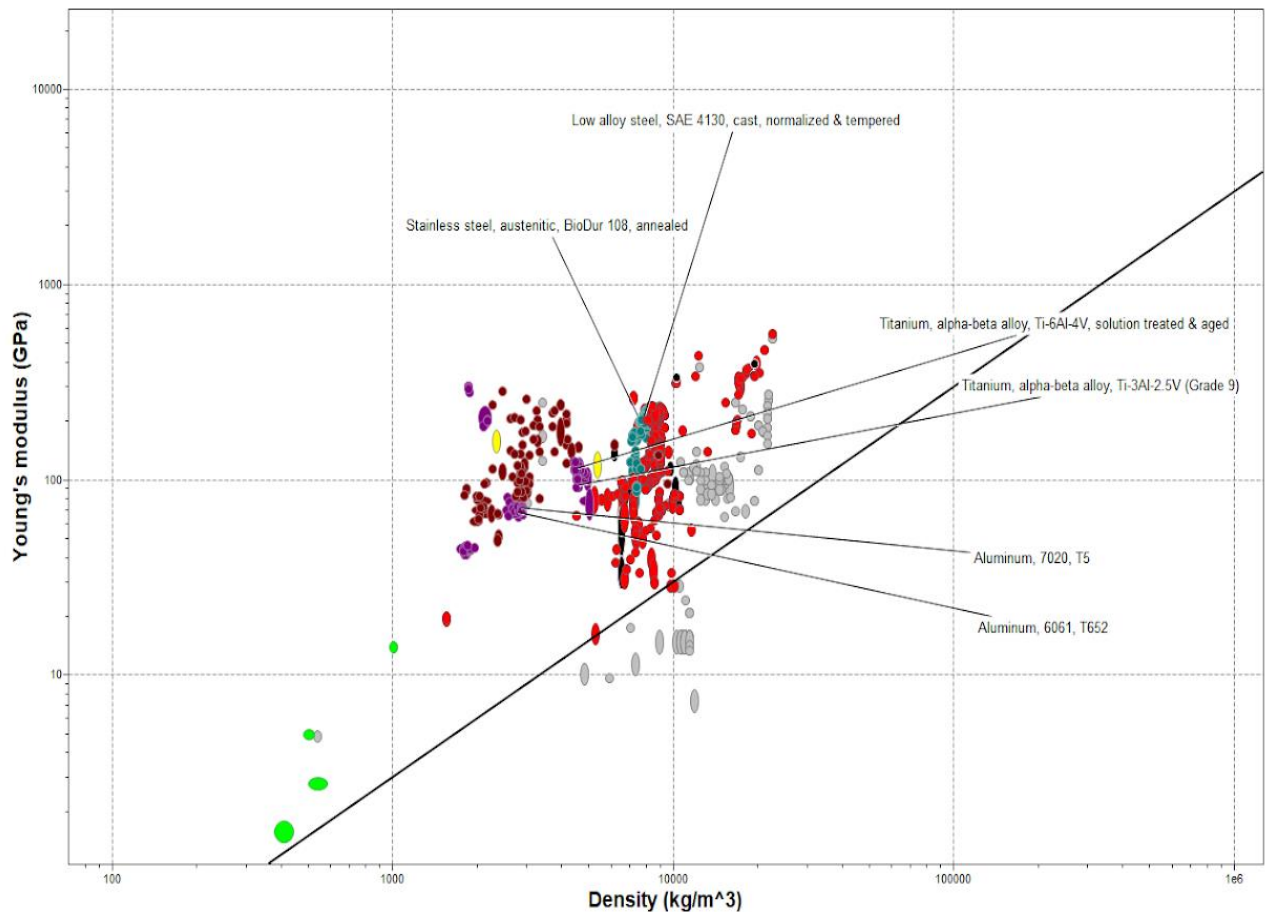


Figure 13 Materials Bubble Chart

The material family that suite best for the transportation mode selected are metals. This is due to the product usage and environmental situations. Metals has the most optimal all-round mechanical properties for the situations that can occur. They are hard, high fatigue strength, ductile and have great moldability.

However, this metal groups are plotted by using a material property chart. The density and young modulus are the significant properties considered in the chart above. Density is used since the customer survey stated the weight of the product is important. Another important factor is the durability of the transportation mode. Young's modulus used as a measurement of different metals maximum capability of stress and deformation due to the influence of forces.

From *Figure 11*, the screening results of the metal universe in relation to the requirements inputs is illustrated. Six metal types are chosen due to project demand of variation of materials and compatibleness to the design demands:

- Aluminium 6061 T652
- Aluminium 7020.T5
- Titanium alpha beta alloy Ti-6AL-4V solution treated aged
- Titanium alpha beta alloy Ti-3Al-2.5V grade 9
- Stainless steel austenitic, biodur 108, annealed
- Low alloy steel SAE 4130 cast normalized

Table 6 Selection of material types (extracted from CES, Edupack)

Metal type	Aluminium 2.7 kg/dm <sup>3</sup> t: 20 c	Aluminium 2.7 kg/dm <sup>3</sup> t: 20 c	Titanium 4.5 kg/dm <sup>3</sup> t: 20 c	Titanium 4.5 kg/dm <sup>3</sup> t: 20 c	Stainless steel 7.9 kg/dm <sup>3</sup> t: 20 c	Stainless steel 7.9 kg/dm <sup>3</sup> t: 20 c
Specific type	Aluminium 6061 T652	Aluminium 7020.T5	Titanium alpha beta alloy Ti- 6AL-4V solution treated aged	Titanium alpha beta alloy Ti- 3Al-2.5V grade 9	Stainless steel austenitic, biodur 108, annealed	Low alloy steel SAE 4130 cast normalized
Young modulus	66,6 - 70 GPa	70 - 74 GPa	110 - 117 GPa	91 - 95 GPa	198 - 202 GPa	198 - 206 GPa
Strain	10 - 14,4 %	13 - 15,1 %	10 - 12 %	15 - 20 %	51,5 - 52,5 %	17,8 - 19,7 %
Cost	19,6 - 22,8 SEK/kg	38,4 - 45,1 SEK/kg	176 - 210 SEK/kg	178 - 208 SEK/Kg	19,1 - 20,3 SEK/Kg	8,12 - 8,38 SEK/Kg
Specific strength	88,8 - 104 KN.m/kg	107 - 119 KN.m/kg	187 - 241 KN.m/kg	108 - 138 KN.m/kg	75,6 - 77,8 KN.m/kg	60,7 - 67,1 KN.m/kg

### 4.3.3 CAD Product

Computer aided design (CAD) is a tool for simulating a physical phenomenon (Narayan, K. Lalit, 2008). The CAD virtual tools help to better understand how the behaviour of the designed product will look like and if it will fulfil the design requirements. To increase the enhancement of product selection, CAD enables simulation on the electric scooters, frame alternatives and materials selected according to the specification in *Table 7*.

Table 7 Design variants

Model concept	3
Material type	3
Geometry	2
Total design	$3*3*2 = 18$

Furthermore, the 18 design variants of the E-scooter as shown in *Table 7* are simulated using the CAD program called Catia software.

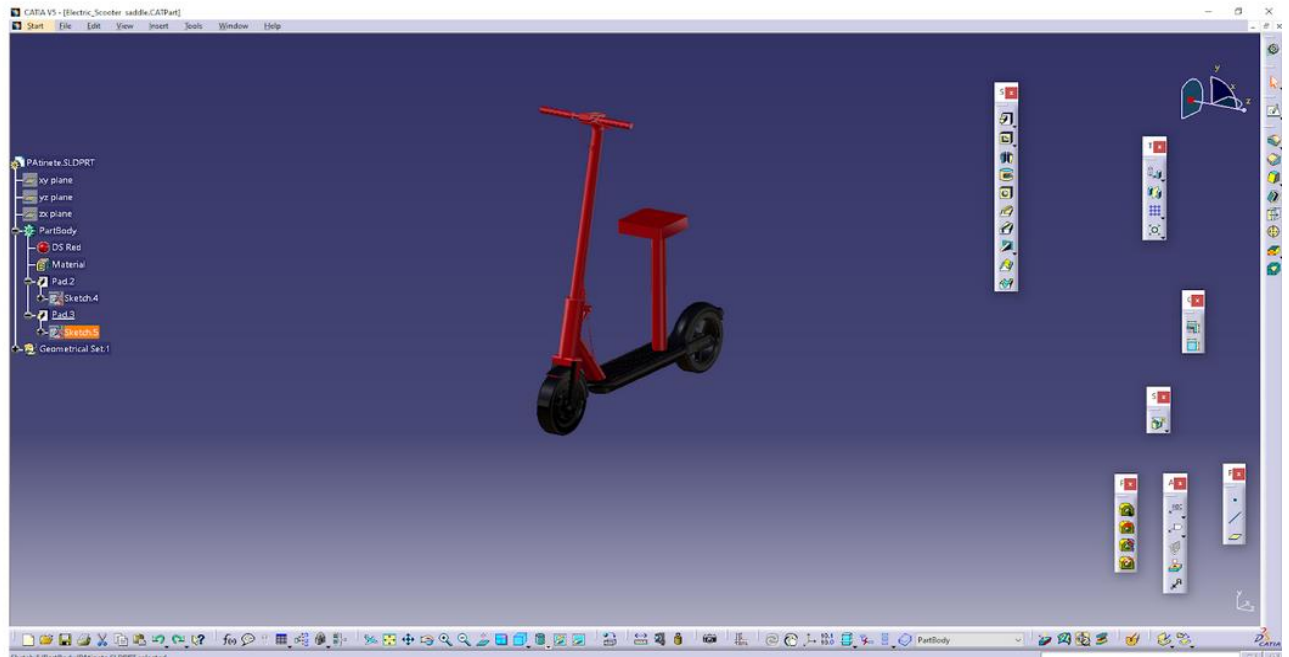


Figure 14 E-scooter product prototype

#### 4.3.4 Finite Element Method (FEM)

The FEM is used to show the stress analysis and determine the acceptable strength for each part of the different design variants after modelling the E-scooter product. According to Daryl L. Logan, 2011, acceptable strength limit of a constructed design part can be calculated and retrieved with FEM.

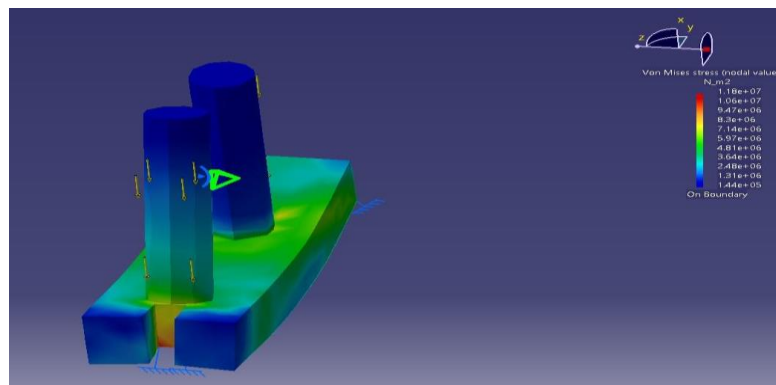


Figure 135 FE analysis of product prototype

The FEM stress analysis was done in order to evaluate the part variations. This is to understand and measure how the structural part design will behave when a load effect is been applied. The purpose of this objective is to gain knowledge on which part with the combined parameters will result in the most optimal solution among the 18 design variants. The forces applied on the deck, handlebar, pole bar and seat pole are given in *Table 8*.

Table 8 Applied Load

Direction and force	X	Y	Z
Deck/Seat pole	0 Kn	0 Kn	-90 Kn
Handlebar	-25 kn	35 Kn	-35 Kn
Pole	-25 kn	35 Kn	-35 Kn

The FEM analysis results after the design parts has been subjected to structural load is presented in *Table 9*. The parts with the highest-ranking stress is denoted by star while O and M stands for Original and Modified geometry respectively.

Table 9 Part strength limits

<b>Models (Von mises stress, Unit: Pa)</b>												
Material	Sitting/Standing						Skate					
	Aluminium		Stainless steel		Titanium		Aluminium		Stainless steel		Titanium	
Parts	O	M	O	M	O	M	O	M	O	M	O	M
Handlebar	9,51e7	2,12e8	1,28e8	2,34e8*	9,59e7	2,14e8	-	-	-	-	-	-
Pole bar	8,02e8	3,74e8	1,67e9*	4,06e8	8,05e8	3,77e8	-	-	-	-	-	-
Deck	4,25e7	2,97e7	4,35e7*	3,03e7	4,26e7	2,97e7	1,3e7	1,17e7	1,33e7	1,29e7	1,3e7	1,18e7
	313,2e6	205,2e6										

*Table 9* result shows that Stainless steel material is the best material option that can withstand the different applied forces more than the other material types. Stainless steel as a metal family has the highest strength limit on all design parts and dimensional variation.

#### 4.3.5 Weight of the design parts

One of the most important parameters regarding the design of the E-scooter product is “Lightness”. There is a direct correlation between the weight of the transportation mode and its fuel consumption. The heavier the parts, the more fuel consumed. The operating performance of a transportation mode could be increase provided that its weight is relatively low. Weight influences the mechanical ability of a product because the acceleration and the negative forces are proportional thereby impacting the operation of the transport mode. The specification for each part weights in presented in *Table 10*.

Table 10 Specifications of part weights

Parts	Outer Volume (mm <sup>3</sup> )	Inner volume (mm <sup>3</sup> )	$\Delta$ Volume (mm <sup>3</sup> ) (dm <sup>3</sup> )	Area (mm <sup>2</sup> )	Dimension (mm)	Aluminium Mass (kg) Density 2.7 kg/dm <sup>3</sup> t:20 c	Titanium Mass (kg) Density 4.506 kg/dm <sup>3</sup> t:20 c	Stainless steel Mass (kg) Density 7.9 kg/dm <sup>3</sup> t:20 c
O. Handlebar	785000	659400	125 600 (0.1256)	1962.5	25 rad., 400 H th:10	0.3391 *	0.5659	0.9922
M. Handlebar	514960	353460	161500 (0.1615)	1256	20 rad., 410 H, th:11,2	0.436	0.7277	1.2758
O. Pole bar	6 829 500	6 331 500	498000 (0.498)	7850	50 rad., 870 H, th:13,5	1.344	2.243	3.934
M. Pole bar	7296575	6 908 575	388000 (0.388)	13266	65 rad., 550 H, th:15	1.049 *	1.748	3.0652
O. Deck	40000000	39 000 000	1000000 (1)	40*10 <sup>6</sup>	1000x400x100 th:10	2,7 *	4.506	7.9
M. Deck	42750000	41 650 000	1 111 111 (1.11)	42.75*10 <sup>6</sup>	950x300x150 th:11.11	3	5.00166	8.769
O. Seat pole	4710000	4 285 900	424100 (0.4241)	7850	50 rad., 600 H, th:15	1,145	1.91	3.35
M. Seat pole	9286550	8 886 550	400000 (0.4)	13266	65 rad., 700 H, th: 13,5	1.082 *	1.802	3.16
Weight of O. Standing	-	-	-	-	-	4,326	7,2549	12,8262
Weight of M. Standing	-	-	-	-	-	4,485	7,45936	13,11
Weight of O. Skate	-	-	-	-	-	-	-	-
Weight of M. Skate	-	-	-	-	-	-	-	-
Total weight of O. Model	-	-	-	-	-	5,4976	9.2249	16.1762
Total weight of M. Model	-	-	-	-	-	5,567	9.27936	16.27

The *Table 10* illustrates the different parts and its respective weights. There is a correlation between the weight and the density. The parts with metals that has dense density will also result in higher weight. Therefore, the lightness is the focus since the demand is to design a light E-scooter and each part with lighter weight is marked in red colour.

## 4.4 Risk of Musculoskeletal Disorders

The musculoskeletal disorders (MSD) is related to the design of product in term of its ergonomic effect in which a body is subjected to during work task.

### 4.4.1 Third screening generation: Ergonomics effect

The last screening process focuses on the ergonomic part of the product where the design product is investigated based on how it will affect the body posture.

#### 4.4.2 Sitting E-scooter design

**Assumptions:** The Sitting E-scooter from an ergonomic point of view should have the least score since the human body is subjected to less strain. The arm, wrist and leg are the most affected body posture that deviates.

**Result from employee assessment worksheet (See appendix G):**

Table 11 Sitting MSD risk

Reba Employee assessment worksheet			
Section A: Neck, Trunk and leg analysis.			
Design: Sitting e-scooter			
Location:	Points		
Step 1: Locate neck position	1		
Neck score			
Step 2: Locate trunk position	1		
Step 3: Legs	3		
Step 4: Look-up posture score in table A	3		
Step 5: Add Force/Load score	0		
Step 6: Score A, Find row in Table C	3		
Section B: Arm and wrist Analysis			
Step 7: Locate upper arm position	1		
Step 8: Locate Lower arm Position	2		
Step 9: Locate wrist Position	1		
Step 10: Look-up posture score in Table B	2		
Step 11: Add coupling Score	0		
Step 12: Score B, Find column in table C	2		
Step 13: Activity Score	1		
Step 14: Table C score	3		
Step 15: Reba score	4		

#### 4.4.3 Standing E-scooter design

**Assumptions:** The Standing E-scooter is believed to give a posture value that is between the Standing and Skate-model. The best posture point will be received from the leg and neck analysis. This is because the leg and the neck do not deviate as much from normal posture. The arm, trunk and wrist are the body postures that deviates often. This is because the rider needs to grip the handlebar in order to gain stability on the motion and leads to a negative impact on normal body posture.

**Result from employee assessment worksheet (See appendix G):**

Table 12 Standing MSD risk

Reba Employee assessment worksheet			
Section A: Neck, Trunk and leg analysis.			
Design: Standing e-scooter			
Location:	Points		
Step 1: Locate neck position Neck score	1		
Step 2: Locate trunkposition	2		
Step 3: Legs	2		
Step 4: Look-up posture score in table A	3		
Step 5: Add Force/Load score	0		
Step 6: Score A, Find row in Table C	3		
Section B: Arm and wrist Analysis			
Step 7: Locate upper arm position	2		
Step 8: Locate Lower arm Position	1		
Step 9: Locate wrist Position	3		
Step 10: Look-up posture score in Table B	3		
Step 11: Add coupling Score	0		
Step 12: Score B, Find column in table C	3		
Step 13: Activity Score	1		
Step 14: Table C score	3		
Step 15: Reba score	4		

#### 4.4.4 Skate E-scooter design

**Assumptions:** This design concept has the highest MSD risk. This means that it would put a negative complication for the user in the region of posture stance and equilibrium of total load. The largest deviation regarding the E-scooter should be the trunk, leg and neck position in term of the body posture.

**Result from employee assessment worksheet (See appendix G):**

Table 13 Skate MSD risk

Reba Employee assessment worksheet			
Section A: Neck, Trunk and leg analysis.			
Design: Skate e-scooter			
Location:	Points		
Step 1: Locate neck position Neck score	1		
Step 2: Locate trunkposition	4		
Step 3: Legs	4		
Step 4: Look-up posture score in table A	7		
Step 5: Add Force/Load score	1		
Step 6: Score A, Find row in Table C	8		
Section B: Arm and wrist Analysis			
Step 7: Locate upper arm position	2		
Step 8: Locate Lower arm Position	1		
Step 9: Locate wrist Position	1		
Step 10: Look-up posture score in Table B	1		
Step 11: Add coupling Score	3		
Step 12: Score B, Find column in table C	4		
Step 13: Activity Score	1		
Step 14: Table C score	9		
Step 15: Reba score	10		

#### 4.4.5 Results summary

The MSD points collected shows the “Skate E-scooter” has the highest risk level among the other product designs. In summary, design that falls in red region of the MSD table means that immediate changes need to be implemented. In the case of the Skate E-scooter product design, re-design is required. Moreover, further investigations are also suggested for the Sitting and Standing E-scooter product design since they have the same accumulated point closely to the MSD high risk boundary. Thus, the accumulated points for each of the three-product designs in terms of physical ergonomic are presented in *Table 14*.

Table 14 Summary on the MSD risk level

Design concepts	MSD points	Risk level	Actions
Sitting E-scooter	4	Medium	Further investigation
Standing E-scooter	4	Medium	Further investigation
Skate E-scooter	10	High	Investigate and implement change

### 4.5 Production Systems Development

Development of a production system is a significant process for improving the level of output, efficiency and quality products (Bennett D., 1986). For the case of E-scooter production, several activities or processes are lined up for the delivery of the different varieties through respective layout design. Assumptions made during the process of production system design are:

#### 4.5.1 Description of manufacturing processes

##### Production hours

The production line is available for manufacturing 320 E-scooters of different variants, 40 hours per week (Monday to Friday) for 52 weeks. The significant stations in the assembly line are casting, cutting, welding, painting, drying and sticker respectively.

##### Handling of materials

The material handling within the factory are managed with equipment in loading and unloading the materials from the different stations.

##### Casting

The casting stations is the first activity in the production system process. The materials used are molded into two shapes e.g cylindrical and trapezium shape.

##### Cutting

The cutting stations is the next activity in the assembly line placed with two cutting machines. This station is where the casted materials are cut into different lengths and

accurate sizes. Here, the changing of the cutting tool like the saw blade is part of maintenance work as a preventive measure.

### **Buffer**

Buffers allows smooth running operation to stabilize fluctuations. It helps to keep different parts or assembled parts in queue when the next machine is in working condition.

### **Welding**

The welding stations with two arc robotic machines are used to weld the parts into a complete frame. The servicing of the two robots are outsourced to the service vendor.

### **Heat treatment, quality control and alteration**

After the three significant processes, the welded frames will pass through the first heat treatment. Upon been heat treated, then quality inspector controls the frames. Frames with defects that are unapproved will have to undergo rework before going through the second heat treatment. Moreover, approved frames proceed directly to the second heat treatment process. These actions are for quality reason to ensure that the frames are produced satisfactory.

### **Painting**

A completed frame is painted individually with painting robots at each of the painting stations. Frames are taken directly from buffer 4 pass to first painting station and allow to be dried in drying station before the second painting station.

### **Drying**

The drying stations are operated with conveyor where the painted frames are moving in the drying house to be dried up. These stations can accommodate two painted frames at a time with order first in-first out.

### **Assembling**

The assembling station is where the seat is assembled to the saddle support.

### **Stickers**

The stickers is the final station where each of the completed frame are labelled or trade mark

### **Final product**

The finished E-scooter to be transported.

## **4.5.2 Current production systems layout**

A well-designed facilities layout contributes to the overall efficiency of the manufacturing operation and reduces the total operating expenses significantly (Tompkins et al 1996). The production layout that suite the design of the three E-

scooter would either be product-oriented or work-cell layout. This is because the E-scooter design manufacturing process involves arrangement of machines in line assembly.

### 4.5.3 First generation screening: Production Systems Layout (PSL)

Since a tangible product is the focus and its process is a continuous production flow because of low variety and high volume. Thus, the product-oriented layout is chosen to be the preferred layout. A product-oriented layout is a layout based on arrangement of machine and equipment utilization in a repetitive or continuous production process. However, production systems layout designed for each of the E-scooter product design based on their number of parts are shown in *Figure 14, 15 & 16* respectively.

#### 4.5.3.1 PSL for Sitting E-scooter model

The designed layout for the Sitting E-scooter with parts consisting the deck, handlebar, pole bar and seat pole.

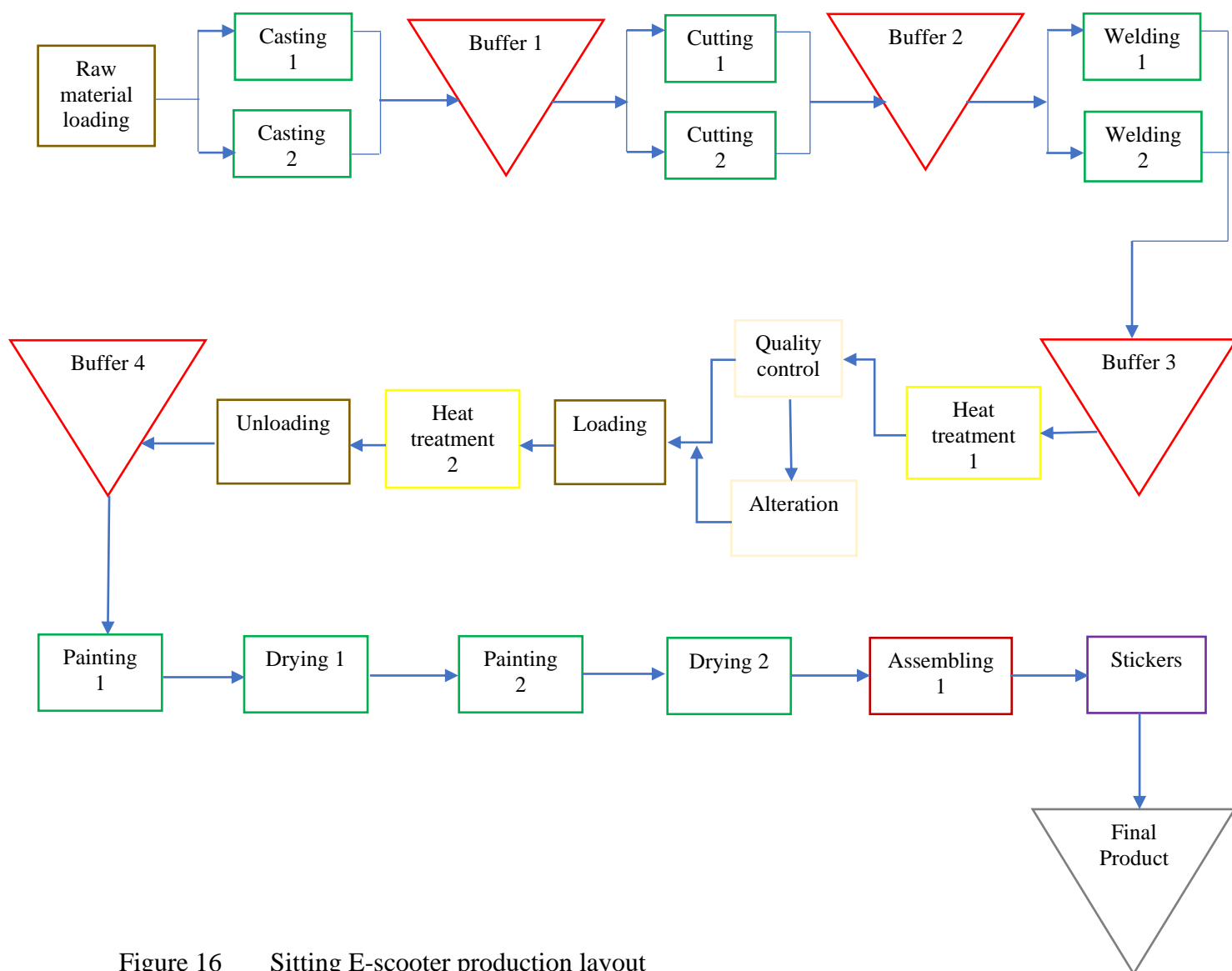


Figure 16 Sitting E-scooter production layout

### 4.5.3.2 PSL for Standing E-scooter model

For the Standing E-scooter design, its production systems layout looks like that of the Sitting layout design but without the assembling station where the seat is mounted in the case of Sitting E-scooter design.

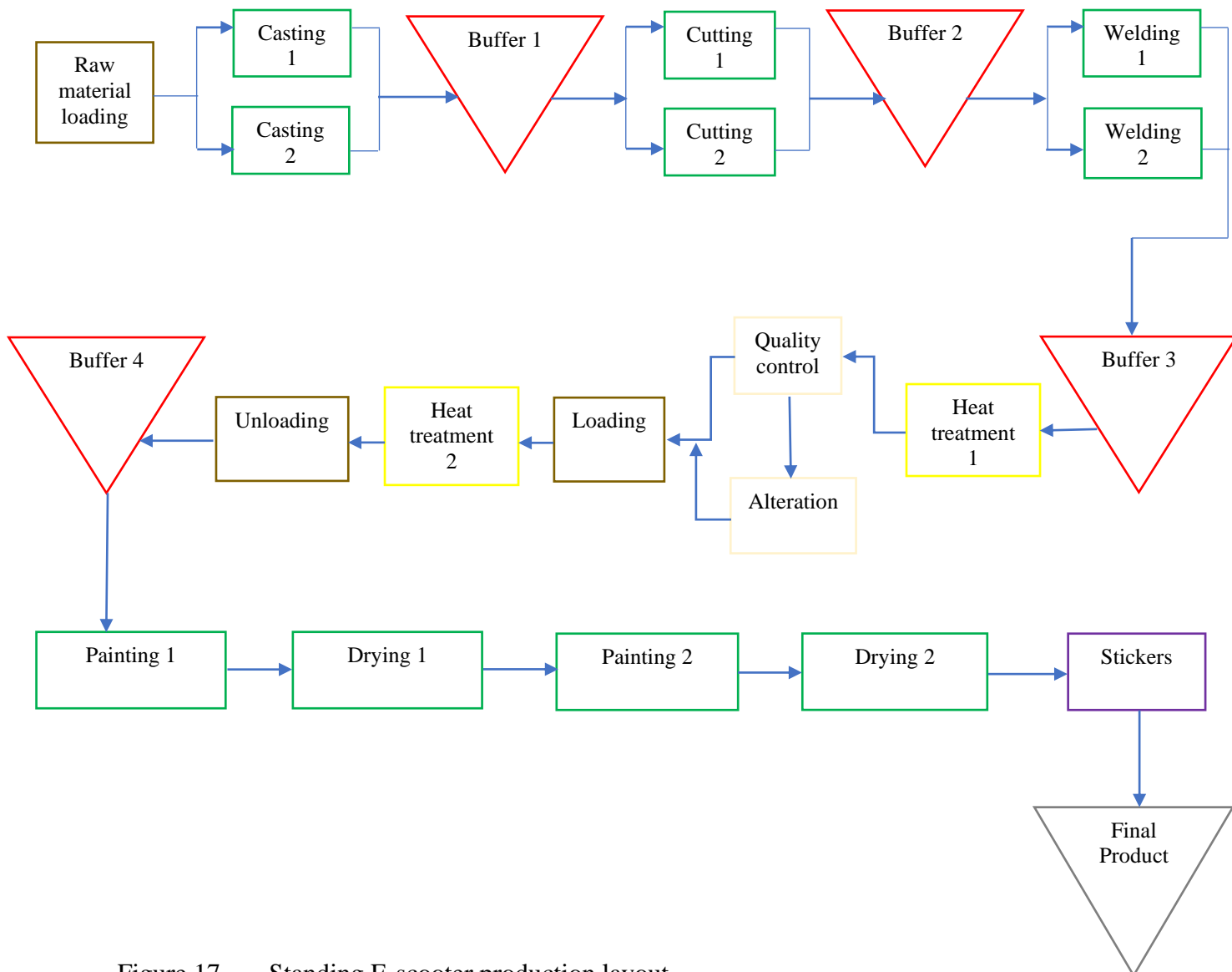


Figure 17 Standing E-scooter production layout

### 4.5.3.3 PSL for Skate E-scooter model

In the Skate E-scooter design, only the deck is needed thereby making it lesser in term of production flow.

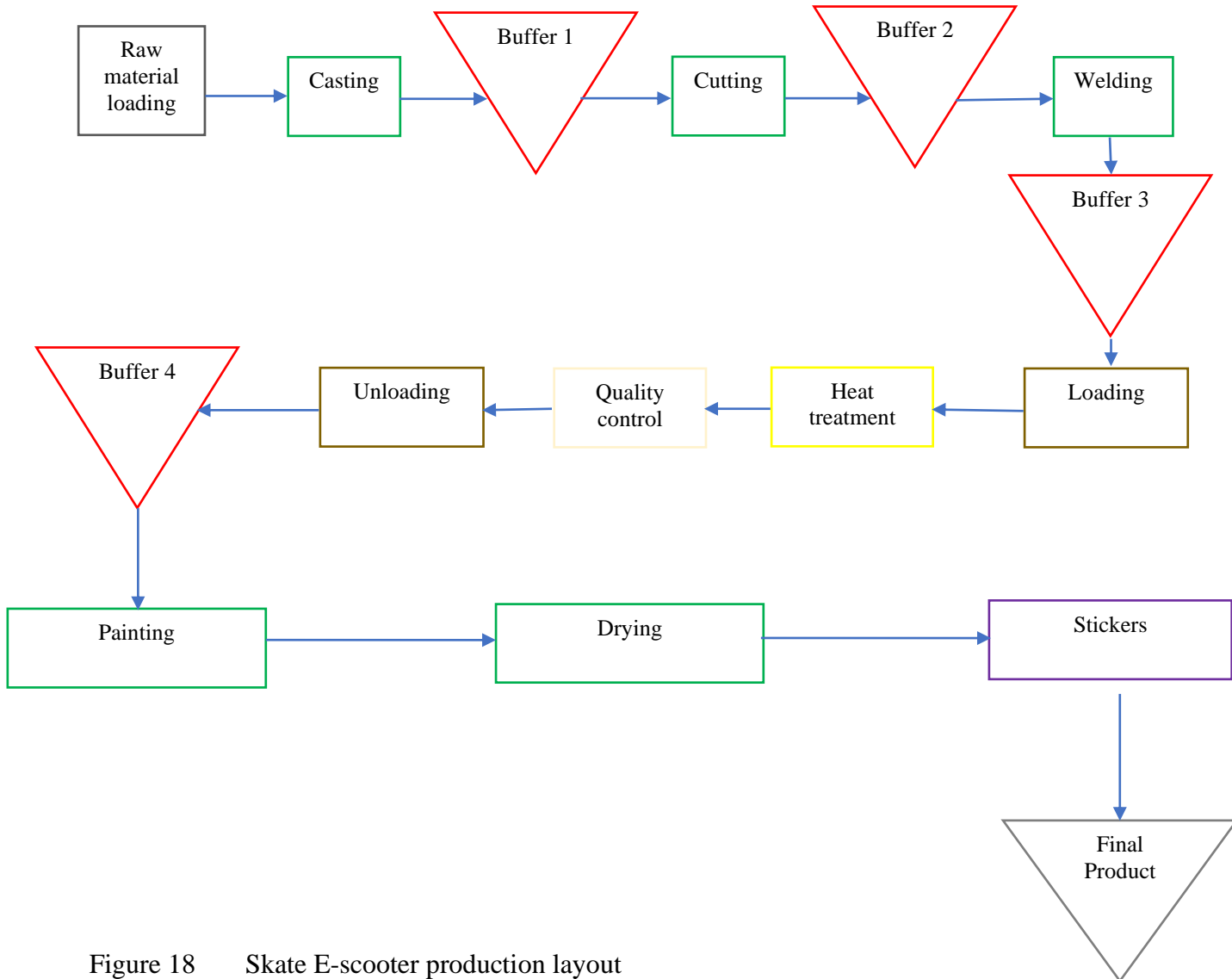


Figure 18 Skate E-scooter production layout

Furthermore, with the onion model representation (see appendix H), production engineer can add or reduce process steps depending on three-product design to be produce due to standardized parts. Also, the manufacturing process is done on one production systems layout instead of three separate layouts since they utilize the same machines. Hence, the design of the production layouts is integrated into one manufacturing model (see appendix I).

### 4.5.4 Second generation screening: Production systems process

In quest to achieve high productivity (throughput), it is imperative to control the manufacturing process to determine the system's bottleneck with the Reliability Centered Maintenance (RCM) methodology. RCM is a framework for preserving system functions, rather than preserving physical asset. It is used to evaluates planned

maintenance schedule that will guarantee the availability of a machine in terms of reliability and maintainability. To develop the maintenance policy with the RCM methodology, its framework includes different activities with five steps as shown in *Figure 17*.

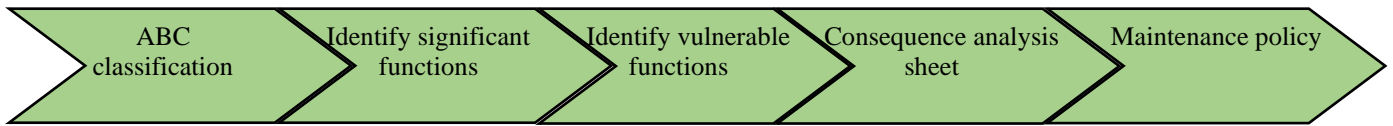


Figure 19 RCM Methodology

#### 4.5.4.1 Maintenance policy selection using RCM

To create a maintenance plan for the system’s critical machine, most of the significant machines such as casting, cutting, welding and painting used in the manufacturing process are ranked using the ABC classification (see appendix J). Upon critical machines identification with the ABC classification, three machines ended up as category "A" which are casting, cutting and welding. These results are presented in *Table 15*.

Table 15 RCM-ABC classification

Process	ABC Classification Ranking							
	Environment	Safety	Quality	Working Time	Delivery	Reliability	Maintainability	Results
Casting	C	B	A	-	-	-	-	A
Cutting	B	A	-	-	-	-	-	A
Welding	A	-	-	-	-	-	-	A
Painting	B	B	B	C	A	B	B	B
Drying	-	-	-	-	-	-	-	-
Sticker	-	-	-	-	-	-	-	-

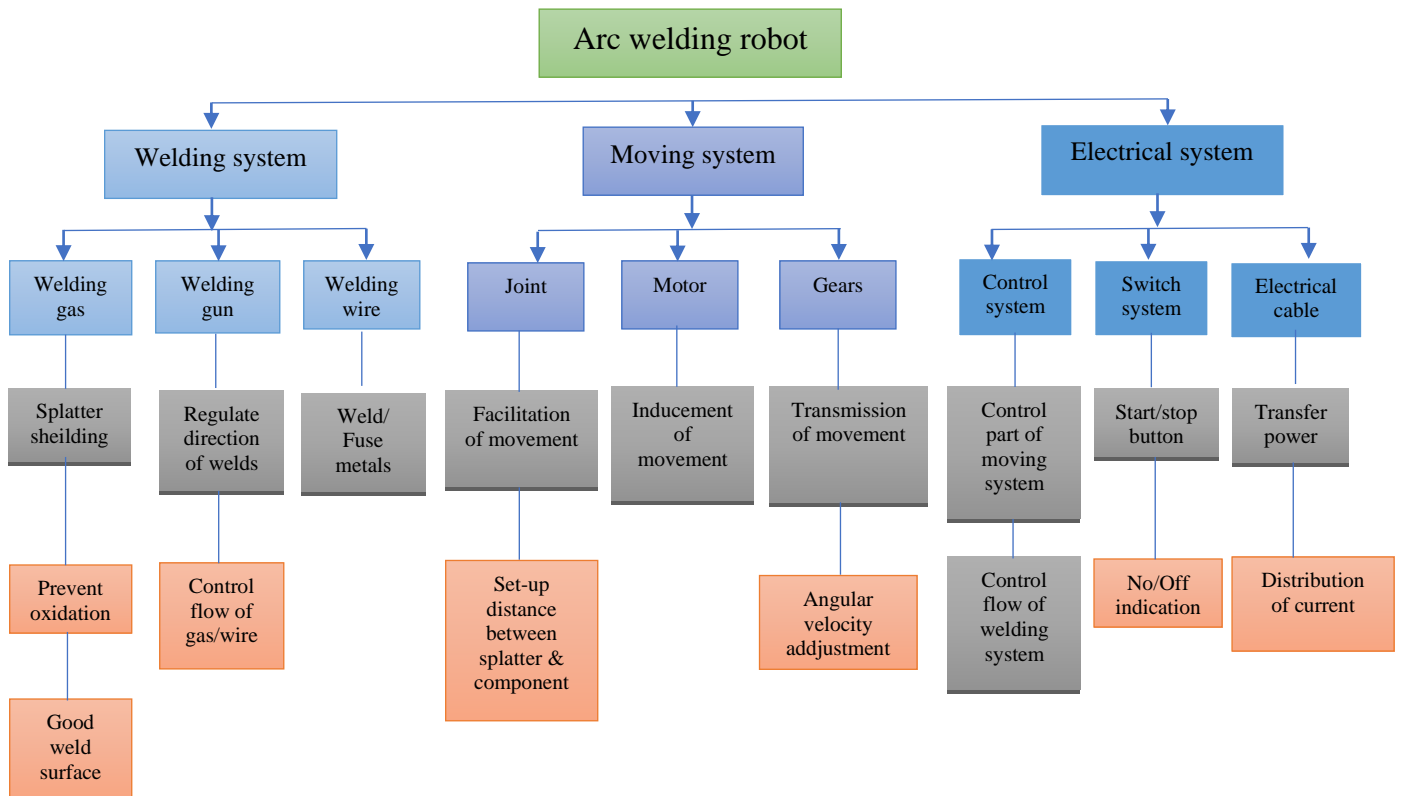
In order to establish the system’s bottleneck machine after identifying the critical machines, the vulnerable components for each of these machines classified as "A" category as well as painting machine are later analyzed separately based on the flowchart criticality process as shown in *Table 16*.

Table 16 Machines Components Analysis

Process	Analysis of machine criticality							
	Environment	Safety	Quality	Working Time	Delivery	Reliability	Maintainability	Results
Casting	Molten metal	Intense heat	Mold failure	-	-	-	-	A
Cutting	Coolant is liquid	Saw blades	-	-	-	-	-	A
Welding	Welding gas	-	-	-	-	-	-	A
Painting	Paint is liquid	No huge damage	Inspection failure	One or possibly two shifts	Under critical situation	60% reliable	Reparation time > 45 minutes and < 90 minutes	B
Drying	-	-	-	-	-	-	-	-
Sticker	-	-	-	-	-	-	-	-

Hence, the welding machines (arc robot) is the bottleneck machine of the system. Its components are more critical and vulnerable than others apart from the fact that it got “A” directly but also due to its negative effect if the machine fail according to the flowchart criticality priority setting.

Furthermore, *Figure 18* illustrates the bottleneck machines (arc welding robot) functional tree of all its systems and subsystems to identify functions and significant functions.



Colour Indication		
	Arc welding robot	
All blue-like	Machine's system	System's components
	Machine's sub-system	Primary function
	Machine's sub-system	Secondary function

Figure 140 Function analysis of arc welding robot

With the RCM decision diagram (see appendix K), the best suitable maintenance strategy is optimized for the task on the identified components to increase the performance of the bottleneck machine (arc welding robot). The schedule maintenance policy decided for the bottleneck machine to ensure its availability in terms of reliability and maintainability is given in *Table 17*.

Table 17 Maintenance Policy Plan

Significant function	Failure mode	Failure cause	H	S	E	O	Candidate task	Selective decision	Estimated frequency
Weld pieces of metal	Control system makes wrong decisions	Broken sensors	N	Y	N	N	S1	Schedule on condition	Unlikely
Move welding equipment	Poor wire feeder	Liner and wire feeder defect	Y	N	N	N	H1	Schedule on condition	Very likely
Transmit power	Welds inconsistency	Weld gun neck bends	N	N	N	Y	O3	No schedule maintenance	Very likely
	Poor consumable performance	Loose of joints or gears wear	Y	N	N	N	H1	Schedule on condition	Very likely
	Premature wire cable	Incorrect wire length	N	N	N	Y	O3	No schedule maintenance	Very likely
	Jammed start/stop button	Button life span wears	N	Y	N	N	S4	Combined task	Unlikely
	knock engine	Low lubricant level	N	N	N	Y	O1	Schedule on condition	Likely
	Reduced weld quality	Irregular of welding gas distribution	Y	N	N	N	H1	Schedule on condition	Unlikely

## 4.6 Simulation process of Model-based Product Development

The simulation process was performed with the model tool called discrete event system (DES). This method is used to know the nature of action agent by observing the behaviour of individual operation. To run this process, gathered data from the product architecture were used as the input to get a generic algorithm in order to calculate the time that each operation will take throughout the entire production system.

### 4.6.1 Data collection process

The process of data gathering involves the part identification architectures for the E-scooter design with regards to the three materials (Aluminium, Stainless steel and Titanium). The input data were later processed through the assembly line consisting of casting, cutting, welding and painting. *Table 18* shows a condensed variable from equations used on how these values were calculated based on the input data from the product architecture.

#### 4.6.1.1 Summary of the equations

The formula that is used to calculate the process duration i.e time to produce the standardized parts in some of the significant stations with the equation's variables are summarized in *Table 18*.

Table 18 Summary of the equation's variables

Function of variables		Values	Reference
Cm	Thermophysical properties function of the mold constant	Aluminium 2 Stainless steel 4 Titanium 3 (since it is as strong as steel but lighter compared to steel)	Chvorinov's rule
Vc	Cutting speed with high speed steel (HSS)	Aluminium 91.4 Stainless steel 15.2 Titanium 18.2	Fundamentals of machine tools
Ft	Transverse feed/feed rate	500mm per minute	Data obtained from company practitioners
N	No. of teeth	40 wheel	Data obtained from company practitioners
S	Travel speed	300mm per minute	Data obtained from company practitioners
T	Range of service temperature (°F)	Aluminium 150 - 350 Stainless steel 1700 - 2000 Titanium 500 - 1000	Millerwelds.com
Heat input	The amount of energy needed to form a weld to the workpiece	Equivalent of average service temperature with Aluminium of 250	Based on the above service range
M	Mass of the part	Using the CAD model, the material parts masses are known	CAD models

Table 19 displays a functional model created for the significant stations to know the time needed to produce each of the different variants of the E-scooter product design after all information on the parts has been calculated.

Table 19 Processing times of design parts

Casting Station	Aluminium		Stainless steel		Titanium	
	Original	Modified	Original	Modified	Original	Modified
<b>Time</b>						
Deck (min)	1,715	2,765	3,429	5,530	2,572	4,147
Handlebar (sec)	7,078	17,884	14,156	35,768	10,617	26,826
Pole-bar (sec)	5,944	4,777	11,887	9,555	8,915	7,166
Seat-pole (sec)	8,635	3,282	17,271	6,563	12,953	4,922

Cutting Station	Aluminium		Stainless steel		Titanium	
	Original	Modified	Original	Modified	Original	Modified
<b>Time</b>						
Deck (min)	2,011	1,890	2,003	1,901	2,003	1,898
Handlebar (min)	0,169	0,108	0,156	0,130	0,154	0,120
Pole-bar (min)	0,337	0,380	0,312	0,403	0,308	0,409
Seat-pole (min)	0,337	0,380	0,312	0,403	0,308	0,409

Welding Station	Aluminium		Stainless steel		Titanium	
	Original	Modified	Original	Modified	Original	Modified
<b>Time</b>						
Pole-bar (min)	1,047	1,361	7,745	10,069	3,14	4,082
Seat-pole (min)	1,047	1,361	7,745	10,069	3,14	4,082

Painting Stations	Aluminium		Stainless steel		Titanium	
	Original	Modified	Original	Modified	Original	Modified
<b>Time</b>						
Station 1 (min)	1,5	1,5	1,5	1,5	1,5	1,5
Station 2 (min)	1	1	1	1	1	1

## 4.6.2 Automod Simulation Process

With the Automod software, five different options as presented in *Table 20* are simulated for 2080 hours (86 days 16 hours).

Table 20 Percentage of design production

S/N	Production rate/month	% production		
1	320	Sitting		
2	320	Standing		
3	320	Skate		
4	320	40 of 1	30 of 2	30 of 3
5	320	50 of 1	40 of 2	10 of 3

Sitting = 1                      Standing = 2                      Skate = 3

The virtual representation of the Automod used to simulate the manufacturing process of the E-scooter is graphically illustrated in *Figure 19* with ergonomics and material as input factor from product design while high throughput as output factor from production systems perspective in terms of maintainability, reliability and maintenance. For the Automod simulation source file (See Appendix B) and the simulation results of the 18 design variants for each significant station with respect to material types (see Appendix C).

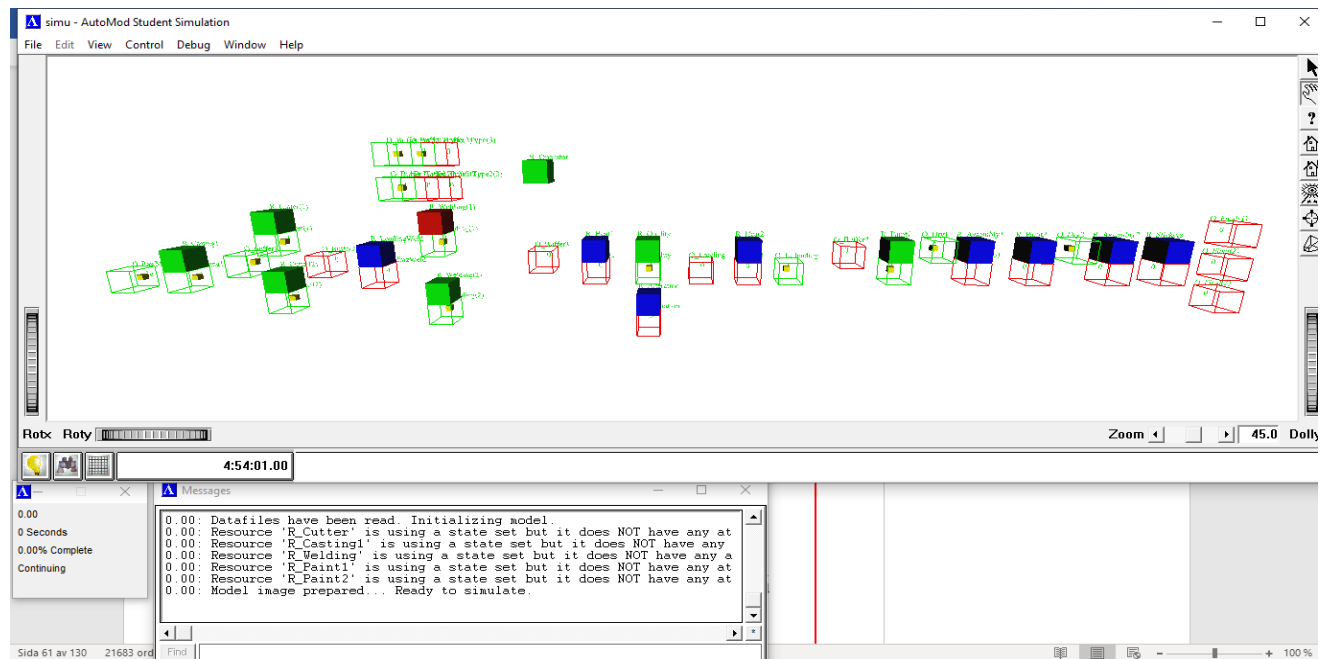


Figure 215 Automod Event Process

The throughputs obtained with the Automod software for the first three with 100% variants (see Appendix D). These designs throughputs are later grouped and mapped under same material due to same mechanical properties and characteristic. The Aluminium family happens to have the highest throughputs for the original and modified geometry respectively as shown in *Figure 20 & 21*.

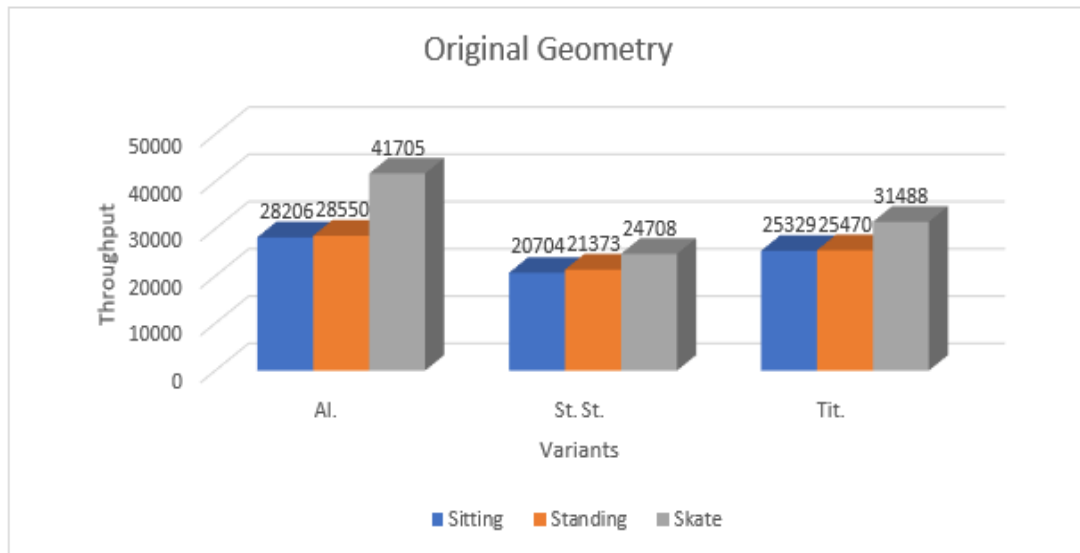


Figure 162 100% Original of the three designs

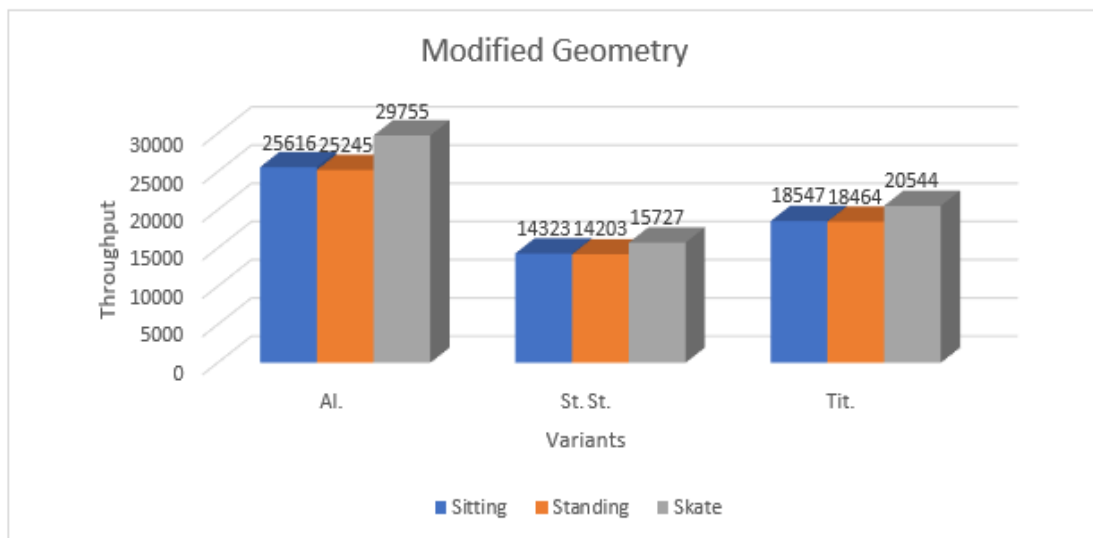


Figure 173 100% Modified of the three designs

After mapping, each design variant in the Aluminium family is evaluated with respect to its mean time between failure (MTBF) and mean time to repair (MTTR) of the system's bottleneck machine i.e welding arc robot. This screening is to be able to select the best variant. *Table 21* shows the result analysis for the original geometry of the design only, but the same principle can be applied for the modified geometry of the design.

Table 21 Design mapping

S/N	Variant	Aluminium	Stainless steel	Tiatnium
1	Sitting	28206	20704	25329
2	Standing	28550	21373	25470
3	Skate	41705	24708	31488

Variant			Sitting	Standing	Skake
Aluminium	Welding 1	MTTR	42.8	40	43
		MTBF	2.8	2.7	2.9
	Welding 2	MTTR	43.8	42.2	42.3
		MTBF	3	2.9	2.9
Stainless steel	Welding 1	MTTR	41.4	39.9	41.9
		MTBF	2.8	2.8	2.7
	Welding 2	MTTR	42	40	41.3
		MTBF	2.8	2.7	2.7
Titanium	Welding 1	MTTR	45	40.1	38.8
		MTBF	2.9	2.8	2.7
	Welding 2	MTTR	45.1	40.9	43.4
		MTBF	2.9	2.8	2.7

The figures highlighted in red colours denoted the average values for original geometry with respect to MTTR & MTBF since the machines are in parallel. The original geometry of Aluminium material for Standing design and modified geometry of Aluminium material for Sitting design resulted to have the highest throughput respectively.

For Mix A: Original

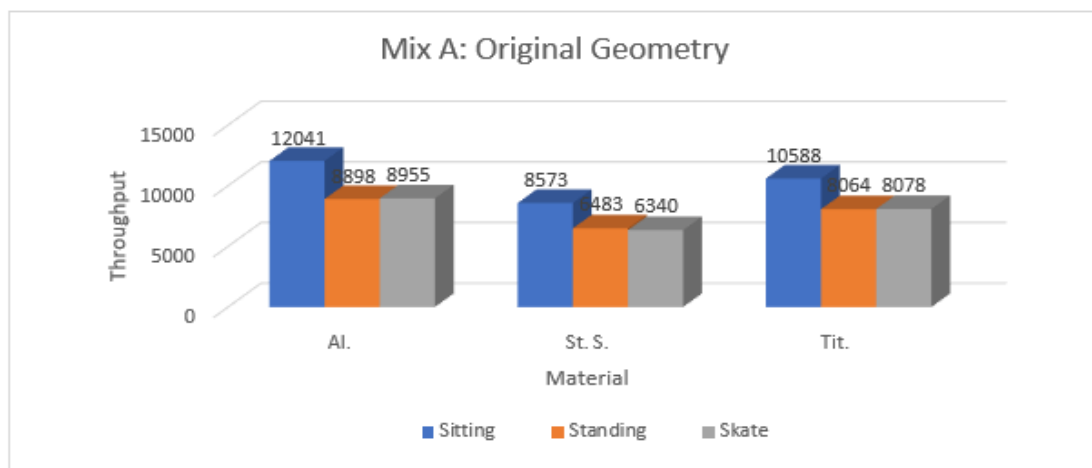


Figure 184 Mix A % Original of the three designs

For Mix A: Modified

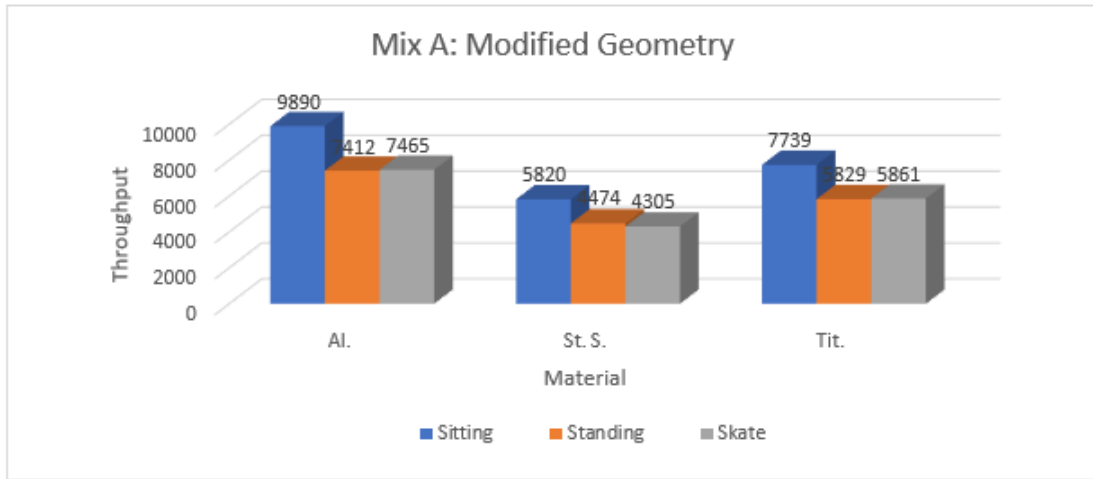


Figure 195 Mix A % Modified of the three designs

The result on the option 4 for both original and modified geometry when compared with the other materials variant in term of MTTR and MTBF (see Appendix E) shows that the Stainless steel material is the best with the 40% of Sitting, 30% of Standing and 30% of Skate.

For Mix B: Original

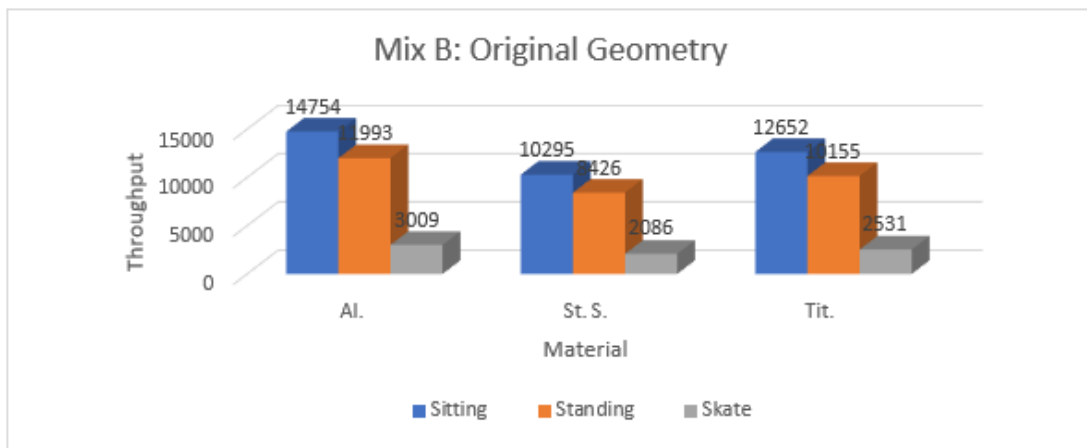


Figure 206 Mix B % Original of the three designs

For Mix B: Modified

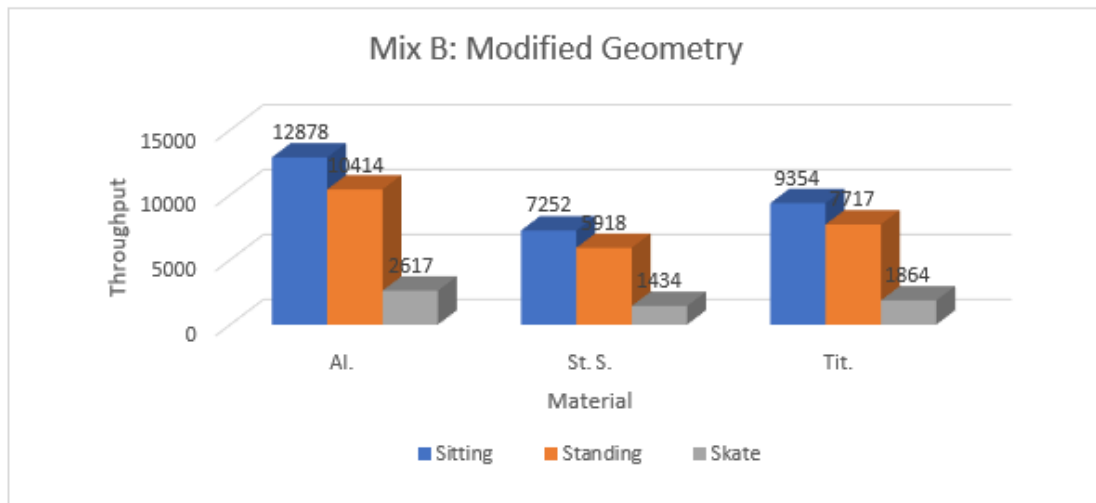


Figure 217 Mix B % Modified of the three designs

The Aluminium and Stainless steel happens to be the best alternatives (see Appendix F) with slightly fraction difference with MTTR & MTBF for both the original and modified geometry with 50% of Sitting, 40% of Standing and 10% of Skate.

## 4.7 Description of Concurrent Design (Anylogic)

For the concurrent design, the inputs and output from Automod simulation is exported as an input to the Anylogic simulation with the added total product development life cycle investments.

### 4.7.1 Product development cost calculation

**Usage cost: Electricity cost \* distance \* Fm**

According to Newton's laws of motion, an object is described to its acceleration, deformation and position change on how it affected by external forces. Newton's law explains three laws that describes the connection between force and motion.

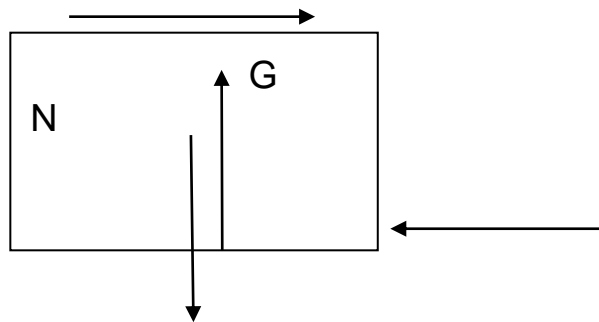
- Newton's first law: law of inertia describes: a body remains in a state of rest or uniform movement. if it is not influenced by a force that changes that movement if the vector sum of all external forces acting on the body is zero. Equation:  $\sum \text{Force} = 0$ .
- Newton's second law: The time derivative of the amount of motion has the same direction and magnitude as the applied force acting on a body of constant mass. Equation:  $\text{Force} = \text{mass} * \text{acceleration}$
- Newton's third law: Two bodies will affect each other equally but with large force but with opposing forces. In a closed system internal forces will take each other out by the reaction force so that the sum of internal forces nullifies.

Therefore, an object Body (X) is subjected to the following variables,

Force (Fm),  $G = \text{Mass (m)} * \text{gravity (g)}$

Friction (Fr) = Friction coefficient ( $\mu$ ) \* Normal (N)

Where  $F_m$  = minimum power propulsion needed,  $g = 9,82 \text{ m/s}^2$  and  $\mu = 0,5$



Forces in X and Y direction:  $\downarrow \rightarrow$

$$F_x: F_m - F_r = 0 \Leftrightarrow F_m = F_r \Leftrightarrow F_m = \mu * N \Leftrightarrow F_m = \mu * m * g$$

$$F_y: N - G = 0 \Leftrightarrow N = G \Leftrightarrow N = m * g$$

### Electricity cost

Electrical cost (G) = 2,3 SEK/KWh

Max E-scooter's speed ( $V_{max}$ ) = 20 km/h = 5.55m/s

$$\text{Watt (W)} = V_{max} * F_m$$

### Distance

Distance (D): Free variable

Presumed highest mean weight of users is 90 kg(h).

$$\text{Electricity cost: } F_m * V_{max} * G * D$$

$$\text{Electricity cost: } 90 * 9,82 * 0,5 * 5,55 * 2,3 = 5,6396 \text{ kr/KWh}$$

## 4.7.2 Revenue

Formula: Revenue (R) = X \* Price

Price: Different price models used are based on ergonomics, total production, material deterioration and usage cost.

Population density Molndal (S) = 415 people/100km<sup>2</sup>

X = Usage of hours/month

## 4.7.3 Material deterioration

The deterioration of the material selected is based on fatigue strength with respect to applied loads and cycle limit to know the expected maintenance cost for the product design. The maintenance cost involved in the product is based on the material deterioration level. This was done on comparing three different metals, Aluminium 6061T6552, Low alloy steel, SAE 4130, cast normalized & tempered and Titanium, alpha-beta alloy, Ti-3 AI-2.5V (Grade 9). The comparison helps to determine the material that can withstand the highest load when same cycle load is applied on the three design materials. This action will reveal each material deterioration scenario.

Table 22 Material Deterioration

Metal	Cycle limit (N)	Fatigue strength stress range (MPa)	Fatigue strength stress range mean value (MPa)	Equivalent value of Titanium	X (N/MPa)
Aluminium, 6061, T6552	10e7	96,6 - 136	116,3	3,47	85984
Low alloy steel, SAE 4130, cast normalized & tempered	10e7	293 - 365	329	1.23	30395
Titanium, alpha-beta alloy, Ti-3 Al-2.5V (Grade 9)	10e7	325 - 483	404*	1	24752,47

In figure 26, Aluminium and Stainless-steel materials are compared to the fatigue strength of Titanium material used as the reference point. In the end, Titanium material appears to be the metal that manages the most load in the same cycle limit.

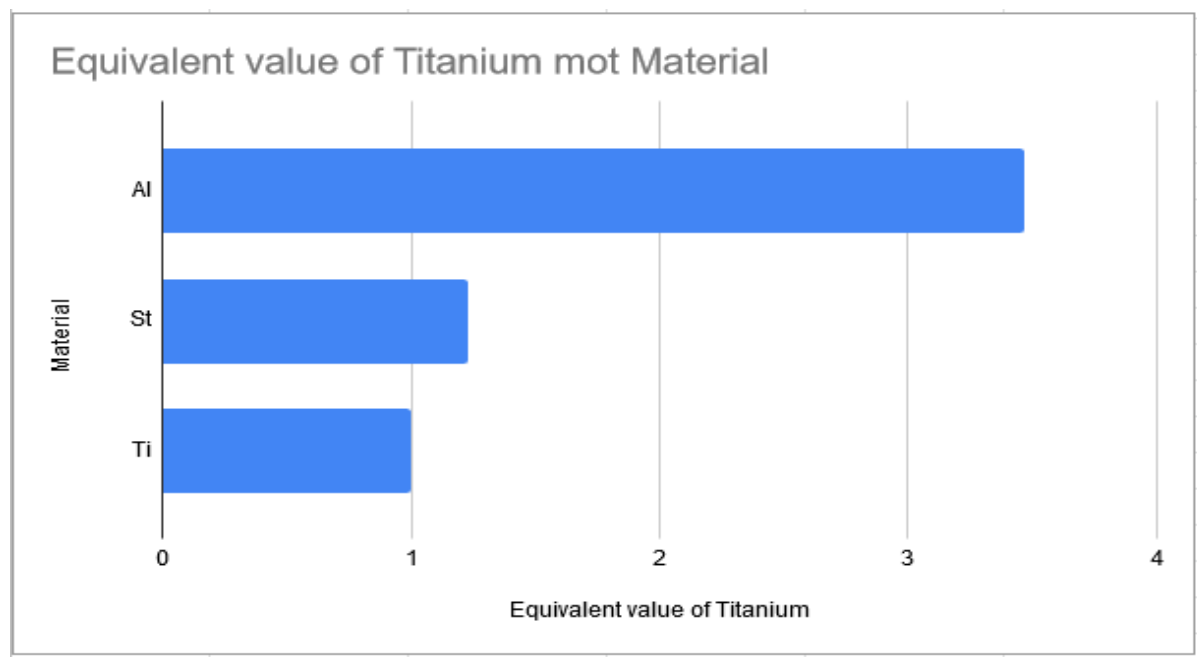


Figure 228 Titanium Material Deterioration Equivalency

## 4.8 Production Systems LC cost calculation

The significant working hour for a whole year = working hour/week \* 52 weeks

Working hour/week = 8 hour/day \* 5 days (Monday to Friday)

Annual working hour = 40 hours/week \* 52 weeks

= 2080 hours/year

In the manufacturing process of the E-scooter design, the number of parts for each of these designs differs but each of them has two geometry models called Original and Modified. These parts undergo the manufacturing processes casting, cutting, welding, paint 1 and paint 2 respectively to determine the time required to perform the design of the E-scooter with respect to material types. *Table 23* demonstrates the part requirement for each E-scooter design where A stands for applicable and NA means not applicable.

Table 23 Total Manufacturing Time

Parts	Deck	Handlebar	Pole bar	Seat pole
Sitting	A	A	A	A
Standing	A	A	A	NA
Skate	A	NA	NA	NA

Processes	Aluminium		Stainless steel		Titanium	
	Original	Modified	Original	Modified	Original	Modified
Casting time						
Deck	1.7	2.8	3.4	5.5	2.6	4.1
Handlebar	7.1	17.9	14.2	35.8	10.6	26.8
Pole bar	5.9	4.8	11.9	9.6	8.9	7.2
Seat pole	8.6	3.3	17.3	6.6	13	4.9
Cutting						
Deck	2.0	1.9	2.0	1.9	2.0	1.9
Handlebar	0.2	0.1	0.2	0.1	0.2	0.1
Pole bar	0.3	0.4	0.3	0.4	0.3	0.4
Seat pole	0.3	0.4	0.3	0.4	0.3	0.4
Welding						
Chasis	1.0	1.4	7.7	10.0	3.1	4.1
Painting 1						
Frame	1.5					
Painting 2						
Frame	1.0					

For instance, the total time required to perform the production process for Aluminium material with original geometry will be the summation of all the time in each of the manufacturing processes which is given as  $1.7+7.1+5.9+8.6+2.0+0.2+0.3+0.3+1.0+1.5+1.0 = 29.6$  min (0.5 hours).

With human/manual operation, 4160 units/year of the Aluminium are produced as to 28206 units/year for theoretically with simulation process. Thus, the same approach applies to the other design variants.

However, 80% were assumed to be the real throughput of the theoretical results obtained through simulation process for each of the design variants in a whole year. This simply means that the real throughput will be  $0.8 * 28206 = 22564,8$  units/year for the case of Aluminium. Hence, 13.56 units/hours and 10.84 units/hours were produced using 28206/2080 and 22564,8/2080 as the theoretical and real throughput respectively while the inefficiency resulted to 2.71 (13.56 – 10.84) of units' throughput.

The weight of design geometry is specified as above by product designers as an input in the production process. To lower the life cycle cost to a minimal level, material screening was adopted from CES. Three materials were selected from six commonly used metals with the cheapest price and assumed that mechanical character is the same.

To calculate the maintenance inefficiency cost as a result of unplanned reactive downtime, the total MTBF for each of the processes are determined. For example, it takes 32 hours/year to produce 28206 units/year. This is derived from the operating machines in the assembly layout. The machines are arranged in sequence and comprises casting, cutting (1&2), welding (1&2) and Painting (1&2) as (1.9+2.1+2.2+2.8+3+10+10) hours respectively. Range of acceptable unplanned downtime in Europe is 40€-500€/hours. Hence, cost of the unplanned downtime is  $32*500 = 16000$ kr/year and 7.7kr/hours.

A normal operator salary in Sweden, Volvo as a case study is 28000SEK/month before tax.

## **4.9 Concurrent Engineering Design**

### **4.9.1 Units throughput production cost calculation**

Material deterioration are used as an input factor for calculating the production cost for the throughput units produced. Since metals has different mechanical properties and behavior differs, the titanium value strength was set as reference to determine the equivalent value of Aluminium and Stainless-steel materials.

Formula: Production cost/Throughput unit \* equivalent value of titanium.

#### **4.9.1.1 Economics cost**

The company budgeted approximately 20 million SEK (research and development) for project development. The size of the factory 2000m<sup>2</sup>. Data obtained from Vattenfall as energy consumption for such manufacturing factory is 777 KWh and 2.3 SEK/hours as electrical cost. Therefore, the factory consumption electricity cost amounted to  $777 * 2.3 = 1787.1$  SEK/hours.

#### **4.9.1.2 Present Net Value**

To obtain the net present value of the investment, 6% was assumed to be the discount rate since money invested today will grow with a certain percentage overtime. Formula used in calculating the NPV are:

Revenue: The number of users \* price

Where prices are based with respect to ergonomic, total production cost, material deterioration and usage cost.

X=usage of hours in a month

Population density @ mölndal = 45 people/100km<sup>2</sup>

#### **4.9.2 Concurrent Cost Calculation**

The concurrent calculations are the sum of the cost of the product designer and production engineer for deciding the product life cycle cost. The product life cycle was established for three calendar years in order to see the design cost trend or pattern. These trends show the break-even positions, profits and return of investments in each of the design variants. Below parameters are considered in calculating the economic forecast for the first three years.

- Revenue
- Variable expenses
- Total LCC cost/hr
- R&D
- Total variable cost
- Contribution margin
- Fixed expenses Y1
- Fixed expenses Y2
- Fixed expenses Y3
- Profit
- Total usage hours
- Days in a month
- Net present value

#### **4.9.2.1 Revenue**

Revenue is the total production life cycle cost multiplied by price and numbers of users.

#### **4.9.2.2 Variable expenses**

These are expenditure cost that comprises the following:

##### **Total LCC**

It is the amount of the money incur to produce units of product in an hour.

##### **Research & Design**

It is the cost invested for developing the products

##### **Total variable cost**

It is the sum of the total life cycle cost and research & design in hours

##### **Contribution margin /Profit**

This is the difference between the revenue and the total variable cost

##### **Fixed expenses Y1, Y2 and Y3**

These are cost that are constant over time. The production facility cost is the fixed expenditures in this case. However, the production facility differs in terms of the operating time over the three-year calendar.

- Year 1 is the initial year of investment; the facility usage is 100 % capacity.
- Year 2,  $\frac{1}{3}$  of the product fleet is renewed and the usage of the facility capacity is  $\frac{1}{3}$  of the initial year.
- Year 3,  $\frac{2}{3}$  of the product fleet is renewed and the usage of the facility capacity is  $\frac{2}{3}$  of initial year.

#### **4.9.2.3 Days in a month**

The days in a month is 30 days

#### **4.9.2.4 Total usage hours**

This is the total usage of the products in hour in a month.

#### **4.9.2.5 Net Present Value**

The NPV is based on the profit divided on the discount rate (previous month + current month)

### **4.10 Final product design selected**

The selection of the final E-scooter product is achieved after calculating the product life cycle cost of all the 18 product design variants for a period of three years. Their product life cycle cost in term of contribution margin (profit) is plotted against the investment for three years period to determine the design variant that will first break-even as shown in *Figure 29*. In the end of this process, the Sitting E-scooter design with original geometry of Titanium material is obtained as the best product design. However, this is in contrary to the result obtained from the simulation process.

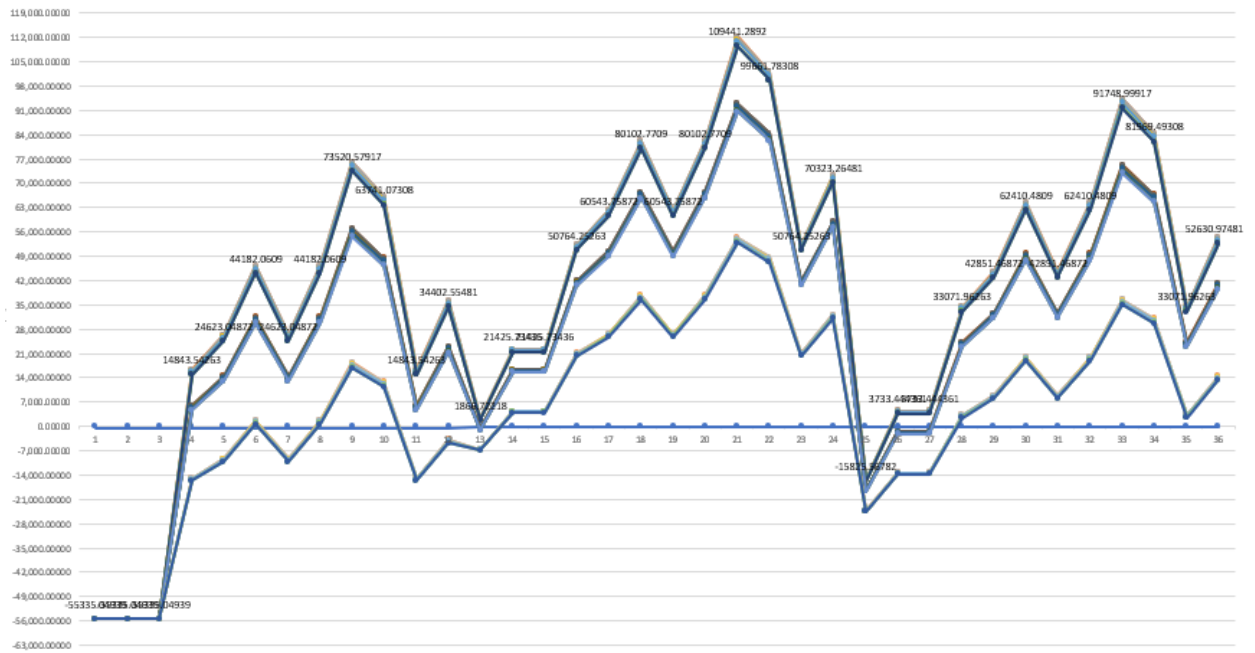


Figure 239 Product Life Cycle Cost

However, the Sitting E-scooter product design resulted to be the first to break-even. Even though that the total production cost for the Sitting E-scooter has the highest total investment, it only loses market share in the third part of year but pick up back in less than one month. Hence, the Sitting E-scooter with Titanium material is presumed to be the best product for the GoCo health innovation centre due to its material deterioration strength. All the E-scooter product designs are represented in *Figure 30*.

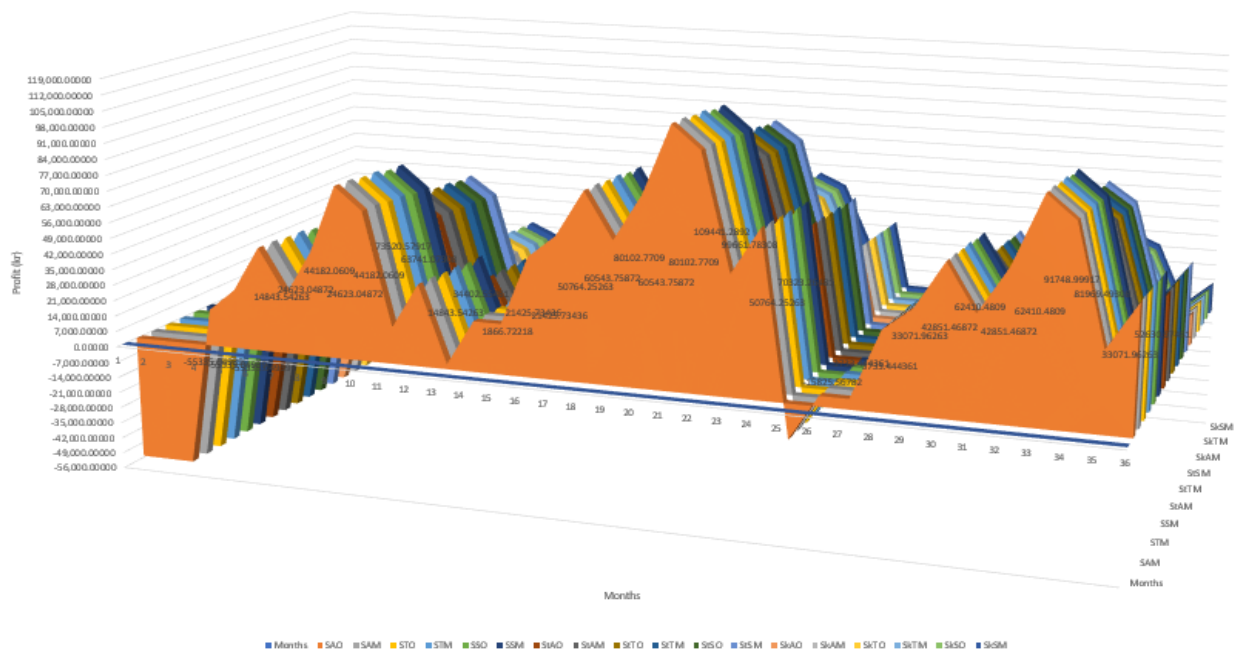


Figure 30 The 18 E-scooter product design

## **5 Chapter Five: Result analysis**

*This chapter covers the discussion and conclusion on how the methodology regarding the findings of this thesis work is carried out.*

### **5.1 Discussion**

The discussion part explains the approach for case study and how the result to the study case is obtained. The first part addressed the methodology around modes of land transportation established for the case study result. Exploring the future opportunity within PSS concerning product and production development is the second part.

#### **5.1.1 New knowledge design**

In this study, a case study was created to understand the abstract mechanisms of PSS. Today there is plenty of information on how the Product Service System has been implemented as a business model in various stages of the entire product life cycle. The application of PSS in companies is often realized separately within departments in the organization structure. This nonlinear activity between these departments however creates technical conflicts around the product due to their inability to reach their respective goals but on the long run will result in hampering the company vision.

As a result of this, this problem was recognized as a “grey-zone” which needs to be explored and understood to be able to establish an effective PSS design. A need in the industry is recognized to develop a new-state-of-the-art business model which does not encourage separate PSS but instead a concurrent PSS design. This thesis is in the absolute frontier of unified product development making it almost little to none to find any documented report within this area of expertise.

#### **5.1.2 Case study result: Development of Product & Production Service System (PPSS)**

In the process of retrieving case results, already renowned methodology tools were used to collect different data. An Automod software program was used to simulate the first model by using different inputs gathered from the stakeholders. This was to determine the throughput of the 18 model variants and evaluate which will be the optimal final product as the best transport mode.

For the first simulation mode, six factors were used as an input established by co-screening between the involved stakeholders of the project. After the simulation process with consideration to the system’s bottleneck machine in terms of its MTBF, the Sitting and Standing design of Aluminium material are selected.

The second simulation was done by using Anylogic, the inputs used for the simulation was material deterioration, ergonomics, costs and throughput. These factors represent the entire product life cycle which will indicate the budget frame for each variant model. The final decision of the product is based on a three-year prognose on which variant model is the fastest to break even and who has the best difference between revenue and total expenses.

When we performed the Anylogic, the assumption was that the variant model with the greatest throughput result derived from Automod would resonate with the Anylogic result. The variant model with the best throughput is skate and Stainless steel as the preferred material because it is the cheapest. But when performing the Anylogic simulation with the four different factors as inputs, the results showed us that our assumption was wrong. The variant model with the best output was Sitting Skate with Titanium material. Based on the factors and price model used. The Skate model has the best ergonomics, earliest break even, and highest profit after three years.

#### **5.1.2.1 Compare current PSS knowledge**

The case result has revealed the tendency of using the concurrent PSS in physical nature. It has shown the different ways that a product life cycle can be established. Decision making of product development elements on micro and macro level can be postponed much later in the product life cycle than traditional PSS and product development. This makes it possible to have all the options viable for selection.

Traditional PSS focuses on classic product development phases which includes screening methods. These screening methods are most often based on cost in the beginning of the product development to eliminate the elements that are undesirable for the stakeholders. During the process of traditional PSS making, the decision maker is locked in separate entity thinking and can't visualize PSS in a nuanced way (Alix et al, 2014) & (Leber et al, 2014).

For the concurrent PPSS, the screening process is implemented in the later end of the product development. This adopted approach enables alternative solutions possible (redesign) in order to have multiple variant models. Subsequently, it helps the stakeholders involved to make late changes in the projects and customized it after occurred needs with minimal increased iterations. This is because broad knowledge is required to fully understand what decision to make that ensure good quality, throughput rate and cost effectiveness (Ullman, 2008)

Collaboration in the conceptual phase in PPSS is done in the initial stages of the product development. Having cross functional teams to derive as much expertise and knowledge as possible. The goal is to create a team which is coherent as possible and to avoid conflicts between different business activities and barriers. Which could harm the fulfillment of the main mission to satisfy stakeholders.

In traditional PSS the collaboration between product designer and production system perform in the operation stages of the product development. This stage is where the activities of the two stakeholders meet known as checkpoint which reveals the technical conflict between them. As mentioned in PSS life cycle in chapter 3, it is when the production and design teams meet for the first time to create a joint PSS-design known (Kimita et al, 2012).

#### **5.1.2.2 Consequence of the New Knowledge**

The new knowledge gained during this project shows a proposed methodology on how to implement a concurrent PSS design between production and design teams when executing a product development. When designing a product development,

reaching set goals is the focus with the traditional PSS while increasing the efficiency between the entities is the vital focus of the new PPSS. PSS is usually set on developing one or few ideas while the PPSS has implemented methods from set-based concurrent engineering due to the possibilities of having multiple ideas viable and gradually selling out weaker design variants until the final optimal variant of the model is decided.

Further, the methodology of PPSS allows unified collaboration and co-development of the PPSS design business model on an equal level between production and design team. This cooperation enables increased transparency, resource sharing and goal coherence which will decrease level of conflicts and barriers.

The design of a product development during the conceptual phase with the PPSS methodology conceptual phase involves potential of multiple ideas which most likely may results in higher initial cost, especially in the research and design area. This will however on the long run level out the design activities process and enable shorter market introduction than the traditional PSS.

### **5.1.3 The study weaknesses**

Prior to the development of the production system, it has been presumed that the product design variants should be performed on a different production layout. In contrast, the three design products later configured together and passed through the assembly line designed for the product with the four components (deck, handlebar, pole bar and seat pole) to stimulate the process. After the simulation process, a prognose was established and the result showed that throughputs obtained from the simulation and manually calculated were almost the same.

When designing the different model variants CAD was used as the primary design tool. Even though it is a powerful tool, its function is limited and has only a set of standard material types like, Stainless steel, Aluminium and Titanium. Nonetheless, the characteristic is similar, but it does not correspond with the metals that were used in the project. This in the end affects the stress analysis which is not actual numbers for the metals stated in the report.

Further on, the calculated numbers of fatigue strength are below the wöhler curve used to estimate the cycle limit of the material. Therefore, we based our calculations on the characteristics of the metals and multiplied them with 100. The assumption was that the materials will behave in the same way as the wöhler curve and therefore the number of cycles can be estimated.

During the Anylogic simulation, we did not put the usage time and the different seasons into consideration under a 12 months period. This will however affect the prognosis and the end results. We believe that during the winter the usage of the scooter will drop but during warmer periods it will rise. This makes an increase on usage cost but also on revenue. The main weakness of the project is that it is based on a case study with fictive data. Thus, very hard to make assumptions based on real scenarios.

### **5.1.4 Recommendation for further study**

Since this project is a case study, there is need to experiment and validate the results obtained through concurrent PPSS in the PSS design of product development. Hence, it is important to develop a real case scenario to show the essence of product design and production system of working together simultaneously during a product development to further this PPSS framework approach.

## **5.2 Conclusion**

The aim of this study is to negotiates the possibility to enable a concurrent PPSS design in product development. As of today, there is minimal or none literature that has talked about integration on design and supporting systems. Due to this non-coexistent, there is a call for a unison approach between product design and production systems in the industry to further increase the efficiency and reduce conflicts between stakeholders on the current PSS design.

In addition, the intention of the study is summarized by the research question:

*Research question: How can a PSS model-based approach be developed to reduce design iterations between product development and production service system development?*

However, the intention was never to create a new PSS but to develop PPSS to enhance the current PSS business model. This is to understand the underlying mechanisms that are important for product life cycle efficiency. By creating a unison PSS, the main stakeholders of product development have an equal partnership.

The results of the study have shown that integration of production and product development on the initial stages of the product life cycle creates a business model which generates coherency between the main stakeholders. Result of the PPSS has elaborated its significant through increased transparency of information, reduced conflicts and barriers. This process of decision support in turn optimizes product design, production flow and reduces process iterations which shortens market introduction of the product.

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# Appendix A Questionnaire

## Survey/Questionnaire

### Collaboration for an effective rental transportation sharing

The following questions are focused on the different modes of land/surface transport sharing, mainly mini cars, bicycles and scooters.

A grading score from 1 – 10 with two different statements at every end of the grading score.

(All respondents are confidential)

Name:

Age:

Sex:        Man                  Female

Term of use    Private                  Public

Occupation    Student                  Non-student

Survey/Questionnaire

A. Is the rental cost important?

Bad	1	2	3	4	5	6	7	8	9	10	Good

B. Is the land sharing transport available today easy to use?

Not important	1	2	3	4	5	6	7	8	9	10	Important

C. How important is the comfort with the use of the land sharing transport modes?

Not important	1	2	3	4	5	6	7	8	9	10	Important

D. Should they be easily accessible?

Not agree	1	2	3	4	5	6	7	8	9	10	

E. Is it important that the power source is electric?

Not important	1	2	3	4	5	6	7	8	9	10	Important

F. How important should the safety level be?

Not important	1	2	3	4	5	6	7	8	9	10	Important

G. Is it important that they have an attractive look?

Not agree	1	2	3	4	5	6	7	8	9	10	Agree

H. Is the maneuverability level important?

Not important	1	2	3	4	5	6	7	8	9	10	Important

I. Is it vital to increase the possibility of high mobility?

Not vital	1	2	3	4	5	6	7	8	9	10	Vital

J. Should they be adjustable?

Not agree	1	2	3	4	5	6	7	8	9	10	Agree

K. Is the speed important?

Not important	1	2	3	4	5	6	7	8	9	10	Important

L. Do you prefer large or small sizes?

Small	1	2	3	4	5	6	7	8	9	10	Large

M. How important is the environmental footprint?

Not important	1	2	3	4	5	6	7	8	9	10	Important

## Appendix B : Automod Simulation (Source file)

Begin model initialization function

```
create 1 load of load type L_Init to P_Init
create 1 load of load type L_Init to P_Weld_Assembly
create 1 load of load type L_Init to P_Weld_Assembly2
```

```
// Parameters you change to change variants in the model
// Material types: 1 = Aliminium, 2 = Steel, 3 = Titanium
```

```
set VI_Geometry = 2 //original/modified == 1/2
set VI_MaterialType = 3 // material
```

```
// PARTS
```

```
set VI_Handle_Type = VI_Geometry //original/modified == 1/2
set VI_Handle_Mat = VI_MaterialType // material
```

```
set VI_Bar_Type = VI_Geometry //original/modified == 1/2
set VI_Bar_Mat = VI_MaterialType // material
```

```
set VI_Deck_Type = VI_Geometry //original/modified == 1/2
set VI_Deck_Mat = VI_MaterialType // material
```

```
// PRODUCTS
```

```
// Average for the whole product rounded upwards
```

```
set VI_Pr_Type = VI_Geometry // Type or size on the product,
original/modified == 1/2
```

```
set VI_Pr_Mat = VI_MaterialType // Material for the whole product (what
material to be counted as after the welding of all parts are done)
```

```
// Machine times (original/modified, material)
```

```
// VI_XXX_Pr_* => 1 = handlebar, 2= bar, 3 = deck
```

```
set VI_Casting_Pr_1(1,1) = 7.07 // seconds
set VI_Casting_Pr_1(1,2) = 14.15 // For the handlebar
set VI_Casting_Pr_1(1,3) = 10.61
set VI_Casting_Pr_1(2,1) = 17.88
set VI_Casting_Pr_1(2,2) = 35.76
set VI_Casting_Pr_1(2,3) = 26.82
```

```
set VI_Casting_Pr_2(1,1) = 14.5 // seconds
set VI_Casting_Pr_2(1,2) = 29.1 // For the bar
set VI_Casting_Pr_2(1,3) = 21.86
set VI_Casting_Pr_2(2,1) = 8.06
set VI_Casting_Pr_2(2,2) = 16.11
set VI_Casting_Pr_2(2,3) = 12.09
```

```
set VI_Casting_Pr_3(1,1) = 1.71*60 // seconds
set VI_Casting_Pr_3(1,2) = 3.43*60 // For the deck
```

set VI\_Casting\_Pr\_3(1,3) = 2.57\*60  
set VI\_Casting\_Pr\_3(2,1) = 2.76\*60  
set VI\_Casting\_Pr\_3(2,2) = 5.53\*60  
set VI\_Casting\_Pr\_3(2,3) = 4.15\*60

set VI\_Cutting\_Pr\_1(1,1) = 10.11 // second  
set VI\_Cutting\_Pr\_1(1,2) = 9.36 // For the handlebar  
set VI\_Cutting\_Pr\_1(1,3) = 9.23  
set VI\_Cutting\_Pr\_1(2,1) = 6.47  
set VI\_Cutting\_Pr\_1(2,2) = 7.78  
set VI\_Cutting\_Pr\_1(2,3) = 7.22

set VI\_Cutting\_Pr\_2(1,1) = 20.23 // second  
set VI\_Cutting\_Pr\_2(1,2) = 18.71 // For the bar  
set VI\_Cutting\_Pr\_2(1,3) = 18.47 // remember that there are 2 cuts for the bar  
(to cut out the saddle as well)  
set VI\_Cutting\_Pr\_2(2,1) = 22.79  
set VI\_Cutting\_Pr\_2(2,2) = 24.18  
set VI\_Cutting\_Pr\_2(2,3) = 24.52

set VI\_Cutting\_Pr\_3(1,1) = 120.63 // second  
set VI\_Cutting\_Pr\_3(1,2) = 120.17 // For the deck  
set VI\_Cutting\_Pr\_3(1,3) = 120.18  
set VI\_Cutting\_Pr\_3(2,1) = 113.37  
set VI\_Cutting\_Pr\_3(2,2) = 114.09  
set VI\_Cutting\_Pr\_3(2,3) = 113.88

set VI\_Welding\_Pr (1,1) = 62.8 // Time it takes to weld the product if all parts  
are made of type and material  
set VI\_Welding\_Pr (1,2) = 8.49  
set VI\_Welding\_Pr (1,3) = 20.93  
set VI\_Welding\_Pr (2,1) = 81.64  
set VI\_Welding\_Pr (2,2) = 11.03  
set VI\_Welding\_Pr (2,3) = 27.21

set VI\_Heat1\_Pr (1) = 60 // Time for heat-treatment depending on material  
type  
set VI\_Heat1\_Pr (2) = 60  
set VI\_Heat1\_Pr (3) = 60

set VI\_Heat2\_Pr (1) = 60 // Time for heat-treatment depending on material  
type  
set VI\_Heat2\_Pr (2) = 60  
set VI\_Heat2\_Pr (3) = 60

set VI\_Paint1\_Type (1) = 1.5\*60 // Time it takes to paint depending on the  
product type (Size-modifier) == 1 or 2  
set VI\_Paint1\_Type (2) = 1.5\*60

set VI\_Paint2\_Type (1) = 1\*60

```

set VI_Paint2_Type (2) = 1*60

// Repair priority

set VI_Cutting_Priority (1) = 1
set VI_Cutting_Priority (2) = 1

set VI_Welding_Priority (1) = 2
set VI_Welding_Priority (2) = 2

set VI_Paint_Priority (1) = 3
set VI_Paint_Priority (2) = 3

// Machine downtime in minutes
set V_casting_MTBF = 100
set V_casting_MTTR = 15

set V_cutting1_MTBF = 100
set V_cutting1_MTTR = 15

set V_welding_MTBF = 130
set V_welding_MTTR = 16

set V_painting1_MTBF = 500
set V_painting2_MTBF = 650

set V_painting1_MTTR = 10
set V_painting2_MTTR = 15

// Operators
set R_Operator capacity = 1 // How many maintenance operators there are

// Preventive maintenance (hours)

set V_casting_MTBFPrev = 60
set V_casting_MTTRPrev = 5

set V_cutting_MTBFPrev = 60
set V_cutting_MTTRPrev = 2

set V_welding_MTBFPrev = 40
set V_welding_MTTRPrev = 3

set V_painting_MTBFPrev (1) = 150
set V_painting_MTTRPrev (1) = 1

set V_painting_MTBFPrev (2) = 150
set V_painting_MTTRPrev (2) = 1

```

```

        return 0
    end

begin P_Init arriving procedure

    create 1 load of load type L_RawMaterialGenerator to P_Material // create the
load responsible for arriving raw material
    create 1 load of load type L_Init to P_casting_downtime
    create 1 load of load type L_Init to P_cutting1_downtime
    create 1 load of load type L_Init to P_cutting2_downtime
    create 1 load of load type L_Init to P_welding1_downtime
    create 1 load of load type L_Init to P_welding2_downtime
    create 1 load of load type L_Init to P_painting1_downtime
    create 1 load of load type L_Init to P_painting2_downtime

    create 1 load of load type L_Init to P_casting_downtimePrev
    create 1 load of load type L_Init to P_cutting1_downtimePrev
    create 1 load of load type L_Init to P_cutting2_downtimePrev
    create 1 load of load type L_Init to P_welding1_downtimePrev
    create 1 load of load type L_Init to P_welding2_downtimePrev
    create 1 load of load type L_Init to P_painting1_downtimePrev
    create 1 load of load type L_Init to P_painting2_downtimePrev
    send to die
end

begin P_Material arriving procedure
    while 1=1 do begin
        create 1 load of load type L_RawMaterial to P_RawMaterial
        wait to be ordered on OL_NewMaterial
    end
end

begin P_RawMaterial arriving procedure
    set priority = 10 // the higher value to lower priority
    set AI_Product = one of (50:1, 40:2, 10:3) // Sitting, standing, Skate % change
for each product type
    // AI_Product = one of (A:1, B:2, C:3) A/(A+B+C) = % to get assigned value
1

    if AI_Product = 1 then begin
        clone 2 loads to P_Warehouse
    end
    if AI_Product = 2 then begin
        clone 2 loads to P_Warehouse
    end
    //if AI_Product = 3 then begin // there is only 1 part for the last product type,
so no new parts are necessary
    //    clone 1 loads to P_Warehouse
    //end
    move into Q_RawMaterial // move raw material into the warehouse

```

```

        order 1 load from OL_NewMaterial to continue
        send to P_Casting
end

begin P_Warehouse arriving procedure
    move into Q_RawMaterial // move raw material into the warehouse
    send to P_Casting
end

begin P_Casting arriving procedure

    if AI_Product = 1 then begin // give component ID
        set AI_Type = next of (1, 2, 3) // 1 = handlebar, 2= bar, 3 = deck, 4 =
saddle
    end
    if AI_Product = 2 then begin
        set AI_Type = next of (1, 2, 3) // 1 = handlebar, 2= bar, 3 = deck
    end
    if AI_Product = 3 then begin
        set AI_Type = 3 //3 = deck
    end
    end

    move into Q_Casting1

    if AI_Type = 1 then
        use R_Casting1 for VI_Casting_Pr_1 (VI_Handle_Type,
VI_Handle_Mat) sec // time for casting
    if AI_Type = 2 then
        use R_Casting1 for VI_Casting_Pr_2 (VI_Bar_Type, VI_Bar_Mat) sec
// time for casting
    if AI_Type = 3 then
        use R_Casting1 for VI_Casting_Pr_3 (VI_Deck_Type, VI_Deck_Mat)
sec // time for casting

    move into Q_Buffer1

    send to P_Cutters
end

begin P_Cutters arriving procedure
    set priority = 9
    if Q_Cutter (1) remaining space > 0 then// Just to make sure that the parts are
not waiting for the slowest cutting machine
        set AI_Cutter = 1
    else if Q_Cutter (2) remaining space > 0 then
        set AI_Cutter = 2
    else wait to be ordered on OL_CuttersFull

    move into Q_Cutter (AI_Cutter)

```

```

use R_Cutter (AI_Cutter) for normal 55, 0.1 sec //loading time

if AI_Type = 1 then
    use R_Cutter (AI_Cutter) for VI_Cutting_Pr_1(VI_Handle_Type,
VI_Handle_Mat) sec // time for cutting
    if AI_Type = 2 then
        use R_Cutter (AI_Cutter) for VI_Cutting_Pr_2(VI_Bar_Type,
VI_Bar_Mat) sec // time for cutting
    if AI_Type = 3 then
        use R_Cutter (AI_Cutter) for VI_Cutting_Pr_3(VI_Deck_Type,
VI_Deck_Mat) sec // time for cutting

    move into Q_Buffer2
    order 1 load from OL_CuttersFull to P_Cutters
    send to P_Welding
end

begin P_Welding arriving procedure

if AI_Product = 1 then begin
    if AI_Type = 1 then begin
        move into Q_Buffer_Type (1)
        wait to be ordered on OL_Type1
    end
    if AI_Type = 2 then begin
        move into Q_Buffer_Type (2)
        wait to be ordered on OL_Type2
        send to die
    end
    if AI_Type = 3 then begin
        move into Q_Buffer_Type (3)
        wait to be ordered on OL_Type3
        send to die
    end
end

if AI_Product = 2 then begin
    if AI_Type = 1 then begin
        move into Q_Buffer_Type2(1)
        wait to be ordered on OL_Type21
    end
    if AI_Type = 2 then begin
        move into Q_Buffer_Type2(2)
        wait to be ordered on OL_Type22
    end
    send to die
    if AI_Type = 3 then begin
        move into Q_Buffer_Type2(3)
        wait to be ordered on OL_Type23
        send to die
    end
end

```

```

        end
    end

    move into Q_LoadingWeld
    use R_LoadingWeld for 45 sec // change to real
    send to P_WeldingPart2
end

begin P_WeldingPart2 arriving procedure // Just to make sure that the parts are not
waiting for the slowest welding machine
    if Q_Welding (1) remaining space > 0 then
        set AI_Welding =1
    else if Q_Welding (2) remaining space > 0 then
        set AI_Welding=2
    else wait to be ordered on OL_WeldersFull

    move into Q_Welding (AI_Welding)
    use R_Welding (AI_Welding) for VI_Welding_Pr (VI_Pr_Type, VI_Pr_Mat)
    sec // time for welding

    move into Q_Buffer3
    order 1 load from OL_WeldersFull to P_WeldingPart2
    send to P_HeatTreatment
end

begin P_Weld_Assembly arriving procedure
    wait for 4 sec
    if Q_Buffer_Type (1) current loads = 0 then
        send to P_Weld_Assembly
    if Q_Buffer_Type (2) current loads = 0 then
        send to P_Weld_Assembly
    if Q_Buffer_Type (3) current loads = 0 then
        send to P_Weld_Assembly
    order 1 load from OL_Type1 to continue
    order 1 load from OL_Type2 to continue
    order 1 load from OL_Type3 to continue
    send to P_Weld_Assembly
end

begin P_Weld_Assembly2 arriving procedure
    wait for 4 sec
    if Q_Buffer_Type2(1) current loads = 0 then
        send to P_Weld_Assembly2
    if Q_Buffer_Type2(2) current loads = 0 then
        send to P_Weld_Assembly2
    if Q_Buffer_Type2(3) current loads = 0 then
        send to P_Weld_Assembly2
    order 1 load from OL_Type21 to continue
    order 1 load from OL_Type22 to continue

```

```

    order 1 load from OL_Type23 to continue
    send to P_Weld_Assembly2
end

begin P_HeatTreatment arriving procedure

    move into Q_Heat1
    use R_Heat1 for VI_Heat1_Pr (VI_Pr_Mat) sec
    move into Q_Quality
    use R_Quality for 120 sec
    set AI_Quality = one of (4:0, 96:1) // decide if the product passed the quality
test
    if AI_Quality = 0 then begin
        move into Q_Alteration
        use R_Alteration for 240 sec
    end
    if AI_Product = 3 then //if it is the skate type skip heattreatment 2
        send to P_Paint1

    send to P_Heat2
end

begin P_Heat2 arriving procedure

    move into Q>Loading
    wait for 60 sec //

    move into Q_Heat2
    use R_Heat2 for VI_Heat2_Pr (VI_Pr_Mat) sec

    move into Q_Unloading
    wait for 60 sec //

    move into Q_Buffer4
    send to P_Paint1
end

begin P_Paint1 arriving procedure
    move into Q_Paint1
    use R_Paint1 for VI_Paint1_Type (VI_Pr_Type) sec //
    move into Q_Dry1
    wait for 160 sec //
    send to P_Assembly1
end

begin P_Assembly1 arriving procedure
    move into Q_Assembly1
    use R_Assembly1 for normal 100, 2 sec //
    if AI_Product = 3 then //if it is the skate type skip to stickers
        send to P_Stickers

```

```

        send to P_Paint2
end

begin P_Paint2 arriving procedure
    move into Q_Paint2
    use R_Paint2 for VI_Paint2_Type (VI_Pr_Type) sec //
    move into Q_Dry2
    wait for 120 sec //

    if AI_Product = 2 then //if it is the standing type skip to stickers
        send to P_Stickers

    send to P_Assembly2
end

begin P_Assembly2 arriving procedure
    move into Q_Assembly2
    use R_Assembly2 for normal 100, 2 sec //
    send to P_Stickers
end

begin P_Stickers arriving procedure
    move into Q_Stickers
    use R_Stickers for 120 sec

    if AI_Product=1 then
        move into Q_Final (1)
    if AI_Product=2 then
        move into Q_Final (2)
    if AI_Product=3 then
        move into Q_Final (3)
end
// -----Reactive maintenance---

begin P_casting_downtime arriving procedure

    while 1=1 do begin
        wait for e V_casting_MTBF min
        take down R_Casting1

        wait for V_casting_MTTR min
        bring up R_Casting1
    end

end

begin P_cutting1_downtime arriving procedure
    set priority = VI_Cutting_Priority (1)
    while 1=1 do begin

```

```

        wait for e V_cutting1_MTBF min
        take down R_Cutter (1)
        use R_Operator for V_cutting1_MTTR min
        bring up R_Cutter (1)
    end
end

begin P_cutting2_downtime arriving procedure
    set priority = VI_Cutting_Priority (2)
    while 1=1 do begin
        wait for e V_cutting1_MTBF min
        take down R_Cutter (2)
        use R_Operator for V_cutting1_MTTR min
        bring up R_Cutter (2)
    end
end

begin P_welding1_downtime arriving procedure
    set priority = VI_Welding_Priority (1)
    while 1=1 do begin
        wait for e V_welding_MTBF min
        take down R_Welding (1)
        use R_Operator for V_welding_MTTR min
        bring up R_Welding (1)
    end
end

begin P_welding2_downtime arriving procedure
    set priority = VI_Welding_Priority (2)
    while 1=1 do begin
        wait for e V_welding_MTBF min
        take down R_Welding (2)
        use R_Operator for V_welding_MTTR min
        bring up R_Welding (2)
    end
end

begin P_painting1_downtime arriving procedure
    set priority = VI_Paint_Priority (1)
    while 1=1 do begin
        wait for e V_painting1_MTBF min
        take down R_Paint1
        use R_Operator for V_painting1_MTTR min
        bring up R_Paint1
    end
end

begin P_painting2_downtime arriving procedure

```

```

set priority = VI_Paint_Priority (2)
while 1=1 do begin
    wait for e V_painting1_MTBF min
    take down R_Paint2
    use R_Operator for V_painting1_MTTR min
    bring up R_Paint2
end
end

// -----Preventive maintenance---

begin P_casting_downtimePrev arriving procedure

    while 1=1 do begin
        wait for e V_casting_MTBFPprev hours
        take down R_Casting1
        set R_Casting1 active state to DownPreventive
        wait for V_casting_MTTRPrev hours
        bring up R_Casting1
    end

end

begin P_cutting1_downtimePrev arriving procedure
set priority = VI_Cutting_Priority (1)
while 1=1 do begin
    wait for e V_cutting_MTBFPprev hours
    take down R_Cutter (1)
    set R_Cutter (1) active state to DownPreventive
    use R_Operator for V_cutting_MTTRPrev hours
    bring up R_Cutter (1)
end

end

begin P_cutting2_downtimePrev arriving procedure
set priority = VI_Cutting_Priority (2)
while 1=1 do begin
    wait for e V_cutting_MTBFPprev hours
    take down R_Cutter (2)
    set R_Cutter (2) active state to DownPreventive
    use R_Operator for V_cutting_MTTRPrev hours
    bring up R_Cutter (2)
end

end

begin P_welding1_downtimePrev arriving procedure
set priority = VI_Welding_Priority (1)
while 1=1 do begin
    wait for e V_welding_MTBFPprev hours

```

```

        take down R_Welding (1)
        set R_Welding (1) active state to DownPreventive
        use R_Operator for V_welding_MTTRPrev hours
        bring up R_Welding (1)
    end
end

begin P_welding2_downtimePrev arriving procedure
    set priority = VI_Welding_Priority (2)
    while 1=1 do begin
        wait for e V_welding_MTBFPprev hours
        take down R_Welding (2)
        set R_Welding (2) active state to DownPreventive
        use R_Operator for V_welding_MTTRPrev hours
        bring up R_Welding (2)
    end
end

begin P_painting1_downtimePrev arriving procedure
    set priority = VI_Paint_Priority (1)
    while 1=1 do begin
        wait for e V_painting_MTBFPprev (1) hours
        take down R_Paint1
        set R_Paint1 active state to DownPreventive
        use R_Operator for V_painting_MTTRPrev (1) hours
        bring up R_Paint1
    end
end

begin P_painting2_downtimePrev arriving procedure
    set priority = VI_Paint_Priority (2)
    while 1=1 do begin
        wait for e V_painting_MTBFPprev (2) hours
        take down R_Paint2
        set R_Paint1 active state to DownPreventive
        use R_Operator for V_painting_MTTRPrev (2) hours
        bring up R_Paint2
    end
end

```

## Appendix C : Results of Automod simulation process

Sitting: Aluminium Original, 28206

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	41122	1	59.674	32.772
Working	85275	0	40.714	46.367
DownPreventive	36	0	6975.891	3.354
DownReactive	1079	0	1215.021	17.508

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	1077	0	864.029	12.427
Working	84322	1	52.331	58.929
DownPreventive	45	0	4731.126	2.843
DownReactive	977	0	1977.388	25.800

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	939	0	1018.686	12.774
Working	86580	1	51.725	59.807
DownPreventive	33	0	5777.649	2.546
DownReactive	953	0	1954.299	24.872

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	20964	1	184.866	51.757
Working	21875	0	61.481	17.961
DownPreventive	51	0	7029.544	4.788
DownReactive	744	0	2565.940	25.495

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	6235	1	791.080	65.871
Working	6592	0	61.426	5.408
DownPreventive	49	0	6471.958	4.235
DownReactive	697	0	2630.658	24.487

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	24329	0	164.258	53.368
Working	28286	1	89.756	33.906
DownPreventive	23	0	2161.247	0.664
DownReactive	208	0	4342.371	12.062

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	28046	1	171.642	64.288
Working	28256	0	59.900	22.603
DownPreventive	0	0	0.000	0.000
DownReactive	209	0	4696.616	13.109

Sitting: Aluminium Modified, 25616

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	5597	0	217.954	16.291
Working	77747	0	62.653	65.052
DownPreventive	28	0	5958.269	2.228
DownReactive	1045	1	1177.198	16.429

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15742	0	83.843	17.626
Working	62955	1	65.939	55.438
DownPreventive	33	0	5148.179	2.269
DownReactive	939	0	1967.032	24.667

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	15966	0	111.237	23.718
Working	92180	0	40.069	49.326
DownPreventive	39	0	4695.244	2.445
DownReactive	932	1	1969.246	24.510

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	19498	0	197.623	51.459
Working	20442	0	80.160	21.883
DownPreventive	45	0	6037.000	3.628
DownReactive	719	1	2398.393	23.029

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5051	1	970.831	65.487
Working	5468	0	80.052	5.846
DownPreventive	49	0	7398.717	4.842
DownReactive	743	0	2401.172	23.826

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	22385	1	196.286	58.679
Working	25695	0	89.753	30.799
DownPreventive	25	0	1329.542	0.444
DownReactive	222	0	3399.451	10.078

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	25441	1	201.055	68.310
Working	25687	0	59.851	20.531
DownPreventive	0	0	0.000	0.000
DownReactive	221	0	3780.951	11.159

Sitting: Stainless steel Original, 20704

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	3405	1	241.623	10.987
Working	62995	0	81.528	68.588
DownPreventive	36	0	5550.090	2.668
DownReactive	1045	0	1272.366	17.757

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	13656	0	143.038	26.086
Working	50545	0	69.525	46.930
DownPreventive	36	0	5542.586	2.665
DownReactive	960	1	1896.884	24.319

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	13749	0	181.558	33.337
Working	74866	0	39.357	39.350
DownPreventive	34	0	4143.467	1.881
DownReactive	983	1	1937.290	25.432

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	16406	0	313.980	68.792
Working	16453	0	7.992	1.756
DownPreventive	50	1	6596.823	4.405
DownReactive	755	0	2484.135	25.047

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	4650	0	1141.937	70.914
Working	4272	0	7.993	0.456
DownPreventive	36	0	7145.991	3.436
DownReactive	750	1	2515.455	25.195

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	17830	1	266.934	63.561
Working	20765	0	89.721	24.881
DownPreventive	32	0	3182.731	1.360
DownReactive	255	0	2994.711	10.198

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	20543	1	260.247	71.398
Working	20747	0	59.876	16.590
DownPreventive	0	0	0.000	0.000
DownReactive	228	0	3945.160	12.013

Sitting: Stainless steel Modified, 14323

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	462	1	1239.502	7.648
Working	43974	0	124.494	73.110
DownPreventive	27	0	5834.734	2.104
DownReactive	1110	0	1156.144	17.138

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	11748	0	267.259	41.930
Working	33300	1	70.336	31.279
DownPreventive	32	0	4533.497	1.937
DownReactive	952	0	1954.810	24.853

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	12154	0	290.568	47.163
Working	53393	0	39.329	28.044
DownPreventive	27	0	4690.530	1.691
DownReactive	926	1	1868.118	23.102

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	11905	0	438.547	69.724
Working	11940	0	10.982	1.751
DownPreventive	40	0	6617.041	3.535
DownReactive	771	1	2427.081	24.990

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	2857	0	1859.536	70.949
Working	2405	0	10.986	0.353
DownPreventive	43	0	6857.682	3.938
DownReactive	748	1	2478.616	24.760

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	12943	1	422.804	73.082
Working	14354	0	89.796	17.213
DownPreventive	26	0	3221.563	1.119
DownReactive	222	0	2896.166	8.586

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	14176	1	400.424	75.807
Working	14358	0	59.854	11.477
DownPreventive	0	0	0.000	0.000
DownReactive	200	0	4761.024	12.716

Sitting: Titanium Original, 25329

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	5696	0	225.587	17.160
Working	76795	1	61.028	62.589
DownPreventive	35	0	6201.567	2.899
DownReactive	1050	0	1237.486	17.353

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	14618	0	79.220	15.465
Working	62671	0	67.529	56.518
DownPreventive	38	0	4727.028	2.399
DownReactive	963	1	1991.947	25.618

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	14785	0	110.792	21.876
Working	90666	1	40.494	49.031
DownPreventive	47	0	5657.732	3.551
DownReactive	971	0	1969.717	25.542

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	20027	1	244.003	65.260
Working	20111	0	19.947	5.357
DownPreventive	40	0	5977.229	3.193
DownReactive	727	0	2697.526	26.190

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5628	1	904.210	67.961
Working	5289	0	19.932	1.408
DownPreventive	54	0	6039.796	4.356
DownReactive	727	0	2706.378	26.276

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	21777	1	191.846	55.794
Working	25407	0	89.715	30.441
DownPreventive	33	0	4301.914	1.896
DownReactive	219	0	4058.459	11.870

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	25154	1	197.663	66.400
Working	25382	0	59.875	20.296
DownPreventive	0	0	0.000	0.000
DownReactive	222	0	4487.608	13.305

Sitting: Titanium Modified, 18547

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	1788	0	379.797	9.069
Working	56561	1	94.150	71.117
DownPreventive	34	0	6242.102	2.834
DownReactive	1030	0	1234.436	16.980

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	12898	0	186.953	32.202
Working	44847	1	67.791	40.601
DownPreventive	29	0	4740.757	1.836
DownReactive	912	0	2082.218	25.360

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	12843	0	214.700	36.824
Working	67433	0	39.935	35.963
DownPreventive	31	0	4005.484	1.658
DownReactive	974	1	1964.589	25.554

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	14770	0	327.771	64.653
Working	14841	0	26.898	5.331
DownPreventive	41	0	7078.838	3.876
DownReactive	777	1	2519.160	26.140

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	4141	0	1256.267	69.474
Working	3769	0	26.950	1.356
DownPreventive	63	0	7868.181	6.620
DownReactive	714	1	2364.888	22.550

**Painting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	16191	1	298.354	64.512
Working	18620	0	89.638	22.290
DownPreventive	29	0	3436.968	1.331
DownReactive	230	0	3863.608	11.867

**Painting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	18380	1	297.262	72.966
Working	18594	0	59.848	14.861
DownPreventive	0	0	0.000	0.000
DownReactive	231	0	3945.868	12.173

Standing: Aluminium Original, 28550

**Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	41597	0	57.346	31.856
Working	86251	0	40.717	46.900
DownPreventive	39	1	5508.909	2.869
DownReactive	1075	0	1279.881	18.374

**Cutting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	1069	1	911.170	13.008
Working	85427	0	52.375	59.752
DownPreventive	27	0	4934.433	1.779
DownReactive	1016	0	1876.491	25.461

**Cutting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	933	1	1097.219	13.671
Working	87449	0	51.681	60.356
DownPreventive	33	0	4430.344	1.952
DownReactive	934	0	1925.727	24.020

**Welding 1**

State Name	Total	Current	Average Time	Percent Time
Idle	21348	1	184.490	52.597
Working	22195	0	61.450	18.214
DownPreventive	49	0	6476.575	4.238
DownReactive	778	0	2401.377	24.950

**Welding 2**

State Name	Total	Current	Average Time	Percent Time
Idle	6220	1	795.733	66.099
Working	6608	0	61.475	5.425
DownPreventive	41	0	7133.680	3.906
DownReactive	727	0	2530.725	24.570

**Painting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	24339	1	168.858	54.886
Working	28638	0	89.711	34.310
DownPreventive	27	0	3294.518	1.188
DownReactive	232	0	3103.774	9.616

**Painting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	28369	1	168.007	63.651
Working	28606	0	59.883	22.877
DownPreventive	0	0	0.000	0.000
DownReactive	231	0	4367.134	13.472

Standing: Aluminium Modified, 25245

#### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	5447	1	224.004	16.295
Working	76613	0	62.625	64.075
DownPreventive	30	0	4157.910	1.666
DownReactive	1091	0	1233.006	17.965

#### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15755	0	83.925	17.658
Working	60629	0	66.605	53.929
DownPreventive	36	0	4938.574	2.374
DownReactive	964	1	2022.576	26.039

#### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	15952	0	113.186	24.112
Working	92195	1	40.008	49.259
DownPreventive	27	0	4844.790	1.747
DownReactive	949	0	1963.288	24.882

#### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	18598	1	194.575	48.327
Working	19630	0	80.133	21.007
DownPreventive	54	0	6888.644	4.968
DownReactive	736	0	2614.520	25.698

#### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5432	1	875.934	63.543
Working	5897	0	80.052	6.304
DownPreventive	53	0	6536.881	4.627
DownReactive	729	0	2621.956	25.526

#### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	21542	1	192.511	55.383
Working	25332	0	89.677	30.338
DownPreventive	36	0	3398.945	1.634
DownReactive	253	0	3742.646	12.645

#### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	25045	0	199.005	66.561
Working	25312	1	59.841	20.228
DownPreventive	0	0	0.000	0.000
DownReactive	253	0	3909.949	13.211

Standing: Stainless steel Original, 21373

#### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	3611	0	235.232	11.344
Working	65066	1	81.486	70.807
DownPreventive	23	0	5819.080	1.787
DownReactive	1067	0	1127.215	16.062

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	13789	0	135.555	24.962
Working	52632	1	69.007	48.504
DownPreventive	29	0	4644.871	1.799
DownReactive	1007	0	1839.269	24.735

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	13908	1	171.859	31.921
Working	76832	0	39.542	40.573
DownPreventive	27	0	5222.401	1.883
DownReactive	1005	0	1909.135	25.623

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	16991	1	305.195	69.252
Working	17054	0	7.990	1.820
DownPreventive	47	0	8124.280	5.099
DownReactive	746	0	2391.867	23.829

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	4781	0	1110.149	70.882
Working	4348	0	7.993	0.464
DownPreventive	48	0	6865.878	4.401
DownReactive	758	1	2395.864	24.253

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	18595	1	244.787	60.788
Working	21451	0	89.670	25.688
DownPreventive	25	0	2670.262	0.892
DownReactive	224	0	4222.854	12.632

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	21191	0	247.675	70.092
Working	21417	1	59.879	17.127
DownPreventive	0	0	0.000	0.000
DownReactive	235	0	4072.643	12.781

Standing: Stainless steel Modified, 14203

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	400	0	1418.176	7.576
Working	43525	1	124.693	72.479
DownPreventive	35	0	5164.960	2.414
DownReactive	1024	0	1281.935	17.531

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	11922	1	267.287	42.556
Working	34880	0	69.150	32.211
DownPreventive	26	0	6097.222	2.117
DownReactive	912	0	1897.960	23.116

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	11677	1	295.807	46.129
Working	51076	0	39.008	26.608
DownPreventive	38	0	5270.365	2.675
DownReactive	963	0	1911.951	24.589

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	11663	1	444.822	69.284
Working	11677	0	10.983	1.713
DownPreventive	45	0	6712.885	4.034
DownReactive	754	0	2479.727	24.969

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	3001	1	1785.368	71.553
Working	2554	0	10.966	0.374
DownPreventive	47	0	8490.779	5.329
DownReactive	743	0	2292.110	22.744

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	12539	1	414.830	69.465
Working	14246	0	89.729	17.071
DownPreventive	27	0	5148.350	1.856
DownReactive	241	0	3606.457	11.607

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	14030	0	399.222	74.801
Working	14230	1	59.886	11.381
DownPreventive	0	0	0.000	0.000
DownReactive	258	0	4010.586	13.819

Standing: Titanium Original, 25470

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	5484	0	243.354	17.823
Working	77342	1	61.009	63.015
DownPreventive	29	0	5335.955	2.067
DownReactive	1066	0	1200.905	17.096

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15183	0	77.327	15.679
Working	62738	1	68.239	57.174
DownPreventive	34	0	4946.193	2.246
DownReactive	917	0	2033.380	24.901

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	15419	0	110.340	22.721
Working	91589	1	40.141	49.098
DownPreventive	40	0	4502.637	2.405
DownReactive	931	0	2073.183	25.776

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	20100	1	245.065	65.783
Working	20186	0	19.949	5.378
DownPreventive	49	0	7698.480	5.038
DownReactive	740	0	2408.458	23.802

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5691	0	911.476	69.274
Working	5367	1	19.964	1.431
DownPreventive	49	0	8089.281	5.293
DownReactive	733	0	2451.934	24.002

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	21680	0	189.996	55.009
Working	25582	1	89.638	30.624
DownPreventive	30	0	3280.794	1.314
DownReactive	239	0	4089.276	13.052

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	25298	1	197.059	66.576
Working	25540	0	59.859	20.417
DownPreventive	0	0	0.000	0.000
DownReactive	241	0	4041.463	13.007

Standing: Titanium Modified, 18464

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	1817	0	405.339	9.836
Working	56288	1	94.173	70.791
DownPreventive	32	0	5597.054	2.392
DownReactive	1030	0	1234.563	16.982

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	12648	1	183.483	30.992
Working	45671	0	67.114	40.934
DownPreventive	38	0	5405.857	2.743
DownReactive	981	0	1933.466	25.330

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	12612	1	212.384	35.772
Working	66149	0	39.940	35.283
DownPreventive	44	0	4987.824	2.931
DownReactive	960	0	2029.155	26.015

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	14834	1	323.828	64.151
Working	14925	0	26.902	5.362
DownPreventive	46	0	6473.392	3.977
DownReactive	720	0	2757.010	26.510

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	3984	0	1279.214	68.061
Working	3605	0	26.933	1.297
DownPreventive	49	0	6152.020	4.026
DownReactive	745	1	2675.263	26.617

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15888	1	297.229	63.066
Working	18532	0	89.676	22.194
DownPreventive	29	0	3759.791	1.456
DownReactive	254	0	3916.193	13.284

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	18292	1	294.535	71.950
Working	18510	0	59.854	14.796
DownPreventive	0	0	0.000	0.000
DownReactive	217	0	4573.592	13.254

Skate: Aluminium Original, 41705

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	11084	0	172.115	25.477
Working	42427	1	100.318	56.840
DownPreventive	23	0	5799.648	1.781
DownReactive	1051	0	1132.937	15.902

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	10401	0	170.417	23.671
Working	42418	0	86.221	48.843
DownPreventive	32	0	5320.115	2.274
DownReactive	964	1	1958.419	25.213

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	10039	0	184.622	24.752
Working	42266	1	86.213	48.663
DownPreventive	32	0	4452.935	1.903
DownReactive	959	0	1927.240	24.682

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	23365	0	159.491	49.766
Working	24678	0	61.462	20.256
DownPreventive	51	1	7452.125	5.076
DownReactive	724	0	2575.502	24.902

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	16178	1	252.719	54.600
Working	17404	0	61.459	14.285
DownPreventive	49	0	7814.777	5.114
DownReactive	768	0	2535.113	26.001

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	39907	0	70.249	37.439
Working	41835	1	89.721	50.127
DownPreventive	26	0	3738.999	1.298
DownReactive	227	0	3673.419	11.136

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	221	0	29249.673	86.327
Working	0	0	0.000	0.000
DownPreventive	0	0	0.000	0.000
DownReactive	221	1	4632.680	13.673

Skate: Aluminium Modified, 29755

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	1181	0	984.586	15.529
Working	30584	1	160.552	65.576
DownPreventive	28	0	5612.340	2.099
DownReactive	1065	0	1180.965	16.797

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	10441	1	277.435	38.684
Working	30481	0	82.785	33.699
DownPreventive	35	0	5063.484	2.367
DownReactive	950	0	1990.227	25.250

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	10114	1	292.239	39.473
Working	29880	0	82.869	33.068
DownPreventive	32	0	4670.777	1.996
DownReactive	930	0	2050.206	25.463

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	21723	1	154.433	44.802
Working	22963	0	80.146	24.578
DownPreventive	56	0	5644.436	4.221
DownReactive	741	0	2667.686	26.399

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	6362	1	713.062	60.584
Working	7129	0	79.966	7.613
DownPreventive	47	0	5890.120	3.697
DownReactive	798	0	2637.327	28.106

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	28050	0	133.099	49.859
Working	29841	1	89.742	35.764
DownPreventive	25	0	5052.183	1.687
DownReactive	224	0	4242.373	12.691

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	236	1	27208.020	85.752
Working	0	0	0.000	0.000
DownPreventive	0	0	0.000	0.000
DownReactive	235	0	4540.031	14.248

Skate: Stainless steel Original, 24708

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	334	0	2426.611	10.824
Working	25593	1	197.950	67.657
DownPreventive	40	0	6185.556	3.304
DownReactive	1061	0	1285.542	18.215

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	18839	0	106.982	26.916
Working	40237	1	86.215	46.328
DownPreventive	36	0	4111.319	1.977
DownReactive	978	0	1897.267	24.780

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	4483	1	1051.560	62.956
Working	9916	0	86.283	11.426
DownPreventive	38	0	4382.305	2.224
DownReactive	975	0	1796.665	23.394

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	20198	1	254.228	68.575
Working	20261	0	7.990	2.162
DownPreventive	38	0	5862.726	2.975
DownReactive	783	0	2513.968	26.288

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	4878	1	1086.324	70.768
Working	4478	0	7.995	0.478
DownPreventive	41	0	6262.432	3.429
DownReactive	766	0	2475.654	25.325

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	23615	0	187.579	59.157
Working	24799	1	89.671	29.697
DownPreventive	25	0	4230.224	1.412
DownReactive	236	0	3088.234	9.733

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	220	1	29608.380	86.990
Working	0	0	0.000	0.000
DownPreventive	0	0	0.000	0.000
DownReactive	219	0	4448.202	13.010

Skate: Stainless steel Modified, 15727

**Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	259	0	2706.587	9.362
Working	16617	1	313.587	69.590
DownPreventive	39	0	6331.985	3.298
DownReactive	1043	0	1274.375	17.751

**Cutting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	12432	0	267.464	44.406
Working	26036	0	83.283	28.958
DownPreventive	28	0	4405.975	1.648
DownReactive	951	1	1967.579	24.989

**Cutting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	3102	1	1615.543	66.926
Working	5900	0	83.381	6.570
DownPreventive	31	0	5437.946	2.251
DownReactive	977	0	1858.814	24.253

**Welding 1**

State Name	Total	Current	Average Time	Percent Time
Idle	13186	1	391.805	68.995
Working	13197	0	10.987	1.936
DownPreventive	42	0	7321.698	4.107
DownReactive	755	0	2475.697	24.962

**Welding 2**

State Name	Total	Current	Average Time	Percent Time
Idle	3006	1	1754.613	70.438
Working	2561	0	10.983	0.376
DownPreventive	53	0	6324.729	4.477
DownReactive	732	0	2527.728	24.710

**Painting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	15350	0	343.028	70.319
Working	15783	1	89.686	18.904
DownPreventive	30	0	3669.786	1.470
DownReactive	244	0	2856.180	9.307

**Painting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	231	1	27724.740	85.529
Working	0	0	0.000	0.000
DownPreventive	0	0	0.000	0.000
DownReactive	230	0	4711.239	14.471

Skate: Titanium Original, 31488

**Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	1475	0	716.502	14.114
Working	32377	1	149.802	64.772
DownPreventive	38	0	4778.392	2.425
DownReactive	1067	0	1311.566	18.689

**Cutting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	10771	1	252.192	36.276
Working	32330	0	86.244	37.237
DownPreventive	35	0	4291.302	2.006
DownReactive	965	0	1899.654	24.481

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	10401	0	275.345	38.246
Working	31606	1	86.157	36.366
DownPreventive	25	0	4983.922	1.664
DownReactive	976	0	1820.136	23.724

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	25173	1	193.266	64.972
Working	25280	0	19.940	6.732
DownPreventive	54	0	5907.884	4.260
DownReactive	773	0	2328.339	24.036

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	6648	1	767.903	68.176
Working	6308	0	19.937	1.679
DownPreventive	42	0	5721.957	3.209
DownReactive	775	0	2602.450	26.935

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	29741	1	127.908	50.803
Working	31617	0	89.639	37.849
DownPreventive	24	0	2674.401	0.857
DownReactive	254	0	3092.801	10.491

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	246	1	26717.193	87.773
Working	0	0	0.000	0.000
DownPreventive	0	0	0.000	0.000
DownReactive	245	0	3737.023	12.227

Skate: Titanium Modified, 20544

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	367	0	2576.261	12.627
Working	21432	1	238.726	68.328
DownPreventive	28	0	5756.610	2.153
DownReactive	1078	0	1173.423	16.893

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15665	1	167.693	35.082
Working	33311	0	82.742	36.808
DownPreventive	33	0	3954.621	1.743
DownReactive	976	0	2022.925	26.367

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	3750	1	1262.467	63.225
Working	8398	0	82.840	9.291
DownPreventive	37	0	5250.562	2.594
DownReactive	931	0	2001.919	24.890

**Welding 1**

State Name	Total	Current	Average Time	Percent Time
Idle	16608	1	284.051	63.001
Working	16700	0	26.913	6.002
DownPreventive	53	0	6841.424	4.842
DownReactive	739	0	2650.126	26.154

**Welding 2**

State Name	Total	Current	Average Time	Percent Time
Idle	4263	1	1202.156	68.440
Working	3919	0	26.869	1.406
DownPreventive	49	0	7933.690	5.192
DownReactive	723	0	2585.282	24.962

**Painting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	19669	0	232.979	61.197
Working	20612	1	89.694	24.690
DownPreventive	27	0	5426.631	1.957
DownReactive	228	0	3992.334	12.156

**Painting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	226	1	28785.267	86.879
Working	0	0	0.000	0.000
DownPreventive	0	0	0.000	0.000
DownReactive	225	0	4366.799	13.121

Mix A: Throughput are 12041, 8898, 8955 for Aluminium Original

**Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	21653	0	110.831	32.049
Working	72414	1	48.196	46.609
DownPreventive	38	0	6379.561	3.237
DownReactive	1083	0	1251.812	18.105

**Cutting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	1434	0	872.909	16.717
Working	71613	1	56.523	54.057
DownPreventive	44	0	4458.862	2.620
DownReactive	973	0	2047.540	26.606

**Cutting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	1266	0	1037.592	17.543
Working	73363	1	56.121	54.984
DownPreventive	45	0	4779.966	2.873
DownReactive	943	0	1953.475	24.601

**Welding 1**

State Name	Total	Current	Average Time	Percent Time
Idle	19637	0	200.976	52.705
Working	20863	1	61.479	17.129
DownPreventive	44	0	7458.801	4.383
DownReactive	738	0	2615.986	25.783

**Welding 2**

State Name	Total	Current	Average Time	Percent Time
Idle	8201	0	561.723	61.521
Working	9293	0	61.453	7.627
DownPreventive	50	0	6247.351	4.172
DownReactive	729	1	2740.552	26.681

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	18915	1	200.970	50.766
Working	29981	0	89.732	35.928
DownPreventive	27	0	2695.746	0.972
DownReactive	226	0	4086.818	12.335

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	20758	1	246.194	68.249
Working	20982	0	59.877	16.778
DownPreventive	0	0	0.000	0.000
DownReactive	246	0	4557.580	14.973

Mix A: Throughput are 9890, 7412, 7465 for Aluminium Modified

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	4356	1	339.887	19.772
Working	60160	0	75.155	60.381
DownPreventive	33	0	7006.463	3.088
DownReactive	1048	0	1197.452	16.759

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	14193	0	128.231	24.305
Working	58187	0	61.953	48.142
DownPreventive	35	0	4909.968	2.295
DownReactive	928	1	2038.031	25.258

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	12004	0	191.498	30.699
Working	61761	0	47.701	39.344
DownPreventive	44	1	4135.716	2.430
DownReactive	987	0	2088.356	27.527

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	18478	1	196.490	48.488
Working	19373	0	80.143	20.735
DownPreventive	44	0	7233.417	4.250
DownReactive	706	0	2813.562	26.527

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5110	0	915.991	62.510
Working	5676	0	79.973	6.062
DownPreventive	65	0	5639.802	4.896
DownReactive	746	1	2663.238	26.533

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	16786	1	239.020	53.581
Working	24853	0	89.698	29.771
DownPreventive	21	0	3895.766	1.093
DownReactive	255	0	4567.618	15.555

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	17134	0	320.716	73.386
Working	17347	0	59.847	13.865
DownPreventive	0	0	0.000	0.000
DownReactive	224	1	4261.932	12.749

Mix A: Throughput are 8573, 6483, 6340 for Stainless steel Original

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	1917	0	552.091	14.134
Working	52357	1	96.179	67.250
DownPreventive	29	0	6070.927	2.351
DownReactive	1021	0	1192.886	16.265

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	14630	1	139.500	27.255
Working	47576	0	72.989	46.374
DownPreventive	21	0	4022.752	1.128
DownReactive	948	0	1993.807	25.242

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	10885	1	280.870	40.829
Working	56475	0	41.376	31.206
DownPreventive	34	0	5386.182	2.446
DownReactive	960	0	1990.531	25.520

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	17433	1	298.029	69.385
Working	17479	0	7.992	1.865
DownPreventive	53	0	7222.268	5.112
DownReactive	720	0	2458.332	23.638

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	4337	1	1184.184	68.587
Working	3946	0	7.988	0.421
DownPreventive	52	0	6674.185	4.635
DownReactive	761	0	2593.451	26.357

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15476	0	291.757	60.299
Working	21479	1	89.662	25.719
DownPreventive	34	0	2889.217	1.312
DownReactive	258	0	3677.052	12.669

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	14899	1	375.246	74.663
Working	15093	0	59.857	12.065
DownPreventive	0	0	0.000	0.000
DownReactive	215	0	4622.289	13.272

Mix A: Throughput are 5820, 4474, 4305 for Stainless steel Modified

**Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	464	0	1396.873	8.656
Working	36102	1	148.471	71.583
DownPreventive	34	0	6694.868	3.040
DownReactive	1029	0	1216.833	16.722

**Cutting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	12173	1	271.260	44.098
Working	32300	0	72.561	31.300
DownPreventive	28	0	4568.027	1.708
DownReactive	942	0	1819.888	22.894

**Cutting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	9304	1	425.567	52.878
Working	38800	0	40.648	21.062
DownPreventive	39	0	5006.477	2.608
DownReactive	993	0	1768.516	23.453

**Welding 1**

State Name	Total	Current	Average Time	Percent Time
Idle	12190	0	438.436	71.375
Working	12192	0	10.977	1.787
DownPreventive	37	0	5455.409	2.696
DownReactive	771	1	2344.738	24.143

**Welding 2**

State Name	Total	Current	Average Time	Percent Time
Idle	2912	0	1882.376	73.203
Working	2440	1	10.983	0.358
DownPreventive	40	0	6972.501	3.725
DownReactive	742	0	2292.215	22.714

**Painting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	12902	1	409.458	70.551
Working	14647	0	89.718	17.549
DownPreventive	27	0	6893.404	2.486
DownReactive	229	0	3078.424	9.415

**Painting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	10204	1	591.299	80.577
Working	10322	0	59.843	8.249
DownPreventive	0	0	0.000	0.000
DownReactive	235	0	3560.353	11.174

Mix A: Throughput are 10588, 8064, 8078 for Titanium Original

**Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	4601	0	305.453	18.769
Working	64891	1	72.393	62.735
DownPreventive	25	0	5615.218	1.875
DownReactive	1085	0	1147.101	16.621

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	12741	0	122.382	20.824
Working	61912	1	63.862	52.802
DownPreventive	25	0	4095.857	1.367
DownReactive	986	0	1899.106	25.007

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	12025	0	183.483	29.466
Working	67483	1	48.659	43.852
DownPreventive	32	0	4837.737	2.067
DownReactive	951	0	1938.135	24.615

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	21594	1	219.712	63.361
Working	21684	0	19.951	5.778
DownPreventive	47	0	7386.476	4.636
DownReactive	768	0	2556.965	26.225

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5484	1	921.243	67.469
Working	5121	0	19.965	1.365
DownPreventive	54	0	5770.333	4.161
DownReactive	755	0	2678.230	27.004

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	18189	0	230.157	55.907
Working	26828	1	89.692	32.135
DownPreventive	30	0	3711.269	1.487
DownReactive	238	0	3294.427	10.471

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	18483	0	299.496	73.926
Working	18697	0	59.856	14.946
DownPreventive	0	0	0.000	0.000
DownReactive	227	1	3670.890	11.128

Mix A: Throughput are 7739, 5829, 5861 for Titanium Modified

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	938	0	829.571	10.392
Working	47462	1	112.828	71.515
DownPreventive	26	0	5430.004	1.885
DownReactive	1032	0	1176.010	16.208

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	14149	1	176.428	33.337
Working	42092	0	71.372	40.120
DownPreventive	36	0	4947.739	2.379
DownReactive	1023	0	1768.718	24.164

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	10548	1	317.891	44.780
Working	51954	0	41.855	29.040
DownPreventive	37	0	4600.751	2.273
DownReactive	982	0	1822.937	23.907

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	16128	0	311.778	67.152
Working	16208	0	26.918	5.827
DownPreventive	35	1	6694.009	3.129
DownReactive	738	0	2424.202	23.892

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	3699	1	1433.944	70.835
Working	3278	0	26.942	1.179
DownPreventive	47	0	7410.163	4.651
DownReactive	739	0	2364.339	23.334

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	14538	1	345.643	67.107
Working	19491	0	89.709	23.351
DownPreventive	23	0	2085.521	0.641
DownReactive	229	0	2910.684	8.902

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	13437	1	431.509	77.433
Working	13593	0	59.890	10.872
DownPreventive	0	0	0.000	0.000
DownReactive	219	0	3998.777	11.695

Mix B: Throughput are 14754, 11993, 3009 for Aluminium Original

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	33891	1	73.931	33.461
Working	83847	0	42.921	48.061
DownPreventive	30	0	4873.436	1.952
DownReactive	994	0	1244.888	16.525

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	1099	0	857.594	12.587
Working	83723	1	53.572	59.899
DownPreventive	33	0	5194.796	2.289
DownReactive	983	0	1921.498	25.225

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	941	0	1017.377	12.785
Working	84464	0	52.938	59.713
DownPreventive	32	0	4267.919	1.824
DownReactive	997	1	1928.524	25.678

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	21112	1	181.688	51.226
Working	22317	0	61.414	18.304
DownPreventive	50	0	5685.279	3.796
DownReactive	789	0	2531.517	26.674

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	7005	0	684.089	63.996
Working	7734	0	61.415	6.343
DownPreventive	42	1	6388.038	3.583
DownReactive	781	0	2500.231	26.077

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	23418	1	171.083	53.505
Working	29866	0	89.694	35.775
DownPreventive	31	0	3737.044	1.547
DownReactive	224	0	3066.683	9.174

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	26549	0	187.306	66.410
Working	26802	0	59.877	21.432
DownPreventive	0	0	0.000	0.000
DownReactive	233	1	3907.225	12.158

Mix B: Throughput are 12878, 10414, 2617 for Aluminium Modified

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	5252	0	225.447	15.813
Working	73332	1	66.268	64.898
DownPreventive	32	0	4356.339	1.862
DownReactive	1025	0	1273.137	17.427

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	15978	0	98.217	20.958
Working	63362	1	64.094	54.235
DownPreventive	30	0	6445.466	2.582
DownReactive	905	0	1838.862	22.224

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	14910	0	138.215	27.521
Working	82944	1	42.310	46.867
DownPreventive	21	0	4126.973	1.157
DownReactive	961	0	1905.470	24.455

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	19547	0	188.910	49.314
Working	20497	1	80.141	21.937
DownPreventive	44	0	6256.857	3.677
DownReactive	781	0	2403.888	25.073

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5353	1	908.117	64.919
Working	5696	0	80.161	6.098
DownPreventive	53	0	5986.811	4.237
DownReactive	757	0	2447.757	24.746

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	20887	0	203.994	56.902
Working	26011	1	89.659	31.145
DownPreventive	23	0	3258.047	1.001
DownReactive	226	0	3628.868	10.953

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	23095	0	216.326	66.721
Working	23345	0	59.864	18.663
DownPreventive	0	0	0.000	0.000
DownReactive	261	1	4193.226	14.616

Mix B: Throughput are 10295, 8426, 2086 for Stainless steel Original

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	2796	1	309.824	11.569
Working	59133	0	85.776	67.738
DownPreventive	37	0	7159.660	3.538
DownReactive	1045	0	1229.291	17.156

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	13700	0	148.353	27.143
Working	49990	0	69.935	46.689
DownPreventive	27	0	5244.328	1.891
DownReactive	963	1	1887.771	24.278

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	12521	0	215.423	36.022
Working	67613	0	40.106	36.214
DownPreventive	33	1	5344.616	2.355
DownReactive	993	0	1916.065	25.409

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	16742	0	308.056	68.876
Working	16775	0	7.990	1.790
DownPreventive	48	0	7096.646	4.549
DownReactive	752	1	2467.891	24.784

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	4453	1	1172.696	69.738
Working	4058	0	7.992	0.433
DownPreventive	48	0	7396.734	4.741
DownReactive	760	0	2471.723	25.087

#### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	16937	0	267.286	60.457
Working	20873	1	89.711	25.007
DownPreventive	26	0	3684.889	1.279
DownReactive	246	0	4035.118	13.256

#### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	18563	1	291.972	72.381
Working	18767	0	59.856	15.002
DownPreventive	0	0	0.000	0.000
DownReactive	236	0	4003.380	12.617

Mix B: Throughput are 7252, 5918, 1434 for Stainless steel Modified

#### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	469	0	1225.549	7.676
Working	41907	1	131.439	73.560
DownPreventive	28	0	5614.741	2.100
DownReactive	1055	0	1182.754	16.664

#### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	12086	0	266.263	42.976
Working	33840	1	70.633	31.920
DownPreventive	31	0	4752.773	1.968
DownReactive	978	0	1771.375	23.136

#### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	11179	1	329.828	49.241
Working	48845	0	39.652	25.866
DownPreventive	26	0	4681.873	1.626
DownReactive	964	0	1807.376	23.268

#### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	12337	1	440.032	72.498
Working	12348	0	10.984	1.811
DownPreventive	34	0	6805.572	3.090
DownReactive	783	0	2161.309	22.600

#### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	2766	1	1994.375	73.670
Working	2283	0	10.971	0.334
DownPreventive	41	0	6764.162	3.704
DownReactive	752	0	2219.657	22.291

#### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	13384	1	409.476	73.190
Working	14642	0	89.773	17.554
DownPreventive	17	0	3754.150	0.852
DownReactive	232	0	2712.438	8.404

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	13022	1	453.049	78.787
Working	13195	0	59.891	10.554
DownPreventive	0	0	0.000	0.000
DownReactive	232	0	3440.251	10.659

Mix B: Throughput are 12652, 10155, 2531 for Titanium Original

### Casting

State Name	Total	Current	Average Time	Percent Time
Idle	5311	0	265.477	18.829
Working	71799	1	64.223	61.580
DownPreventive	30	0	6091.918	2.441
DownReactive	1084	0	1184.649	17.150

### Cutting 1

State Name	Total	Current	Average Time	Percent Time
Idle	13808	0	93.992	17.332
Working	62128	1	65.578	54.410
DownPreventive	35	0	5206.870	2.434
DownReactive	968	0	1997.598	25.824

### Cutting 2

State Name	Total	Current	Average Time	Percent Time
Idle	13794	0	135.704	24.999
Working	81174	1	42.964	46.576
DownPreventive	40	0	5432.185	2.902
DownReactive	939	0	2035.393	25.524

### Welding 1

State Name	Total	Current	Average Time	Percent Time
Idle	19721	0	239.418	63.055
Working	19815	0	19.944	5.278
DownPreventive	58	0	7203.961	5.580
DownReactive	755	1	2587.307	26.087

### Welding 2

State Name	Total	Current	Average Time	Percent Time
Idle	5952	1	860.446	68.394
Working	5602	0	19.936	1.491
DownPreventive	44	0	5764.028	3.387
DownReactive	768	0	2605.898	26.727

### Painting 1

State Name	Total	Current	Average Time	Percent Time
Idle	20454	0	207.375	56.646
Working	25419	1	89.719	30.456
DownPreventive	18	0	2807.094	0.675
DownReactive	222	0	4122.795	12.223

### Painting 2

State Name	Total	Current	Average Time	Percent Time
Idle	22607	1	232.910	70.318
Working	22864	0	59.853	18.276
DownPreventive	0	0	0.000	0.000
DownReactive	233	0	3665.726	11.406

Mix B: Throughput are 9354, 7717, 1864 for Titanium Modified

#### **Casting**

State Name	Total	Current	Average Time	Percent Time
Idle	1381	1	486.317	8.969
Working	54074	0	99.236	71.663
DownPreventive	28	0	5975.026	2.234
DownReactive	1105	0	1161.085	17.134

#### **Cutting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	13222	0	185.037	32.673
Working	44736	0	68.504	40.927
DownPreventive	30	0	4769.794	1.911
DownReactive	946	1	1938.447	24.489

#### **Cutting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	11996	0	247.437	39.640
Working	62417	0	40.464	33.729
DownPreventive	35	0	4209.419	1.968
DownReactive	975	1	1894.123	24.663

#### **Welding 1**

State Name	Total	Current	Average Time	Percent Time
Idle	15029	0	324.079	65.045
Working	15126	0	26.904	5.435
DownPreventive	52	0	5855.478	4.066
DownReactive	779	1	2446.709	25.454

#### **Welding 2**

State Name	Total	Current	Average Time	Percent Time
Idle	4219	0	1248.600	70.350
Working	3888	0	26.826	1.393
DownPreventive	43	0	7581.934	4.354
DownReactive	719	1	2489.337	23.903

#### **Painting 1**

State Name	Total	Current	Average Time	Percent Time
Idle	15631	1	315.900	65.943
Working	18998	0	89.696	22.757
DownPreventive	30	0	2925.209	1.172
DownReactive	239	0	3173.135	10.128

#### **Painting 2**

State Name	Total	Current	Average Time	Percent Time
Idle	16890	1	328.753	74.154
Working	17112	0	59.856	13.679
DownPreventive	0	0	0.000	0.000
DownReactive	243	0	3749.359	12.167

## Appendix D 100% E-scooter Design

### Appendix D.1 Sitting design

	Throughput	Casting		Cutting 1		Cutting 2		Welding 1		Welding 2		Paint 1		Paint 2	
		M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)
O. Al.	28206	20. 3	1.9	33	2.1	32. 86	2.2	42. 8	2.8	43. 8	3	72. 4	10	78. 3	10
M. Al.	25616	19. 6	2	32. 8	2.2	32. 8	2.2	40	2.9	40	2.8	56. 7	9.4	63	9.4
O. St. Steel	20704	21. 2	2	31. 6	2.2	32. 3	2.1	41. 4	2.8	42	2.8	50	8.2	65. 8	9.1
M. St. Steel	14323	19. 3	1.9	32. 6	2.2	31. 1	2.2	40. 5	2.7	41. 3	2.8	48. 3	9.4	79. 4	10. 4
O. Tit.	25329	20. 6	2	33. 2	2.2	32. 8	2.1	45	2.9	45. 1	2.9	67. 6	9.5	74. 8	9.4
M. Tit.	18547	20. 6	2	34. 7	2.3	32. 7	2.1	42	2.7	39. 4	2.9	64. 4	9	65. 8	9

### Appendix D.2 Standing design

	Throughput	Casting		Cutting 1		Cutting 2		Welding 1		Welding 2		Paint 1		Paint 2	
		M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)
O. Al.	28550	21. 3	1.9	31. 3	2	32. 1	2.2	40	2.7	42. 2	2.9	51. 7	9	72. 8	9
M. Al.	25245	20. 6	1.9	33. 7	2.2	32. 7	2.2	43. 6	2.8	43. 7	2.9	62. 4	8.2	65. 2	8.2
O. St. Steel	21373	18. 8	2	30. 7	2.1	31. 8	2.1	39. 9	2.8	40	2.7	70. 4	9.2	67. 9	8.9
M. St. Steel	14203	20. 3	2	31. 6	2.3	31. 9	2.2	41. 3	2.8	38. 2	2.8	60. 1	8.6	66. 8	8
O. Tit.	25470	20	2	33. 9	2.7	34. 6	2.2	40. 1	2.8	40. 9	2.8	68. 2	8.7	67. 4	8.6
M. Tit.	18464	20. 6	2	32. 2	2.1	33. 8	2.2	46	2.9	44. 6	2.8	65. 3	8.2	76. 2	9.6

### Appendix D.3 Skate design

	Throughput	Casting		Cutting 1		Cutting 2		Welding 1		Welding 2		Paint 1		Paint 2	
		M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)
O. Al.	41705	18. 9	2	32. 6	2.2	32. 1	2.2	43	2.9	42. 3	2.7	61. 2	9.2	77. 2	9.4
M. Al.	29755	19. 7	2	33. 2	2.2	34. 2	2.2	44. 5	2.8	44	2.6	70. 7	9.3	75. 7	8.9
O. St. Steel	24708	21. 4	2	31. 6	2.1	30	2.1	41. 9	2.7	41. 3	2.7	51. 5	8.8	74. 1	9.5
M. St. Steel	15727	21. 2	2	32. 8	2.2	31	2.1	41. 3	2.8	42. 1	2.8	47. 6	8.5	78. 5	9
O. Tit.	31488	21. 9	2	31. 7	2.2	30. 3	2.1	38. 8	2.7	43. 4	2.7	51. 5	8.2	62. 3	8.5
M. Tit.	20544	19. 6	1.9	33. 7	2.1	33. 4	2.2	44. 2	2.8	43. 1	2.9	66. 5	9.1	72. 8	9.2

## Appendix E Mix A (40% of 1, 30% of 2, 30% of 3)

		Throughput	Casting		Cutting 1		Cutting 2		Welding 1		Welding 2		Paint 1		Paint 2	
			M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)
O. Al.	1	12041	20.	1.9	34.	2.1	32.	2.2	43.	2.8	45.	2.9	68.	9.2	76	8.5
	2	8898	9		1		6		6		7		1			
	3	8955														
M. Al.	1	9890														
	2	7412					8		9		4		1			
	3	7465														
O. St. Steel	1	8573														
	2	6483	9		2		2				2		3			
	3	6340														
M. St. Steel	1	5820														
	2	4474	3		3		5		1		2		3		3	
	3	4305														
O. Tit.	1	10588														
	2	8064	1		7		3		6		6		9		2	
	3	8078														
M. Tit.	1	7739														
	2	5829	6		5		4		4		4		5		6	
	3	5861														

## Appendix F Mix B (50% of 1, 40% of 2, 10% of 3)

		Throughput	Casting		Cutting 1		Cutting 2		Welding 1		Welding 2		Paint 1		Paint 2	
			M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)	M TT R (mi n)	M TB F (hr s)
O. Al.	1	14754	20.	2.1	32	2.1	32.	2.1	42.	2.6	41.	2.7	51.	9.3	65.	8.9
	2	11993	7				1		2		7		1		1	
	3	3009														
1	12878	21.														
M. Al.	2	10414	2		6		8		1		8		5		9	
	3	2617														
	1	10295														
O. St. Steel	2	8426	5		5		9		1		2		3		7	
	3	2086														
	1	7252														
M. St. Steel	2	5918	7		5		1						2		3	
	3	1434														
	1	12652														
O. Tit.	2	10155	7		3		9		1		4		7		1	
	3	2531														
	1	9354														
M. Tit.	2	7717	4		3		6		8		5		9		5	
	3	1864														

# Appendix G Employee Ergonomic Worksheet

## A. Neck, Trunk and Leg Analysis

### Step 1: Locate Neck Position



Step 1a: Adjust...  
If neck is twisted: +1  
If neck is side bending: +1

Neck Score

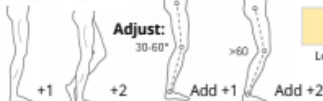
### Step 2: Locate Trunk Position



Step 2a: Adjust...  
If trunk is twisted: +1  
If trunk is side bending: +1

Trunk Score

### Step 3: Legs



Adjust: 30-60° Add +1  
>60° Add +2

Leg Score

### Step 4: Look-up Posture Score in Table A

Using values from steps 1-3 above, Locate score in Table A

Posture Score A

### Step 5: Add Force/Load Score

If load < 11 lbs. : +0  
If load 11 to 22 lbs. : +1  
If load > 22 lbs. : +2

Adjust: If shock or rapid build up of force: add +1 Force / Load Score

Force / Load Score

### Step 6: Score A, Find Row in Table C

Add values from steps 4 & 5 to obtain Score A.

Find Row in Table C.

Score A

### Scoring

1 = Negligible Risk  
2-3 = Low Risk. Change may be needed.  
4-7 = Medium Risk. Further Investigate. Change Soon.  
8-10 = High Risk. Investigate and Implement Change  
11+ = Very High Risk. Implement Change

## Scores

Table A		Neck											
		1			2			3					
Legs		1	2	3	4	1	2	3	4	1	2	3	4
1	Trunk Posture Score	1	2	3	4	1	2	3	4	3	3	5	6
2		2	3	4	5	3	4	5	6	4	5	6	7
3		2	4	5	6	4	5	6	7	5	6	7	8
4		3	5	6	7	5	6	7	8	6	7	8	9
5		4	6	7	8	6	7	8	9	7	8	9	9

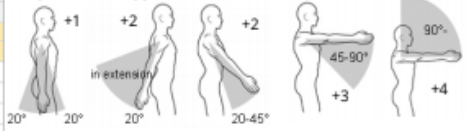
Table B		Lower Arm					
		1		2			
Wrist		1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Score A	Table C														
	Score B														
1	1	1	1	2	3	3	4	5	6	7	8	9	10	11	12
2	1	2	2	3	4	4	5	6	6	7	7	8	9	10	11
3	2	3	3	3	4	5	6	7	7	8	8	8	9	9	9
4	3	4	4	4	5	6	7	8	8	9	9	9	9	9	9
5	4	4	4	5	6	7	8	8	8	9	9	9	9	9	9
6	6	6	6	7	8	8	8	9	9	10	10	10	10	10	10
7	7	7	7	8	9	9	9	10	10	10	11	11	11	11	11
8	8	8	8	9	10	10	10	10	10	10	11	11	11	11	11
9	9	9	9	10	10	10	10	10	10	10	11	11	11	11	11
10	10	10	10	11	11	11	11	11	11	11	12	12	12	12	12
11	11	11	11	11	11	11	11	11	11	11	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score  + Activity Score  = REBA Score

## B. Arm and Wrist Analysis

### Step 7: Locate Upper Arm Position:



Step 7a: Adjust...  
If shoulder is raised: +1  
If upper arm is abducted: +1  
If arm is supported or person is leaning: -1

Upper Arm Score

### Step 8: Locate Lower Arm Position:



Step 8a: Adjust...  
If wrist is bent from midline or twisted: Add +1

Lower Arm Score

### Step 9: Locate Wrist Position:



Step 9a: Adjust...  
If wrist is bent from midline or twisted: Add +1

Wrist Score

### Step 10: Look-up Posture Score in Table B

Using values from steps 7-9 above, locate score in Table B

Posture Score B

### Step 11: Add Coupling Score

Well fitting Handle and mid rang power grip. **good: +0**  
Acceptable but not ideal hand hold or coupling acceptable with another body part. **fair: +1**  
Hand hold not acceptable but possible. **poor: +2**  
No handles, awkward, unsafe with any body part. **Unacceptable: +3**

Coupling Score

### Step 12: Score B, Find Column in Table C

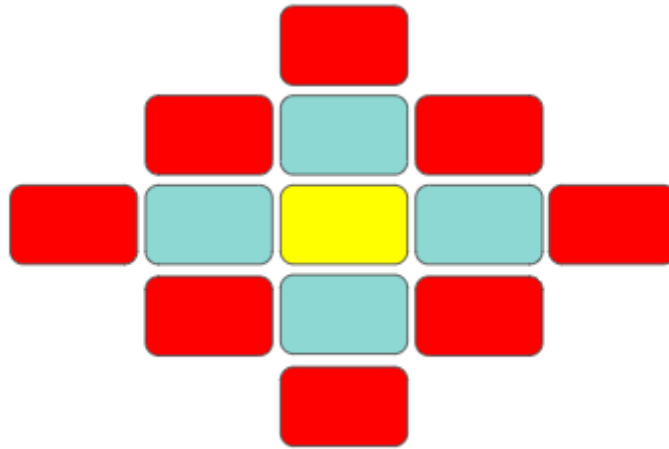
Add values from steps 10 & 11 to obtain Score B. Find column in Table C and match with Score A in row from step 6 to obtain Table C Score.

Score B

### Step 13: Activity Score

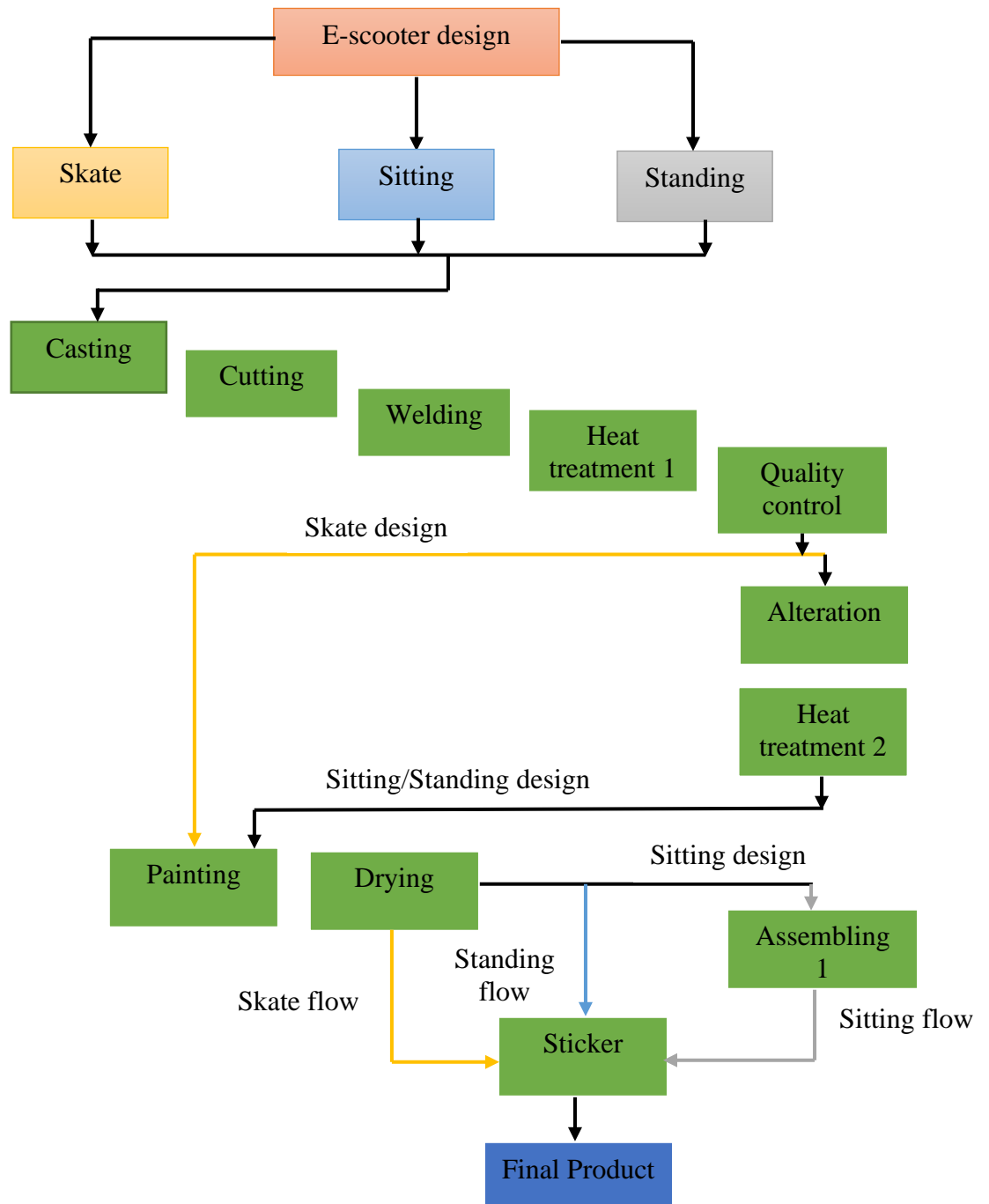
+1 1 or more body parts are held for longer than 1 minute (static)  
+1 Repeated small range actions (more than 4x per minute)  
+1 Action causes rapid large range changes in postures or unstable base

## Appendix H PSL (Onion mode representation)



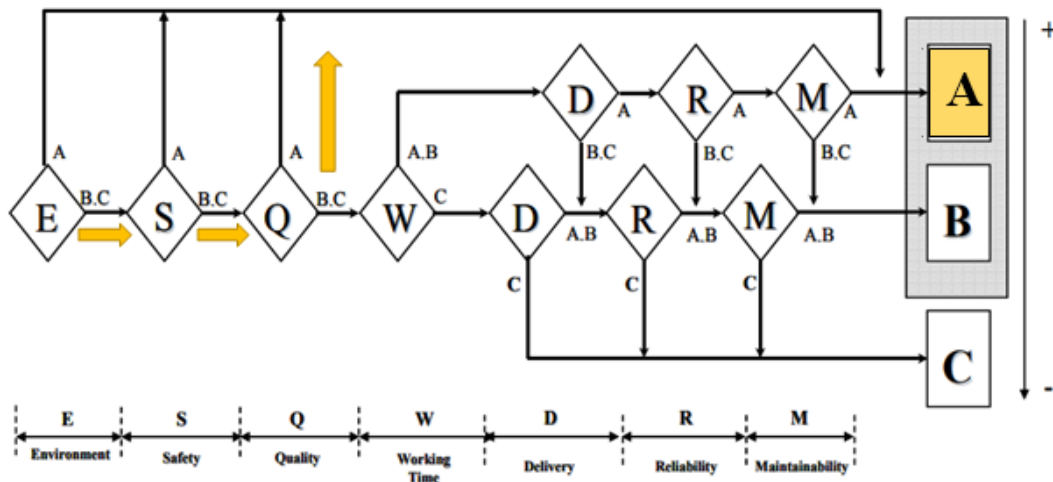
Sitting
Standing
Skate

# Appendix I Manufacturing Model Integration

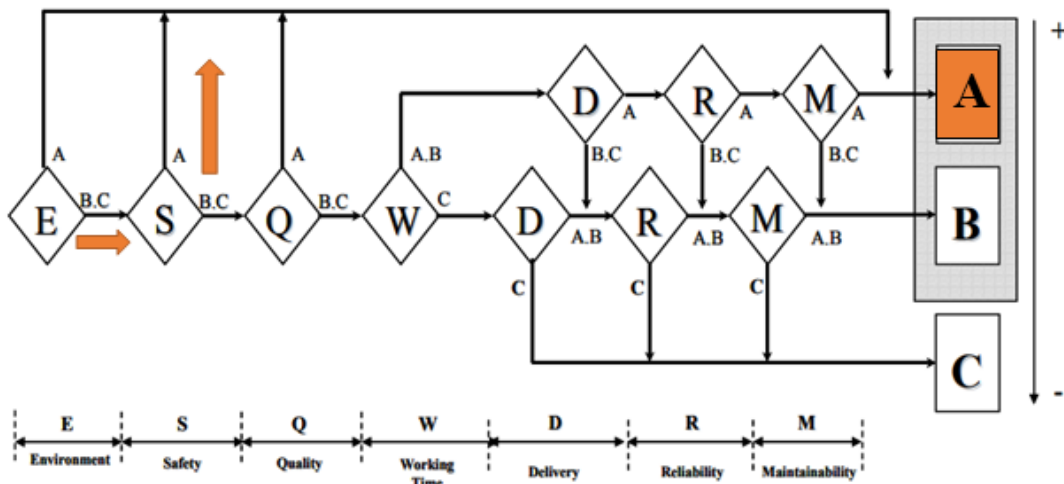


## Appendix J RCM Criticality Flowchart

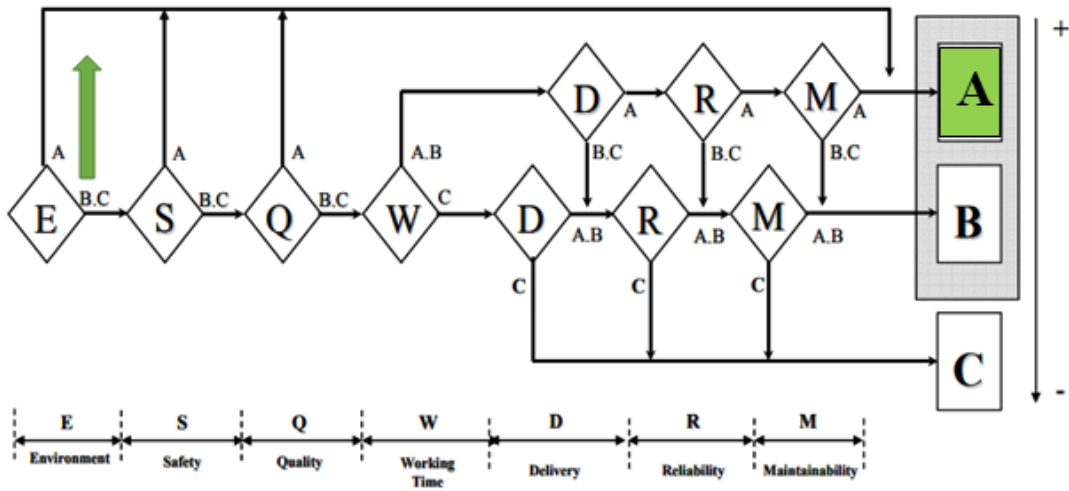
### Appendix J.1 Casting Machine ABC-classification



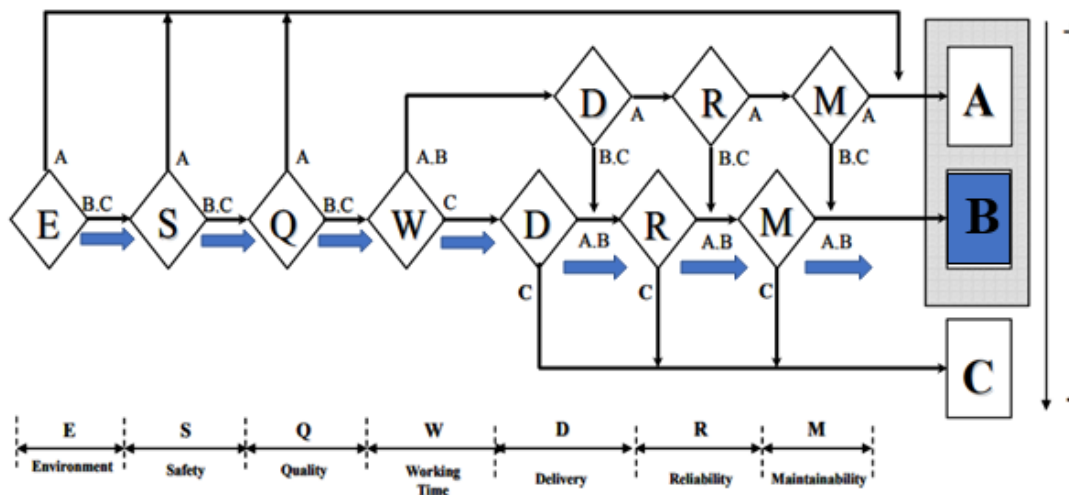
### Appendix J.2 Cutting Machine ABC-classification



### Appendix J.3 Welding Robot ABC-classification



### Appendix J.4 Painting Robot ABC-classification



# Appendix K RCM Decision Diagram

