Manufacturing Facility Layout Design and Performance Analysis for a Greenfield Project using DES and AHP

A Multi- Criteria Decision Making for Qualitative and Quantitative parameters

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Management Summary

Suzlon Blade Technology (SBT) at Hengelo is a research and development unit for Suzlon Energy Limited. The wind turbine blade industry has evolved rapidly in terms of blade design as well as manufacturing processes. The SBT team is working on a greenfield project which involves the designing of the facility layout and manufacturing systems for the new generation blades. This research study aims in helping SBT in developing a methodology for manufacturing layout planning and its performance evaluation. In the past, the company has observed various factors that have affected its production layout. Some of the factors being, the introduction of new technology, the gap in production targets, process changes, etc. Hence, we decided that layout performance needs to be analyzed for both quantitative and qualitative parameters.

To develop a methodology, we compare various works of literature. The steps in the methodology can be divided into three stages.

- Layout planning and generating alternatives
- Quantitative and qualitative performance analysis of layouts
- Selecting the layout based on its performance for both the analysis

We followed the systematic approach for layout planning as defined by Muther (2015). We adapted this methodology by applying lean tools like line balancing for capacity planning for the stations. The alternatives were generated through workshop sessions with the process design team at SBT. The alternatives are the design interventions that the team wanted to evaluate. The alternatives are generated to obtain optimality in:

- Sequencing of the operations
- Space configuration
- Capacity Planning (Number of stations)

Since our study is for a greenfield project and it is not possible to obtain the production performance of the real-life system, we structured our quantitative analysis by implementing a discrete event simulation (DES) model. We collected data and defined a conceptual model of layout for the blade finishing operation to translate into a 2D simulation model. We built the alternatives as the interventions designed by the SBT team. We observed from the results of the simulation experiments that the SBT plants require 2 molding stations to attain the targeted production pace of 12 hrs/ blade from the finishing operations. We also observed that the layout capacity is not enough to meet the production targets. To improve the performance of the layouts we identified the bottlenecks in the system and implemented improvements by re-dimensioning the station numbers. The simulation model helped in analyzing the stochasticity in the system. After the bottleneck analysis, we were able to improve the KPI 'production pace' by around 10% to 34% compared to the 'static line balancing' during the SLP step. We obtained the quantitative performance of the alternatives with the help of an analytical hierarchical process (AHP). The results from both the analysis are combined using the HoQ tool. Through HoQ we

obtain the relative importance of the evaluation parameters. Parameters 'Safety', 'Production Pace' and 'Avg Throughput' are ranked of high importance. This method helped us to identify the positives and the areas of improvement of the alternative. Thus to select the final layout we must combine the results of both the analysis. Figure 1 is the graphical representation of the layout alternatives 6, 7, and 8 performance to the defined parameters. Alternative 7 performs well in all the parameters. Layout alternative 7 is the alternative with the design intervention with rotating stands. The use of rotating stands is the new technology for the blade movement between the stations. From the analysis, the rotating stands in the blade finishing operations result in a layout design that can achieve the production targets for blade production along with being flexible, safe for operation, easily maintainable, operational, and implementable.

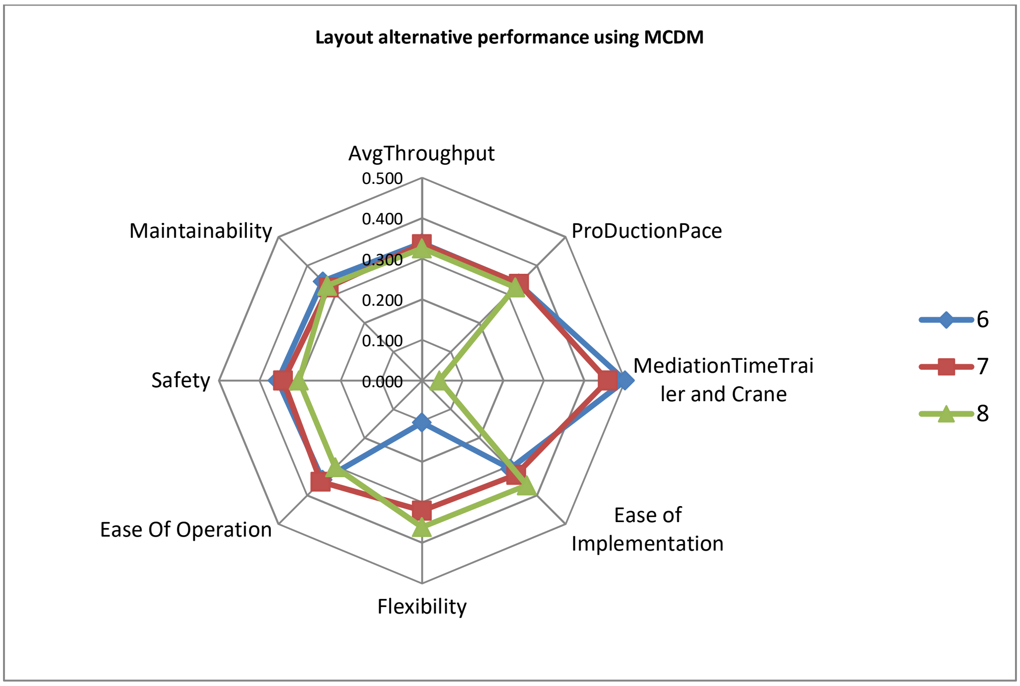

Figure 1 Layout alternative performance combining qualitative and quantitative analysis

In this thesis, we showed the application of this methodology as a strategic decision-making tool for SBT. The benefits of implementing the methodology are:

- It allowed in testing the design and engineering interventions that are at the design phase before taking the ideas for the layout planning to the management.
- It helped in converting the knowledge and the experience of the managers from the various departments into a valued score.
- It helped in aggregating the knowledge available at various levels in the organization in a more valuable form of visual charts, datasheets, and simulation models. It also has generated a need within the team to maintain the records and data in the usable format for the simulation models.

- It helped in realizing the gap when the only deterministic data is considered for the line balancing of the process. The production system needs to account for stochasticity also.

We would like to recommend the SBT team, for further interventions and decision making :

- The SBT team can further extend the methodology to improve its robustness by implementing the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).
- The team can use cost parameters as a cut-off criterion in the initial stage of the alternative generation. This would ensure that the layout s that are beyond the budget of the company will not be considered for the analysis.

Acknowledgment

This thesis marks the end of my amazing master's journey in Industrial Engineering and Management. I am thankful to all the people who made my stay in the Netherlands memorable. Here, I would like to give special thanks to people who have supported and encouraged me during my thesis.

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Abbreviations

SLP Systematic layout planning

SEL Suzlon Energy Limited

SBT Suzlon Blade Technology

SB7XX Suzlon Blade with rotor length 7XX m

SB6XX Suzlob Blade with rotor length 6XX m

DES Discrete Event Simulation

MCDM Multiple Criteria Decision Making

FAHP Fuzzy Analytical Hierarchical Process

AHP Analytical Hierarchical Process

PP Production Pace of Blades

MT Mediation Time of transporting units

Avg TH Average Throughput time

DCT Design Cycle Time

KPI Key Performance Indicator

CRN Common Random Numbers

VRT Variance Reduction Technique

LA Layout Alternative

QFD Quality Function Deployment

HoQ House of Quality

EC Engineering Characteristics

CR Customer Requirements

AIJ Aggregated Individual Judgment

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Chapter 1: Introduction

We carried out this research in Suzlon Blade Technology (SBT) located in Hengelo, Netherlands. It is a Research and Development division of Suzlon Energy Limited (SEL), India. SEL is a leading wind turbine manufacturer with its R&D facilities located in Germany and Netherlands. The SBT departments work in coordination with the production plants located in India.

The research projects are undertaken by the Innovation and Strategic Department (ISD) within SBT. As the name suggests the department helps the company with strategic decision-making regarding the design and production of the turbine blade. The wind turbine is one of the fastest evolving products in terms of designs and technology. The SBT departments are at the initial stage of designing the new blades. ISD, on the other hand, needs to strategize the production of these new blades known as new generation blades. The production of the present blades is done in the facility which was designed for the blades with much smaller dimensions also known as previous generation blades, precisely five to six designs old. So the shop floor production team and the production process design team have been facing a lot of problems with the factory dimension constraints. Therefore the team decided to start a Greenfield project for the new blades' production plant. Generally, the new facility layout projects for the manufacturing plant are of high investments for the firms. Therefore the company must analyze the layout before implementing them. Thus the team would want to know how to propose a new plant layout and how to analyze whether the proposed layout will be suitable for Suzlon's new generation blade production as per the targeted throughput.

The goal of this thesis is to provide a methodology for the production layout generation and how to analyze this layout performance based on a few parameter targets that can be adopted for Suzlon Blade Technology. The SBT aims to use the proposed methodology for every future blade design and technology evolution that will require a change in the plant.

This chapter further introduces the research in more detail. Section 1.1 is about the motivation behind the research. Section 1.2 is about the problem identification for the research study. Subsequently, Section 1.3 discusses the objective and the research questions.

1.1 Motivation

The production processes for wind turbine blade manufacturing are evolving rapidly. There is the frequent introduction of new technologies to improve the structural strength, lifespan, maintenance, and efficiency of wind turbine blades. The wind turbine blades are manufactured in plants in India. The production planning team analyzed that the present factory facilities are insufficient for the new generation blades. The new blades (SB7XX) are bigger in dimensions and are also heavier when compared to the present blades (SB6XX). Considering entitling the project to be a 'brownfield project' i.e. modifying the existing factory to be suitable for the new blades; the team concluded that it would not work for this case. The consequence will be that the team will be iterated to answer the same questions shortly for the preceding next-generation blades. The idea of making this project 'a greenfield approach' uprooted from the above consideration. By definition, a greenfield approach is building new factories and manufacturing plants from scratch with no prior boundary conditions in terms of layout constraints.

The production facility layout planning is among the frequently discussed topics in literature. This research is carried out to know how we can adapt the available knowledge about this topic for SEL. Since the layout is to be designed specifically for wind turbine blade manufacturing, SBT wanted to ensure that the proposed layout has a credible validation method too. The company has strict production targets due to increasing market demand. For an organization, it is necessary to have an efficient and effective manufacturing system to attain production targets. Subsequently, a well-planned and designed facility layout is essential to achieve the desired manufacturing system. P. Juneja (2020) defines a manufacturing facility layout as 'an arrangement of different aspects of manufacturing in an appropriate manner as to achieve desired production results.' Facility layout planning is an important strategic decision as it directly influences factors like space utilization, production targets, the safety of workers and ease of maintenance of machines. Our motivation behind this study is to plan a facility layout for SBT with the following features:

- Effective workflow for next-generation blades (SB7XX).
- The safe and comfortable working environment for the workers at the plant.
- Easy future expansions and changes in the layout to accommodate new products or upgradation of technology.
- Improvement of production capacity when demand increases.
- Better space utilization.
- Better equipment and internal transportation management.

We aim in achieving the SEL plant layout planning for the manufacturing of SB7XX blades by using design techniques as follows:

- **Sequence Analysis:** This technique is for designing the facility layout by sequencing out all activities. It is used for combining or splitting the blade production activities to obtain a better workflow.
- **Line Balancing:** This technique is commonly used to obtain better utilization of the workstations. It eliminates the idle time that occurs when production activities are not synchronized. It is used to obtain the station numbers required for each activity to obtain the targeted Takt Time.
- **Two Dimensional Templates:** This technique is used for the development of a scaled-down model for better visualization of the spatial configurations. It is used as a visual aid in analyzing the qualitative performance of the layouts.

The facility layout planning is influenced by various factors. Before suggesting the layout plan for the implementation it is necessary to analyze them based on their performance. We aim through this study, to select a layout for SEL that helps in attaining production targets along with being safe, flexible, and easy to maintain. From a previous project carried out at SBT, plant simulation using Tecnomatix software was proven to be a validation tool for the blade production at SEL plants. Hence it seems more credible to use plant simulation for quantitative analysis of the layout performance.

Apart from this, many qualitative factors were identified from the discussion with the design and the production team at Research & Development department. This highlights the need to integrate the qualitative assessment along with the quantitative one in the proposed methodology. This research aims in providing a methodology that will be two-fold, firstly proposing the layout alternatives and secondly assessing those layouts based on the qualitative and quantitative criteria leading to the selection of the best one suited. The motivation for the project is that in the future when any changes in the production processes or technology are adapted, the proposed methodology comes in handy for the upgrading or redesigning of the facility layout.

1.2 Problem Identification

The wind turbine design is going through a rapid transition phase with increasing concerns for renewable and sustainable energy generation. This has also increased the demand for wind turbines. The evolution of the wind turbine dimension and energy yield within SEL is shown in Figure 2. The initial rotor diameter was 52m (blade length 25m) with a hub height of 75m. The last turbine in the figure represents the latest turbine in installation with a rotor diameter of 128m (blade length 63m) with a hub height of 140m. The Research and Development team at SBT are working with new product development consequently for improving the efficiency of energy generation of the wind turbines. This creates the need for a robust facility layout that is adaptable to the new and future generation blades

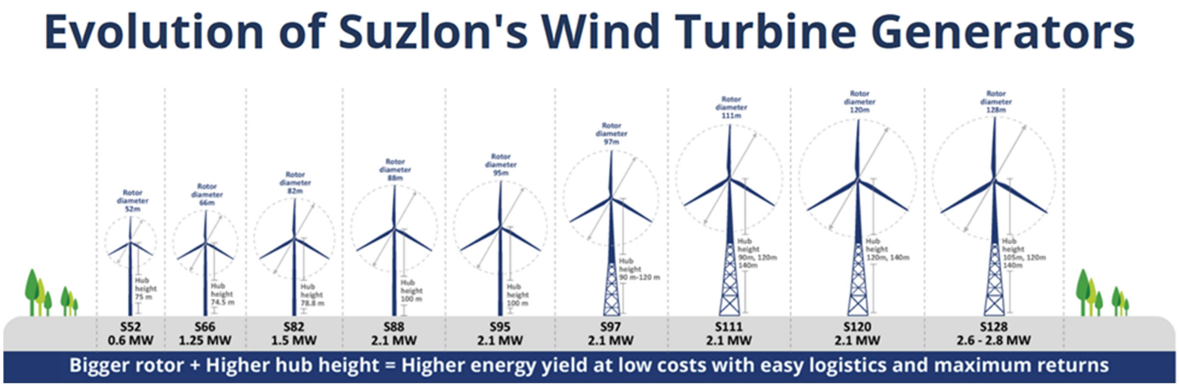

Figure 2 Wind Turbine evolution in Suzlon Energy Limited (https://www.suzlon.com/in-en/energy-solutions)

Presently, the factories in India are manufacturing the blades with a length of 69m (rotor diameter 140m). The production team has growing demand targets to be met. The demand for wind turbine blades is known well in advance so there is not much-expected uncertainty. But still, there is a gap between the set targeted throughput and the actual throughput. After a discussion with the production process design team, a few of the points were realized. Due to the constraint in space availability, the operations are carried out in a lesser number of stations compared to the required number of stations.

For instance, when one of the SEL factories was designed it was designed for the blade with a length of 47.5m represented sixth in Figure 2from left. The blade manufacturing processes can be classified into material preparation processes, component preparation processes. This is followed by the blade moulding process and blade finishing processes. The initial factory layout had four main blade moulding stations with the subsequent finishing stations to meet the demand. When the present blades with blade length 63m were introduced there was a difference in the dimension of the blade's length by approximately 15.5m. Subsequently, the number of stations that could be fit in the layout area reduced. Also, there is an increase in cycle times of the production processes as the cycle times are functions of surface areas. This leads to reduced processing stations with an increase in cycle times. Thus this created a reason for bottlenecks in the production line.

The energy yield of the wind turbine is directly proportional to the rotor diameter. Hence the design of wind turbine blades has seen an incremental change in the blade length. With the increase in blade length, to provide the structural stability to the rotor the composite composition and the number of composite layers in the blades has been always a sought-after research field in SBT. This subsequently leads to various process changes in the production, which lead to new machines being used, reduction or increment in the processing times, splitting or combining subsequent processes, sequencing of operations, etc. These process changes have also put a lot of constraints on the plant layout.

To improve the production of blades new technologies are explored. Few of the technology changes are in the design phase. It is important to analyze the layout performance when new technology is integrated with the existing processes. This calls for the inter-departmental inputs to study the layout requirement in case of changes in the technologies used. As a project from the strategy development department, this makes it reasonable to consider these technology changes into account for layout design. We will explore new internal logistic equipment changes introduced into the production system.

Figure 3 shows a schematic consolidation of the factors that have affected the layouts in SEL. These factors will be important considerations for this research. The attempt will be to devise a methodology that would be able to overcome the identified hurdles.

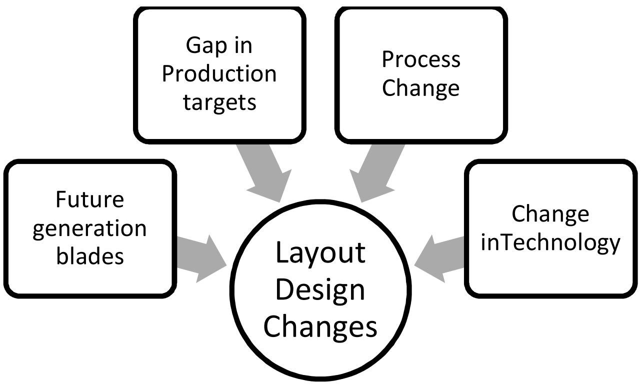

Figure 3: Factors that have affected the Layout changes in the past in SEL

1.3 Objective and Research Questions

In alignment with the motivation and problem identification, we formulate the research objective and research questions. We formulate subsequent sub-research questions to systematize our solution approach. The objective of the research as we define is as below:

"Develop a methodology for facility layout planning for Suzlon Energy Limited and investigate the characteristics of layout alternatives for a new generation blade concerning qualitative and quantitative criteria."

The research questions and the reasoning for them are explained below:

To effectively understand the problem case it is necessary to first understand the existing production system at SEL and the upcoming changes for the new generation blades. Hence we formulate the first research question to gain knowledge about the blade production processes and the facility layout.

1. *What are the current practices regarding the blade production process and the layout at SBT?*
    1.1. What are the basic terminologies used to define the blade manufacturing system in SBT?
    1.2. What are the processes involved in blade manufacturing?
    1.3. What is the present layout plan of SBT for manufacturing?
    1.4. What are the desired characteristics of the SBT layout for the new generation blades?

After the information obtained about the current SEL production processes and the new product development requirements, it is necessary to obtain the required knowledge from the available literature to solve the problem. We carry out the literature research two-fold for the objective. Firstly, the information about how to design a layout for a manufacturing system is to be obtained. Secondly, we need to obtain knowledge on how to assess the performance of the resultant layout from the earlier step under the criteria defined before it can be implemented. Chapter 3 describes the literature review in detail.

2. *What literature is available related to layout design for manufacturing facilities and assessing the layout performance?*
    2.1 What methodologies are available for a facility layout design for manufacturing blades in SEL?
    2.2 What methodologies are available for alternate layout generation?
    2.3 What is the knowledge available in the literature for the layout performance analysis?

After obtaining the required knowledge from the literature on what methods are adopted to solve a similar kind of problem, a framework is defined for SEL.

We have implemented the adopted methodology in three stages. The first step is the generation of alternate layouts for new generation blades at SEL. The second stage is the quantitative and qualitative analysis. Finally, the third step is combining the results of both the analysis to obtain the most suitable facility layout for the blade production at SEL.

3. *How are the layout planning and analysis steps adapted for this research and the generation of layout alternatives?*
    3.1 How do we develop a framework of methodologies for the greenfield project at SBT?
    3.2 What are the steps to plan and generate layout alternatives for the next-generation blades at SBT?
4. *How is the quantitive analysis employed to obtain the production performance data of the alternatives?*
    4.1. What are the input data and the assumption required for quantitative analysis?
    4.2. What quantitative KPIs are used as a performance measure of the layouts?
    4.3. What are the interventions on which the experiment is to be carried out?
    4.4. Which layout performs best in the quantitative analysis?
5. *How is the qualitative analysis employed and the results combined of qualitative and quantitative analysis to select the best performing layout?*
    5.1. What qualitative criteria are used as a performance measure of the layouts?
    5.2. What is the relative importance of the quantitive criteria in the assessment process?
    5.3. Which layout alternative performs best in the quantitive analysis?
    5.4. What are the steps employed to combine the results for the quantitative and qualitative layout analysis?
    5.5. Which layout alternative results as the most suitable one for the SEL from the analysis?

Chapter 2: Overview of the blade manufacturing at Suzlon Energy Limited

The wind turbine has many components few namely rotor blades, tower, hub, rotor, generator box, etc. The components are well schematically represented in Figure 3. This research will focus only on turbine blade manufacturing. This chapter aims in making the reader coherent with the terminology and the processes involved in blade manufacturing. In section 2.2 is a brief description of the types of the layout of the manufacturing facility and the existing layout used for blade manufacturing. It gives information on current practices carried out at SBT for layout changes when a new product is introduced to production. There is a very broad aspect to facility layout design. Section 2.4 is about the characteristics of the SBT layout for the new generation blades that we aim to achieve through this study.

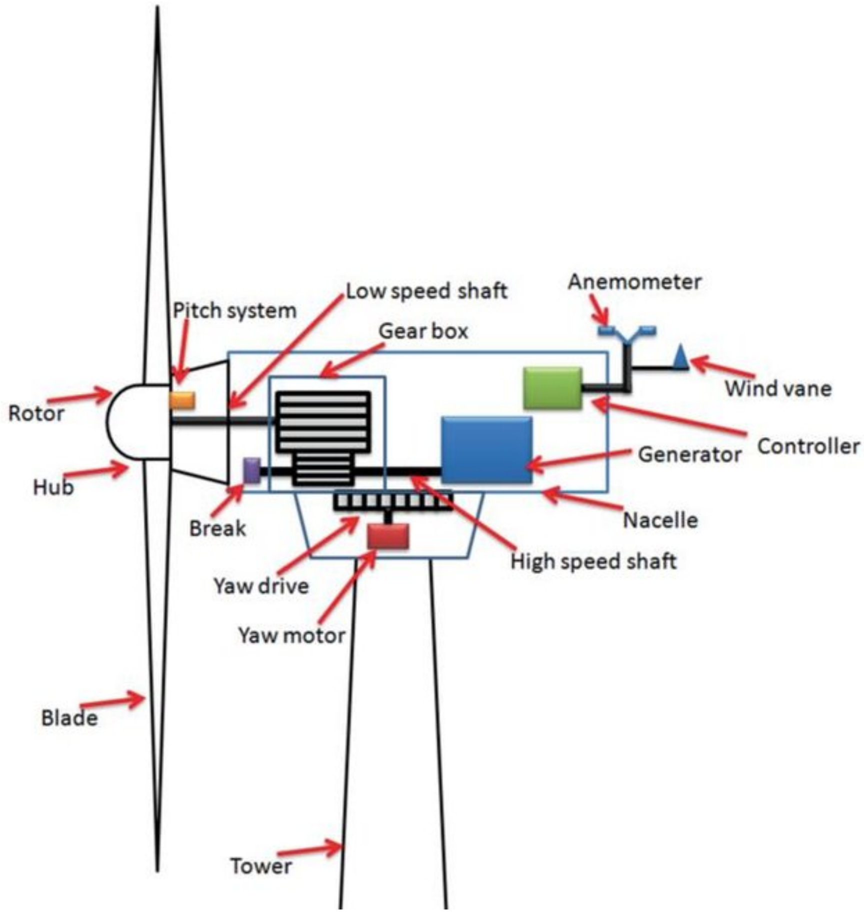

Figure 4: Wind turbine blade components schematic representation (S.Sabeti, 2019)

2.1 Blade Manufacturing Process and Terminology: An Overview

There are many technical terminologies used in this report related to production and operations colloquial to SEL. Therefore to have a better understanding and reduce the ambiguity, the terminologies have been explained. Later in this section, the blade manufacturing processes are made acquainted.

Activity Areas: It infers to various areas or things that need to be included in the facility layout planning. It may be various machines within a department, entrance, exit, etc. based on the level of detailing in planning. In our project case, the activity areas have been defined by combining the work areas according to the flow of materials and workers sharing.

Material Preparation (MP): It is the name of the activity area where the raw materials for blade production are processed and stored in the form of kits. These kits are further used to make sub-components that need to be fitted in the blades.

Component Preparation (CP): It is the name of the activity area where the sub-components for blade manufacturing are made. There are in total four different sub-components in this process. These sub-components are then further assembled in the blade during the moulding operation.

Blade Lead Time (BLT): The time between the initiation and completion of the production process of blades. The blade production is initiated when the blade assembly starts to blade is sent out to the yard for storage. It does not include the material and component preparation times.

Design Cycle Time (DCT): It is the calculated cycle time for a station without any interruptions in the production process.

New Generation Blades: This report frequently refers to the term new generation blades. It is the terminology used in SBT to refer to the new blade for which the layout planning needs to be adapted. It denotes the blade series SB7XX.

Next Generation Blades: It is the terminology used to refer to the blade generations that could be part of future R&D. Considering the trend of blade design development, the SBT team has termed SB8XX and SB9XX series as next-generation blades. The next-generation blades are still in the conceptual stage of design but can be regarded as the future scope for blade design changes.

Super Market logic: This logic is when components from storage units of material preparation and component preparation areas are used in the subsequent downstream process when that particular part is required. The storage units are always stocked up to a certain level to prevent stock out. It is so planned with the supermarket logic that the materials obtained from the upstream do not affect the lead time of the process downstream. This is so because the components are always available (no stock out situation) when they are called to be processed in the downstream stations.

Takt time (Tt): It is the speed with which the blades need to be created to meet the demand of the market.

Throughput (TH): It is the amount of time required for a product to pass through a manufacturing process. It accounts for the processing times, inspection times, time spent in queues, and move times.

Production Pace (PP): It is the time taken by the manufacturing system to complete the production of one blade.

The above-defined terminologies reduce the discrepancy in understanding the production system at SEL. Further, the process of blade manufacturing is briefly explained in this section. The manufacturing system is explained briefly with the help of a conceptual block diagram as represented in Figure 4. The production process consists of four major operations namely; material preparation and storage, component preparation and storage, blade moulding and assembly, and blade finishing.

2.2 Overview of the processes for manufacturing the blades at SBT

The operations for blade manufacturing are arranged in the order of material flow in the plant. Figure 5 is a block diagram representation of the blade manufacturing at SBT. The raw materials are stored in a separate area and are pertained from there as per requirement. The material preparation activity area consists of five stations each with different machines and operations being performed. This activity area has a dedicated workforce employed to work in shifts. The output from these stations is formed in kits and kept in storage until requirement. The material preparation operations are planned to maintain the targeted buffer level in the storage. The materials prepared are used from the storage as per the supermarket logic. As can be seen from the block diagram in Figure 4, the material preparation units are supplied to two downstream activity areas i.e. component preparation and blade moulding and assembly. The internal logistics between the stations and storage happens using a manual trolley.

The next-in-line activity area is component preparation and its storage. In this area, the sub-components for the blade are manufactured and stored in a dedicated area. It has three main segregated operations. The first one is the moulding of components; the second one is finishing operation and then the storage. The storage area for the components also works on supermarket logic. There are four main components prepared in this area. Each component has parallel stations with dedicated workers working in shifts. The stock for each component to be maintained in the storage area is decided as per its requirement in the blade assembly station. It is planned such that there is no stock-out situation. The components are heavy and huge so the internal logistics between the stations and the storage happens with the help of cranes.

The next activity area is blade moulding and assembly station. It is the pacemaker of this production system. The number of the main mould for a manufacturing facility is decided based on the targeted takt time. The workers in this station are dedicated to this area and work in shifts. The blade flows to the downstream stations follow FIFO (First In First Out) logic. In case a new generation blade is introduced in the manufacturing system, the increase in the blade dimension will directly influence the processing time at this station due to blade surface area increment. The blade moulding and the component assembly with the main blade are done in the same station. The waiting of the blades in the mould after the sequence of operations performed is not accepted as the throughput of the blade production will reduce and wouldn't be cost-efficient. Hence the downstream stations need to be planned efficiently to not cause the blade to wait in the mould station.

The blade finishing activity area has a set of many operations performed in a pre-set sequence. The blades have to be intensively moved between the stations at the finishing area. The dedicated synchronized cranes are used for the movement of blades between the finishing stations and also from the mould area to the finishing stations. One of the critical activities in this area includes weighing the blades and segregating the blades based on their weight characteristics into the classes defined. After completion of the processes in this area, the blades are then shifted to the yard where they are placed until transported to the site. The blade manufacturing process can be visualized through the infographics in Figure 6.

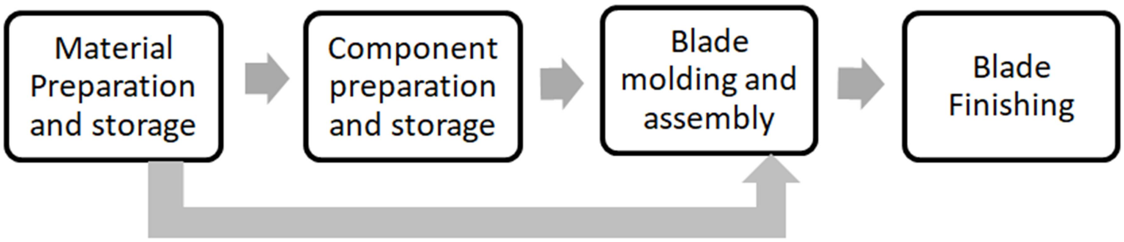

Figure 5: Block diagram of the blade manufacturing process

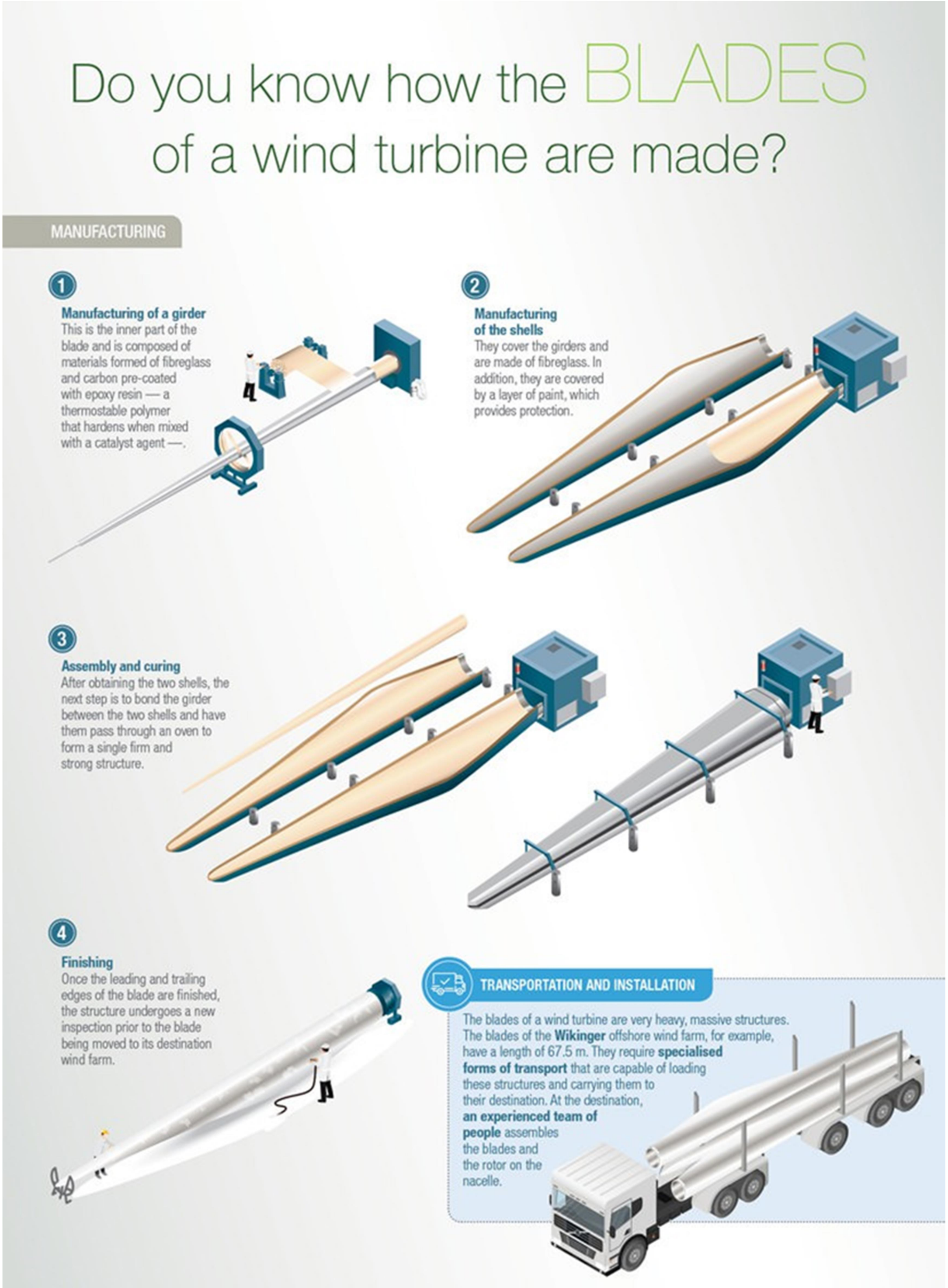

Figure 6: Pictorial representation of blade manufacturing (Ref: https://www.iberdrola.com/press-room/top-stories/wind-turbines-blades)

2.3 Types of Layout and Existing Layout at SEL

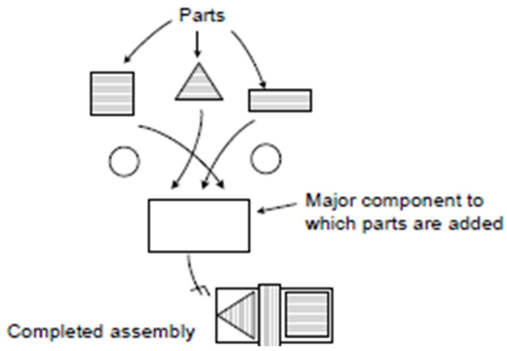

Figure 7 Layout by fixed position (R.Muther, 2015)

To understand the type of layout presently at SEL, the types of layout for the manufacturing facility must be understood. The different types of layout are:

1. **Layout by fixed position:** All the operations are performed with the component placed in the same position. It is common for assembly type of manufacturing process. The sub-components are combined at the assembly station to form the main component. This type of layout is generally adopted when the product is very huge and to be produced in very few quantities. The operations involved mostly manual without heavy pieces of machinery. The layout type is well represented in Figure 7.

2. **Layout by process**: In this layout, all the similar operations are grouped to be performed in the same station or area. The product is thus moved between the areas. The layout is well described with the help of Figure 8. The job is first passed through department A where operation 1 is performed on the job. Subsequently, the flow of the job is through departments B and C. This layout is adopted for small-size jobs that are to be manufactured in large quantities. The processes involved are for a long duration or they require special machine or utility requirements.

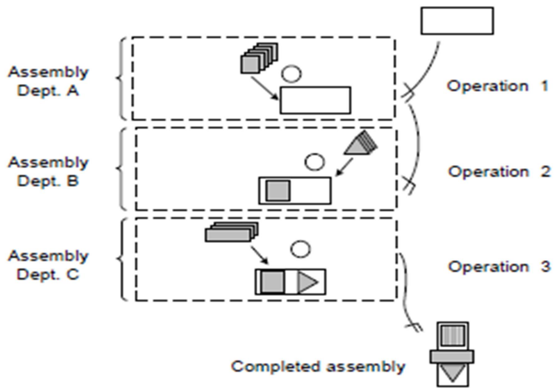

Figure 8 Layout by the process (R.Muther, 2015)

3. **Layout by the product:** The different stations are arranged in the sequence of operations to be performed on the product. The layout is adopted for products to be made in high quantity and the manufacturing processes are simple to be performed. The layout is represented in Figure 9. The product undergoes a different operation in sequence from stations 1, 2, and 3.

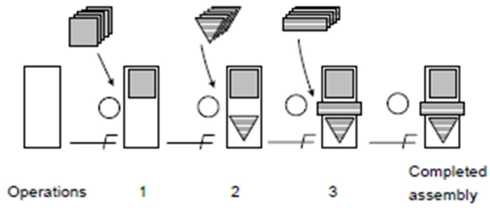

Figure 9 Layout by the product (R.Muther, 2015)

4. **Layout by value stream:** This layout is a combination or hybrid of classical 'layout by-product' and 'layout by process'.

The layout at the SEL manufacturing plant

Figure 10 is the block representation of the facility layout at SEL. This layout is considered as the standard layout by SBT to carry out all the studies related to the blade manufacturing process. This layout is a hybrid of 'layout by fixed position' and 'layout by-product'. Considering the first half of the production line up to the blade moulding and assembly station, all the upstream operations are performed with the major component (i.e. blade in this case) remaining in one fixed position. The sub-components are assembled at the blade moulding and the assembly station. All the operations are mainly performed manually by the workers. The second half of the production system consists of various stations arranged in the sequence of operation for the blade finishing. Hence this part of the layout is the layout by product.

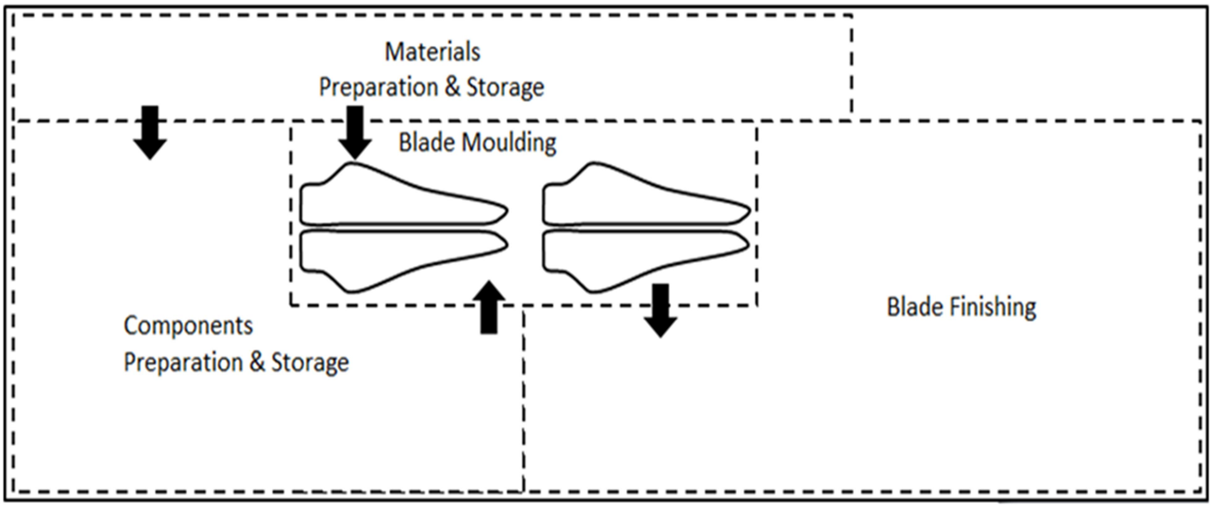

Figure 10 Layout at SEL manufacturing plant by Brunetti (2019)

2.4 SBT layout for the new generation blades

Section 1.3 gave us an understanding of the factors that have led to changes in the production layout at SBT. Thus, we aim in developing a layout plan that would be able to perform to achieve the production targets along with being able to overcome the factors explained in Section 1.3. The wind turbine blades have seen an increasing trend in the dimensions. It is observed from Figure 11 that the increase in the blade dimensions has directly influenced the increase in the cycle time of the production processes. The demand for the turbine blades is observed to be increasing subsequently. Thus, the SBT team aims in developing a layout plan that can be flexible to increasing the stations at the plant. We aim in having a well-balanced manufacturing system with no bottlenecks and starvations of the stations. Thus, reducing the average throughput times of the blades. The team aims in achieving a production pace of 0.5 days/blade for SB7XX blades to meet the demand. Thus, the layout plan should be efficient to achieve the targeted production pace. Through streamlining the processes we aim in reducing the time spent in non-productive activities like waiting time for the stations to get free and for cranes to move the blades. The blades are heavy and huge. The movement of blades between the stations requires resource sharing of cranes and trailers. We must consider the easy movement of blades for better work-flow. Along with the production targets, the layout for the blade manufacturing must have some characteristics that cannot be measured directly. The layout plan needs to be safe for the workers and the machines. The production layout must enable easy maintenance during breakdowns. This study aims to obtain a layout plan that has all the above-discussed characteristics.

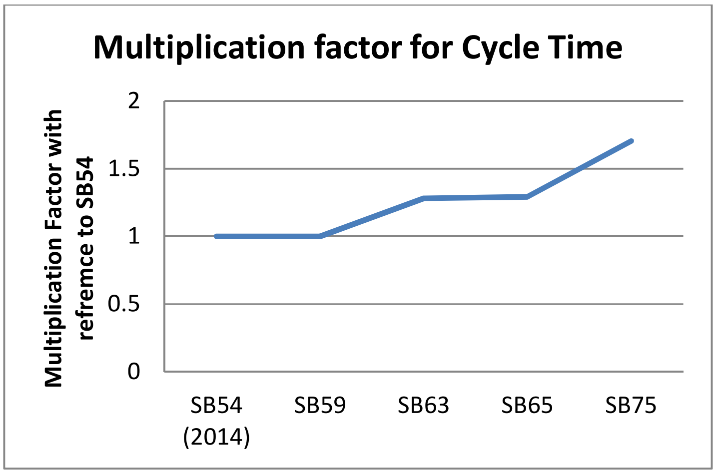

Figure 11 Graph showing an increasing trend in the cycle times with increasing blade dimension

2.5 Conclusion

This chapter allows us to answer the research question '*What are the current practices regarding the blade production process and the layout at SBT?'* We learned about the production process involved in the blade manufacturing at the SEL plants. The blade production process can be broadly classified into material preparation, component preparation, blade moulding, and assembly followed by blade finishing. In this study, we aim to focus on the layout planning and analysis for the blade finishing operations. The current plant layout at SEL is identified to be a combination of 'layout by fixed position' and 'layout by-product'. We also identified the characteristics of the new layout that we aim to inculcate in the design phase. The characteristics are broadly classified into quantitative and qualitative factors. The quantitive characteristics are aligned towards production targets. The qualitative characteristics are factors that cannot be easily measured but are essential. We conclude that along with layout planning, layout performance analysis is also very important. Before suggesting the layout plan to the SBT team we need to make sure that the layout plan has all the desired characteristics.

Chapter 3: Literature Review

In this chapter, we answer the research question '*What literature is available related to layout design for manufacturing facilities and assessing the layout performance?'* Section 3.1 focuses on the literature review for methodologies available for the facility layout design and assessment. Section 3.2, discusses the methodology available in the literature to evaluate the layout alternatives based on the qualitative and quantitative parameters.

3.1 Manufacturing facility layout design problem

When reading the literature for the facility layout planning we realized that there are many methodologies available for study. This is because the topic is frequently discussed and is relatively old. A lot of pieces of literature were very specific for a particular industry for example rolls shop plants, oxy-fuel lignite-fired power plants, etc. Most of the authors referred to the methodology Systematic layout planning (SLP) by Muther (2015). The reason for the SLP, to be the most commonly referred methodology by the authors for defining their framework is because it is much generalized and could be adapted easily for all industrial cases. Though SLP being easy to follow and adapt, Gangal (2009) identified the shortcoming of this methodology specific to his case. It was a very interesting part of this research to see the methods adopted by these authors to fill the gap identified in SLP which is further discussed in this section.

Selecting a methodology that would be best suited for SBT could have been very time-consuming because the available literature is very vast. To constructively narrow down the selection process, it was necessary to define the criteria for the preliminary search. We defined search keywords through a brainstorming session with the main focus on the requirements in context to blade manufacturing. After this, a preliminary comparison of the selected methodologies is tabulated based on criteria with the main focus on the desired characteristics which we want the final methodology to have. The criteria are explained in detail below, within this section. The methodologies obtained after this preliminary comparison are tabulated and described in detail on how that particular methodology fulfills the set criteria that are desirable for SBT facility planning.

3.1.1 Methodologies from the keyword search

The keywords for the literature search were obtained from the brainstorming session. They were defined based on the expectation for the SBT manufacturing facility layout. The methodology is aimed to be used as a strategic tool for decision making. The layout planning should be adaptable for blade manufacturing and also for Greenfield projects thus setting the second criteria and third criteria. Since the product and the production process are in the design phase the designed layout performance can be measured using a discrete event simulation. The layout performance is not only decided to be assessed on the quantitative criteria but also the qualitative criteria. Since qualitative and quantitative assessments are to be considered there cannot be only one solution, we would need to consider a tradeoff therefore alternate layouts need to be generated. This leads to criteria that can cater to the assessment of the alternate layouts generated. The keywords selected for the structured literature review are presented in Figure 12.

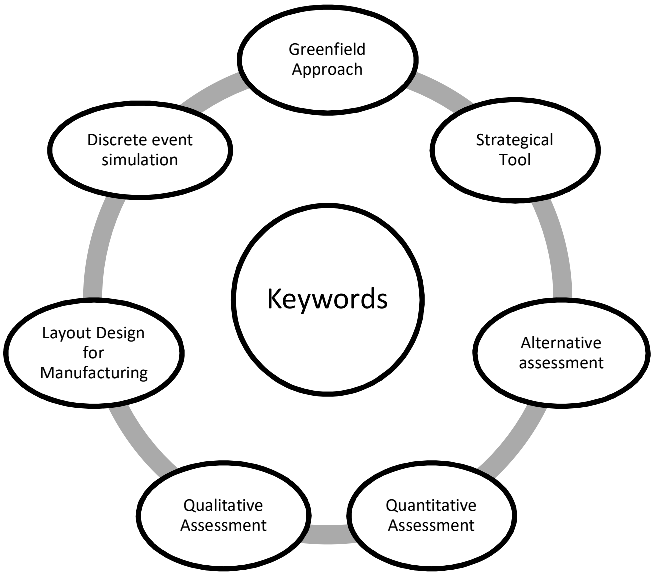

Figure 12: Preliminary keywords for literature review

From the above-stated keyword set, nine papers were shortlisted for further study. The first one is by Hughes (2019). The author does not provide a visual representation of the methodology but has discussed it to be used as a strategic decision-making tool. The methodology is also not specific for a single manufacturing unit but is generalized. The vision for this methodology is to create a digital twin for a factory. The methodology uses a discrete event simulation tool for measuring the performance of the facility designed based on the desired throughput.

The second methodology is by Zhang et al (2019). Their methodology involves a framework of a simulation-based approach and has an integration of mathematical algorithms and heuristic methodology. The author has stated an explicit meta-model for his approach which has components like environment analysis, physical system, simulation model, evaluation index, supporting tools, and the simulation result as a compilation of all. The authors have also incorporated lean principles while planning the production process to attain the targeted throughput. The methodology is generalized for the manufacturing sector.

The third author has a very interesting adaptation of the SLP. Shahin (2011) proposes a methodology for facility layout planning and optimization with an integrated approach of Multi-Criteria Decision Making (MCDC) and simulation. The author uses Muther's SLP methodology to generate alternate layouts but does not use its traditional layout alternate evaluation. Instead, the framework uses the Fuzzy Analytical Hierarchical Process (FAHP) to set the degree of importance of the criteria for layout performance evaluation. Then use Quality Function Deployment (QFD) to prioritize the layout alternatives based on those criteria. The author suggests the use of simulation as a verification and validation method for layout performance in a real-life system. This framework is suitable for production layouts but it would require to be modified as per the company case as QFD is case-specific.

W. Terkaja, et al. (2019) have a set of digital integration tools that helps to assess the candidate's possible solutions regarding the production system. The authors aim to create a digitalization platform to enable the stakeholders in informed decision making. The authors see this framework as a step towards building a digital twin for the factories. The data required for the implementation of the methodology is to be fed directly from the actual working production system. This creates a discrepancy in the implementation of the methodology for a Greenfield project.

The methodology by Motlagh et al. (2019) is using the algorithmic approach rather than a procedural approach. The framework has a three-step approach. The first step involves the formulation of the mathematical model as a multi-objective optimization problem. This model is built taking into account the stochastic nature of the system, using a hybrid approach of simulation with the Design of Experiment (DOE) and regression analysis. The second step involves solving the model using meta-heuristics followed by an evaluation of the performance of this meta-heuristics as the third step. The methodology in this literature is not specific for the facility layout designing but production system-related problem cases in general.

Gangal et al. (2009) suggest a set of frameworks that are integrated for the factory layout planning and commissioning for the Greenfield projects. The methodology is an iterative one that incorporates lean principles at the design phase itself. The methodology is implemented in three iterative steps namely macro level, general level, and micro-level. The macro-level consists of conceptual designs of the production line. The general level involves line balancing and incorporation of lean principles. The third level focus on more details of each station and activities. The authors have stated the clear stages of implementation of specific lean principles. The representation of methodology in Figure 13 gives segregation of lean principles for the design and production phases.

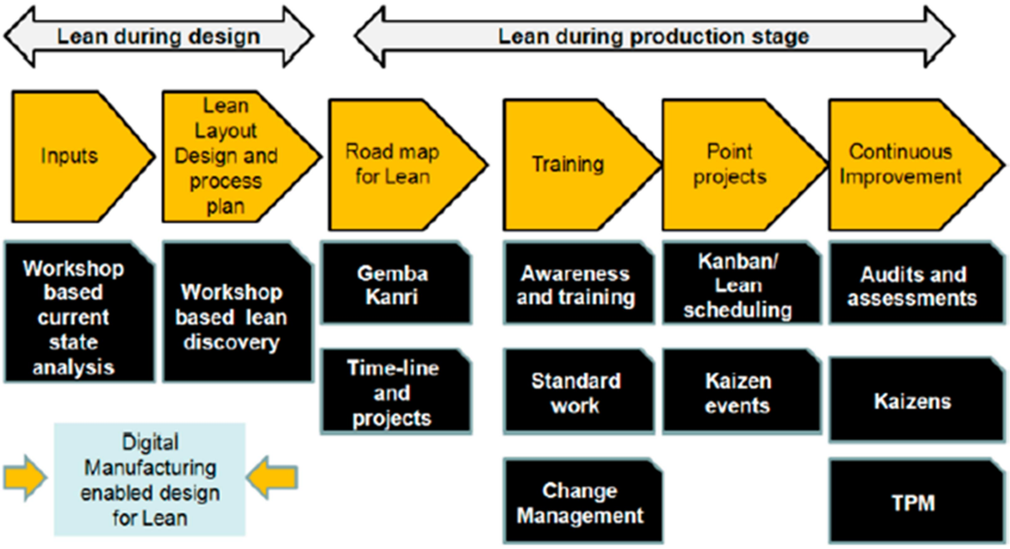

Figure 13 Phases of incorporation of lean principles. Gangal et al. (2009))

The next methodology is from J.E.Branstrator (1989) that focuses on flexible production analysis with a simulation model. The layout for the products in this model is taken as input but has not been explained on how to arrive at that input. The objective of the methodology is to determine the machine capacity, scheduling, types of equipment, and worker capacities for the production system. The methodology focuses on building a flexible simulation model that supports dynamic production processes and scheduling logistics.

The next set of authors E.Kakaras et al. (2007) do not provide a visual representation of the methodology. The methodology involves a quantitative analysis of the production system for a greenfield project of a power plant. The simulation works as the scenario testing tool where the instances were decided by the stakeholders' interests and experiences. Then the performance is measured as the net efficiency of the power plant. The approach does not involve any optimization algorithm.

The last set of authors C.Kuo et al. (2003) has the incorporation of SLP methodology by R.Muther (2015) with Analytical Hierarchical Process (AHP) and Data Envelopment Analysis (DEA). This methodology uses DEA to simultaneously compare the qualitative and the quantitative parameters of the layout performance to identify the efficient frontiers. The SLP is used for the layout of the alternative generation. The authors have attempted in overcoming the gaps in the SLP by incorporating AHP and DEA, for better assessment of the layout alternatives.

3.1.2 Literature Comparison

In this section, the selected methodologies from the literature are compared based on 10 criteria. For the literature comparison, we consider the evaluation criteria are of equal importance. We define the criteria from a brainstorming session with a perspective to identify the methodologies in the listed literature that comply with the overall objectives of the project. We decided the criteria based on the expected use of the methodology.

• This is the company's first attempt to undertake a decision-making platform for a greenfield project. Thus, starting to have a conceptual model would be easy for the understanding of the concept to be implemented.

• The company wants to make all the upcoming and existing projects in the firm adopt lean principles. The ideology underlying is to involve lean methodology practices right from the design phase.

• As already mentioned the facility design problem falls into the procedural approach or algorithm approach. These two criteria are set to see the approaches selected by the authors for their respective cases.

• The substantial effort in the methodology is expected to be executed while generating quality alternative layout designs. So it is of prime importance to know if the authors have included this step in their methodology.

• The goal of the methodology is to generate knowledge for the decision-making process which involves evaluation, comparison, and selection of the best option available from the alternative solutions. The layout performance characterization for a manufacturing system can be done with both qualitative parameters and quantitative parameters. These parameters define the performance evaluation step of the methodology. Thus classifying the selected pieces of literature based on these criteria is helpful.

• The manufacturing system is very dynamic and capital intensive which requires an iterative approach. This would ensure the repetitive performance of a few steps until satisfactory results are obtained.

• Since the methodology needs to be adapted for a non-existing production system a benchmarking study must not be a mandate.

• Lastly there is no similar approach for facility planning at the company in existence; hence it is expected to assess various interventions based on the production targets. This defines the 'what-if' criteria for comparison of literature.

The comparison is done in a tabulated format as shown in Figure 14. The overall ranking of the methodologies from various authors is evaluated whether the given criteria are satisfied or not. The methodologies with maximum positives in the preliminary comparison process are considered for further study.

Sno	Papers for LR and the authors:-	Virtual Simulation Model of the New Boeing Sheffield Facility	A simulation-based approach for plant layout design and production planning	Simulation and Optimization: an Integration of Advanced Quality and Decision	A digital factory platform for the design of roll shop plants	optimization methodology to solve a multi-objective problem in unreliable unbalanced production lines	Integrated, Virtual Plant Design and Commissioning Methodology using Digital Manufacturing and Lean Principles	Simulation analysis of a flexible integrated chemical production facility	Simulation of a Greenfield oxyfuel lignite-fired power plant	A hierarchical AHP/DEA methodology for the facilities layout design problem
Sno	Criteria	Ruby Wai Chung Hughes	Zhinan Zhang1	Arash Shahin	W. Terkaj	Maedeh Mosayeb Motlag	Maneesh Gangal	John E. Branstrator	E. Kakaras	Taho Yang
1	Start with a Conceptual Model	✓	✓	✓	✓	✗	✓	✓	✗	✗
2	Lean Principles used	✗	✓	✓	✗	✗	✓	✗	✗	✓
3	Quantitative Analysis	✗	✓	✓	✓	✓	✓	✓	✓	✓
4	Qualitative Analysis	✓	✗	✓	✗	✗	✓	✗	✗	✓
5	Benchmarking study not required	✗	✓	✓	✗	✗	✗	✓	✓	✓
6	Alternative Layouts compared	✗	✗	✓	✗	✓	✗	✗	✓	✓
7	Iterattive improvement and change in layout	✗	✓	✗	✓	✓	✓	✓	✗	✗
8	What-If Scenario	✓	✓	✓	✗	✗	✗	✗	✓	✓
9	Algorithmic approach	✓	✓	✓	✗	✗	✗	✗	✗	✓
10	Procedural approach	✗	✗	✓	✓	✗	✓	✓	✓	✓
	Number of Favorables	4	7	9	4	3	6	5	5	8
	Number of Lacking	6	3	1	6	7	4	5	5	2

Figure 14 Preliminary Literature Comparison

After completing the preliminary comparison, the selected methodologies are tabulated as shown in Figure 12 based on the intermediate stages. These stages are broadly classified as

- Data collection
- How does the chosen methodology impart flexibility?
- How do we adopt the lean principles?
- How are the alternate layouts generated and iterations done in the methodology?
- Evaluation techniques implemented
- How to evaluate the attributes of the layout performance

sno.	Papers for LR and the authors:- / Criteria	A simulation-based approach for plant layout design and production planning / Zhinan Zhang1	Facility Layout Simulation and Optimization: an Integration of Advanced Quality and Decision Making Tools and Techniques / Arash Shahin	Integrated, Virtual Plant Design and Commissioning Methodology using Digital Manufacturing and Lean Principles / Maneesh Gangal	A hierarchical AHP/DEA methodology for the facilities layout design problem / Taho Yang
1	Data Collection	physical structure of manufacturing unit, manufacturing process flow, logistics plan , production equipment tooling, and CAD drawings	products details, quantities, routing, support, and time considerations, general layout guidelines from managers.	product data (CAD geometry, engineering bill of material, and assembly sequence process), DFMEA, PFMEA, available real estate, standard operation sheets, vehicle and/or product quality history data, historical test and adjust data, annual production requirements, shift and work schedule, system efficiency, operation cap times, time studies along with plant.	characteristics of products, quantities, routing, support, and time considerations
2	Flexibility	in terms of layout design for future process changes	the capability to perform a variety of tasks under a variety of operating conditions and for future expansion	with relationship to resources, machines, routing, sequencing	the capability to perform a variety of tasks under a variety of operating conditions and for future expansion
3	How is Lean principle applied	to develop a simulation model architecture for the plant layout	QFD (Quality Function Deployment) using HoQ and uses Muther's SLP which is based on Lean Principles	the methodology is developed using lean principles in design and the implementation stage of the layout	uses Muther's SLP which is based on Lean Principles
4	Alternatives Generation or Iterations	Algorithuims and heuristics to obtain the global optimum solution to the objective function	Muther's SLP	Follows procedural approach	Muther's SLP
5	Evaluation Techniques	Simulation, algorithms and heuristic methods	Simulation, FAHP, QFD, TOPSIS	simulation is performed for the descision taken and compared if the targeted conditions are reached	Handheld computing, AHP, DEA
6	Attributes Evaluated	Production efficiency, The average utilization rate of equipment	Cost, personnel, ease of implementation	takt time, operators required, capacity utilization, jobs per hour, number of days of operation, lead time	Distance between the department, adjancency, shape ratio

Figure 15: Secondary Methodology Comparison

3.1.3 Methodology for the quantitative analysis

In this section, we discuss the evaluation techniques of quantitative parameters in the literate. In the secondary comparison of the literature, we learned that simulation methodology is used to analyze the production KPIs of the layout designed. Shahin (2011) uses the simulation model to study the planned manufacturing layout in real-life scenarios. The simulation model of the conceptual layout is used by the author to identify the bottlenecks in the system. The author has used a simulation model for obtaining the values of production KPIs. Similarly, Gangal (2009) uses a 2D simulation model for obtaining the production values of the conceptual layout plan for a greenfield project. The conceptual model and the simulation model are shown in Figure 16 and Figure 17. The study of Brunetti (2019) has proved that simulation is a successful technique to evaluate the production performance of the blade manufacturing systems at SBT. Zhan (2019) suggests using the simulation model along with lean principles to obtain an optimal layout configuration. The author uses the simulation model for the analysis of manufacturing process flow and station utilization for the layout design.

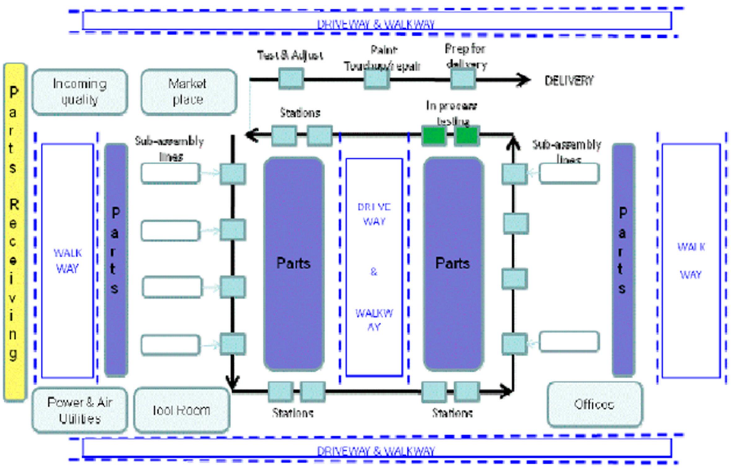

Figure 16 Conceptual layout plan for a greenfield project (M. Gangal, 2009)

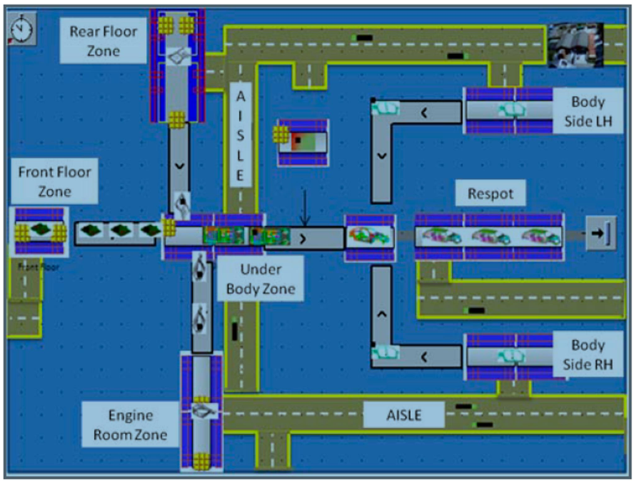

Figure 17 2D simulation model for the conceptual layout design for quantitative analysis (M. Gangal, 2009)

3.1.4 Methodology for the qualitative analysis for layouts

In this section, we discuss the evaluation techniques of qualitative parameters in the literate. From the literature comparison, we observed that Analytical Hierarchy Process (AHP) is a widely discussed and used methodology for layout selection. AHP is used by Khan (1999) as a decision-making tool for the selection of the best performing layouts from a set of layout alternatives. Figure 18 shows the structure of the plant layout selection hierarchy used by Khan (1999). The author explains the advantage of using AHP as the layout evaluation technique as it can capture expert opinion for subjective attributes. The attributes used for the layout evaluation by Khan (1999) are similar to the characteristics of the layout we aim to evaluate for the SBT layout. Thus we can credibly implement AHP for our study. Subramanian (2011) has proposed the steps for the AHP Figure 19. In the AHP approach, the author splits the main objective into composite problems or variables in a hierarchical order. The judgments for the relative importance of the variables are in form of a numerical value. By synthesizing the judgments we can find out the importance of the variable in the assessment of the alternatives. The alternative selection is done by a knowledge-based approach of the individuals who are experienced and have experts of the system.

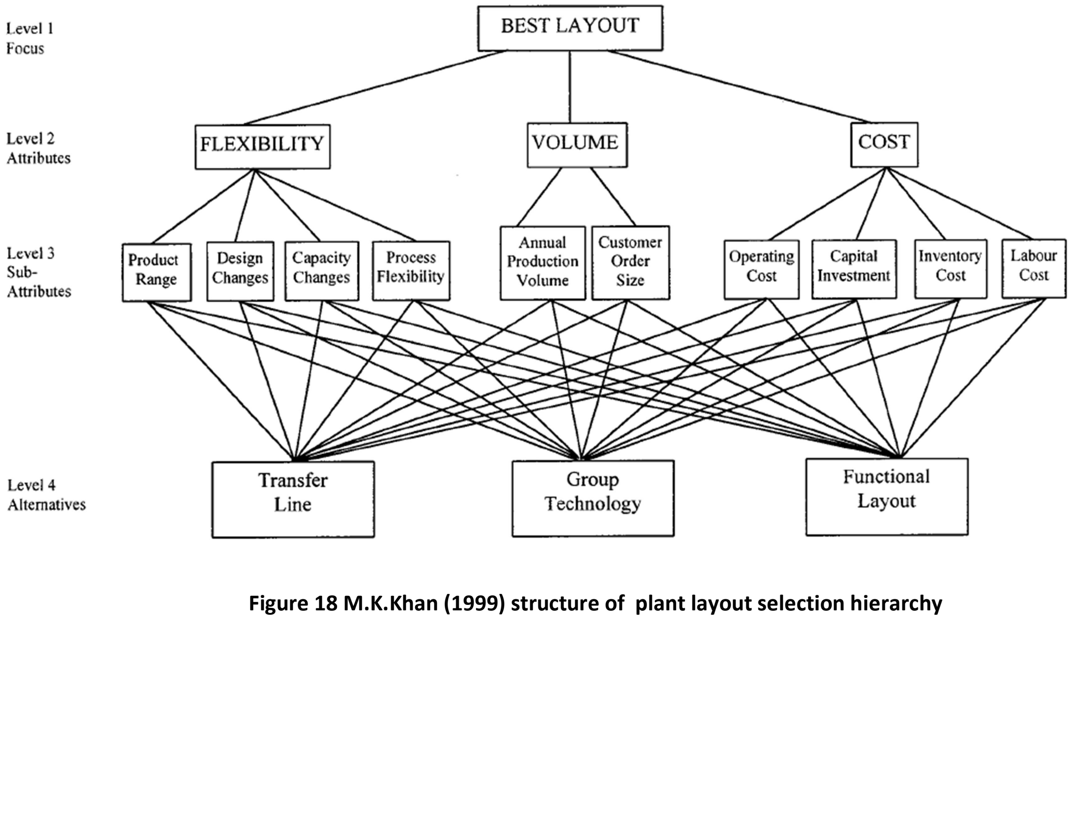

Figure 18 M.K.Khan (1999) structure of plant layout selection hierarchy

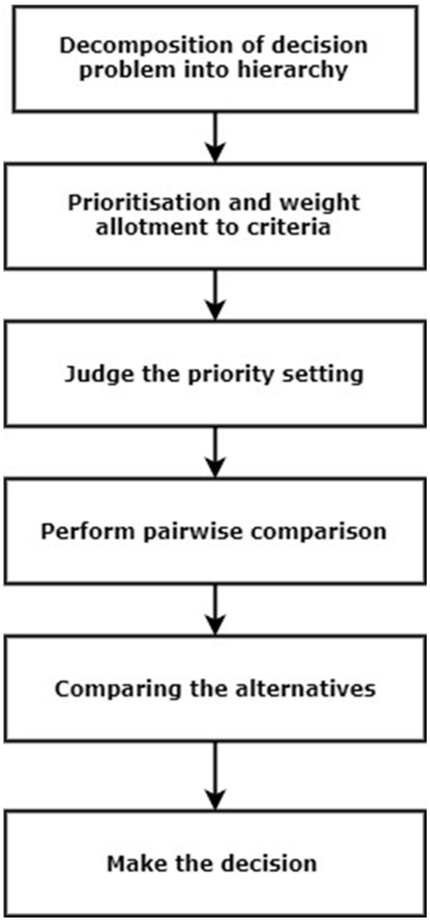

Figure 19 Steps of the analytical hierarchy process (AHP) by S.Subramanian(2011)

3.2 Quality Function Deployment (QFD) using HoQ

In this section, we answer the research question on the knowledge available in the literature to evaluate the layout alternatives based on the qualitative and quantitative parameters. The problem has several parameters to be evaluated to determine the layout performances. By implementing the QFD technique we would be able to integrate the qualitative and quantitative parameters used for assessing the alternatives. It gives a very systematic approach which also helps in obtaining positives and negatives about an alternative. The methodology implemented for decision making is Quality Function Deployment (QFD) using a tool called House of Quality (HoQ). According to Zhan (2019), the QFD involves an inter-functional expert group that helps in decision-making in the stage of planning new or improved products. The objective of QFD is to identify the customer requirements (CR) and translate them into engineering characteristics (EC). HoQ is an inter-linked matrix between CR and EC. The HoQ is illustrated in **Error! Reference source not found.**.

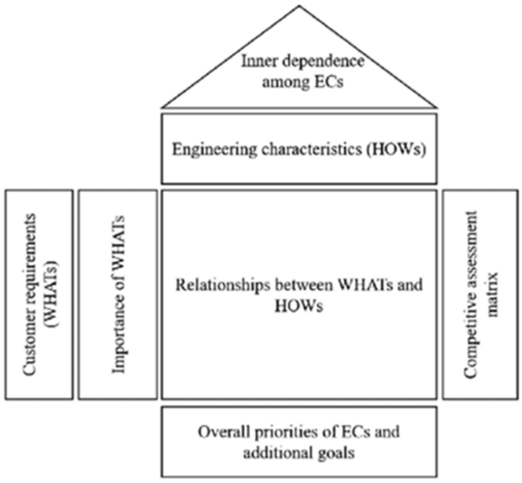

Figure 20 An illustration of HoQ by Wang (2016)

The horizontal part of the matrix shows the information relevant to the customer. The vertical part of HoQ corresponds to the technical translation of the customer needs. The HoQ has seven elements:

1. Customer requirements or the KPIs (Whats)
2. Engineering characteristics also can be considered as design interventions in our study (Hows)
3. The relative importance of the customer needs
4. Competitive assessment matrix with priorities of customer requirement.
5. Correlation between the Engineering characteristics
6. Relationships between 'Whats' and 'Hows'
7. Overall priorities of the design interventions

3.3 Conclusion

In this chapter, we compared the methodologies available in the literature. We have examined the pros and cons of various methodologies. We defined the criteria for the literature comparison based on the requirements for our case study. From the literature comparison and study, we conclude that Systematic Layout Planning by Muther (2015) is a methodology for layout planning and alternative generations for the SBT manufacturing system. We decide to use the simulation technique as suggested by Shahin (2011) for obtaining the production KPIs. By implementing the simulation technique, we aim to identify bottlenecks and enhance resource utilization as suggested by Gangal (2009). For the qualitative analysis, we employ Analytical Hierarchical Process (AHP) as suggested by S.Subramanian(2011) & Khan (1999). For integrating the results of the quantitive and qualitative performance of we choose the Quality Function Deployment (QFD) using a tool called House of Quality (HoQ). This knowledge will be further used in developing the framework in the next chapter that can be adapted for the SBT case study in Chapter 4.

Chapter 4: Case Study

In this Chapter, we answer the research question '*How are the layout planning and analysis steps adapted for this research and how do we implement the steps for the generation of layout alternatives?'* We have obtained knowledge of various methodologies that can be implemented for solving our problem statement in Chapter 3 through literature study. In Section 4.1, we develop a framework of methodologies selected from the literature study to be adapted for the greenfield project at SBT. From the literature review in Chapter 3, we concluded the SLP by Muther (2015) is to be employed for the layout planning and layout alternatives generation. Section 4.2 focuses on the steps to implement SLP to obtain layout alternatives for blade manufacturing processes at SBT.

4.1 The framework from adapted methodologies

This section elucidates the explanation and the chronology of the steps applied in this thesis. Figure 21 gives a schematic representation of the steps followed through the thesis. The methodology can be broadly divided into three main parts. The first part is alternate layout generation, followed by the analysis of the qualitative and quantitative parameters of those alternates. The last step is integrating the results of both the analysis to find the best suitable layout as per the given scenario and constraints of production.

In the first phase, the initial steps are adapted from the Systematic Layout Planning by Muther (2015). The layout alternate generation is carried out through a workshop with an interdisciplinary team at SBT, Hengelo. Before the second stage of the methodology, there is a cut-off criterion of the alternatives based on the cost estimation of the resources.

In the second stage, multi-criteria decision-making technology is adapted. The reason for including this step in the methodology is that it is intended to bridge the gap of irregularities in the opinion of layout quality by experienced professionals. This process is mixed with the layout performance evaluation based on both qualitative and quantitative parameters. For the quantitative parameter evaluation, a live production unit cannot be set up rather an analytical model through simulation methodology is used. The credibility of the simulation model as a decision-making tool for blade manufacturing is proved by Brunetti (2019). If a particular layout does not provide a consistent result then a feedback loop is created which leads to a correction in the simulation model. The Discrete event simulation methodology by Law (2015) is followed. Then the set of the qualitative parameters is evaluated using Analytical Hierarchical Procedure (AHP) as used in the methodology suggested by Kuo (2003) & Shahin(2011). The relative importance of the criteria used for the qualitative evaluation is determined by the same set of inter-disciplinary professionals through a workshop session. We conduct surveys to obtain values of the alternative performance for AHP. The individuals participating in the survey are experienced and expert SBT employees from the R&D.

In the last stage which is referred to as analysis integration methodology, we try to bridge the gap identified in the SLP by Muther (2015). The qualitative and the quantitative analysis are two mutually exclusive procedures and do not provide a holistic view of the problem statement. We use a multi-criteria decision-making technique introduced by Akao (1997) i.e. Quality Function Deployment (QFD). The basic idea behind using QFD for our study is to transform the qualitative attributes into measurable quantitative parameters which would help to deploy the functions that would ensure the targets set to be reached along with the quality assurance. From our evaluation of the performance of the alternatives, we consider that all the quantitive and qualitative parameters are not of equal importance. We want to first establish the relative importance between the parameters used for the assessment. Referring to the work of Shahin (2011) the same kind of situation is overcome by using House Of Quality (HOQ) and TOPSIS which are tools of QFD. The HOQ model is used to identify the overall priorities of the alternatives by first giving the weights to the selected criteria which are then followed by the evaluation of alternatives based on these criteria. TOPSIS is a multi-criteria decision-making methodology that has good potential for solving selection problems. Shahin(2011) uses the TOPSIS methodology to identify the best alternative (which has all the criteria at the desired level) and the worst alternative (which has criteria with tolerable levels). Through this strategy, we can rank the alternatives based on the desirable values. The detailed application of each methodology in the framework is discussed in Section 4.2 and Chapters 5 and 6.

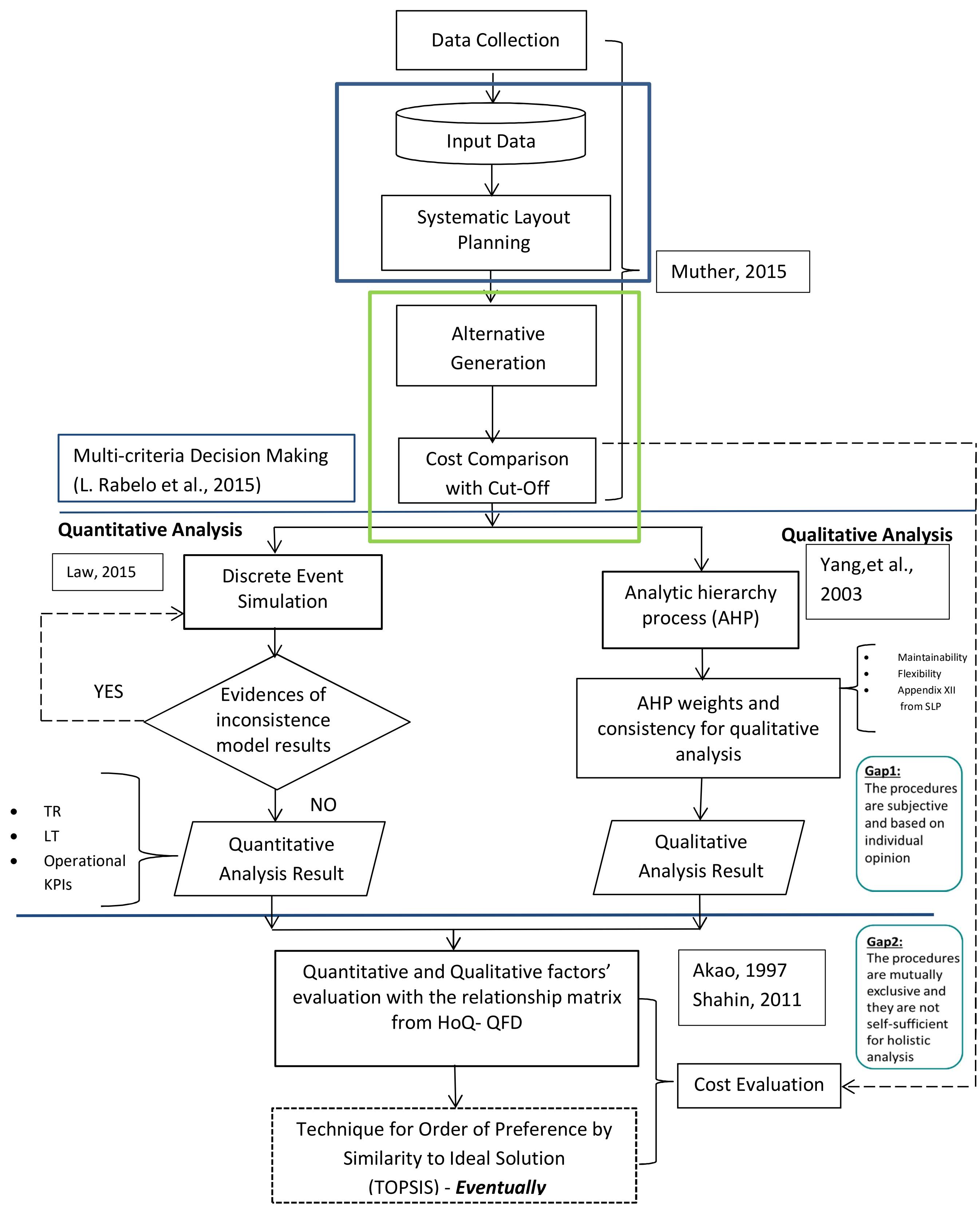

Figure 21 Framework of the methodology for greenfield project at SBT

4.2 Systematic Layout Planning for blade manufacturing at SBT

As per the framework developed in Section 4.1, systematic layout planning (SLP) by Muther (2015) is adopted for developing the alternate layouts for the blade manufacturing plant. In this section, we will answer the sub-research question 'What are the steps to plan and generate layout alternatives for the next-generation blades at SBT ?'

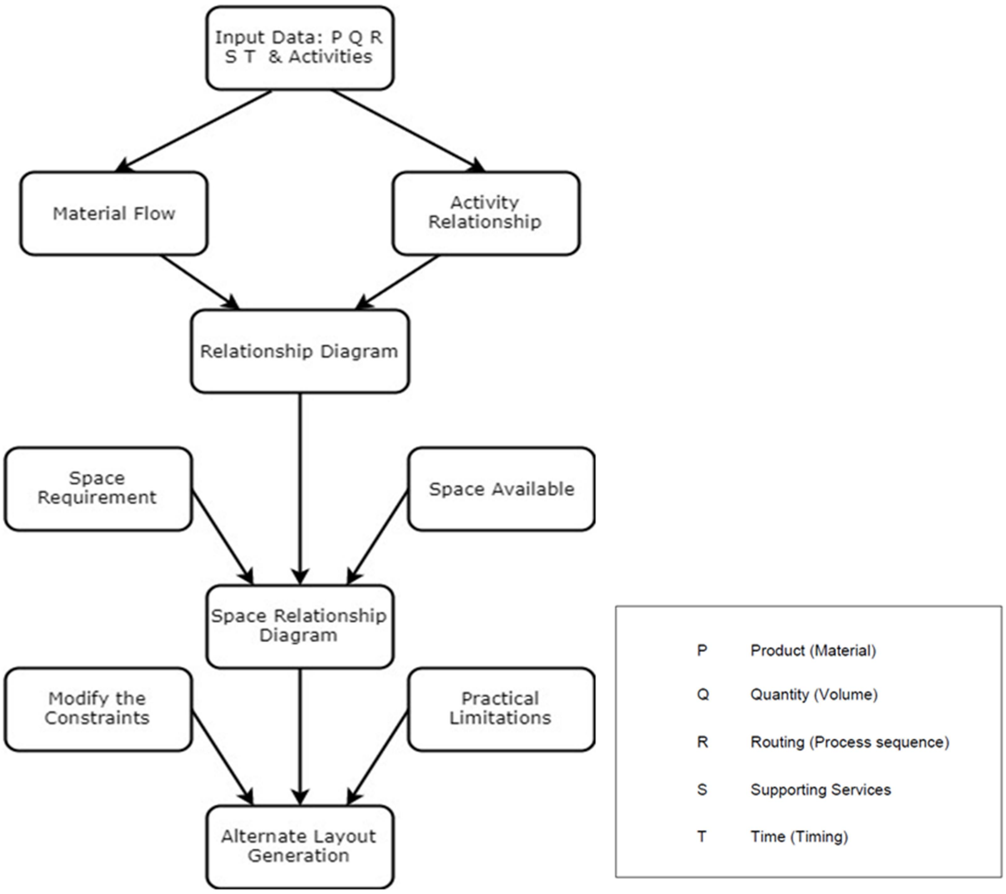

Figure 22: Systematic Layout Planning by R. Muther (2015)

The methodology for SLP is depicted in Figure 22. The first step involves the data collection, which is stratified with the alphabets P, Q, R, S, and T. The significance of each alphabet is stated in Figure 22. The steps of the SLP are sequentially followed to obtain the desired outputs. These outputs are then used collectively to generate alternate options for layout planning. The subsequent outputs for each step of the SLP are illustrated in **Error! Reference source not found.**. Step V highlighted with a box in Figure 23 is the additional step adapted for the SBT. From the literature study in Chapter 3, we learned that SLP falls into the procedural approach for facility layout planning. The right side blocks represent the steps of SLP and the left side blocks outputs are aimed for. The subsequent steps are explained in detail below:

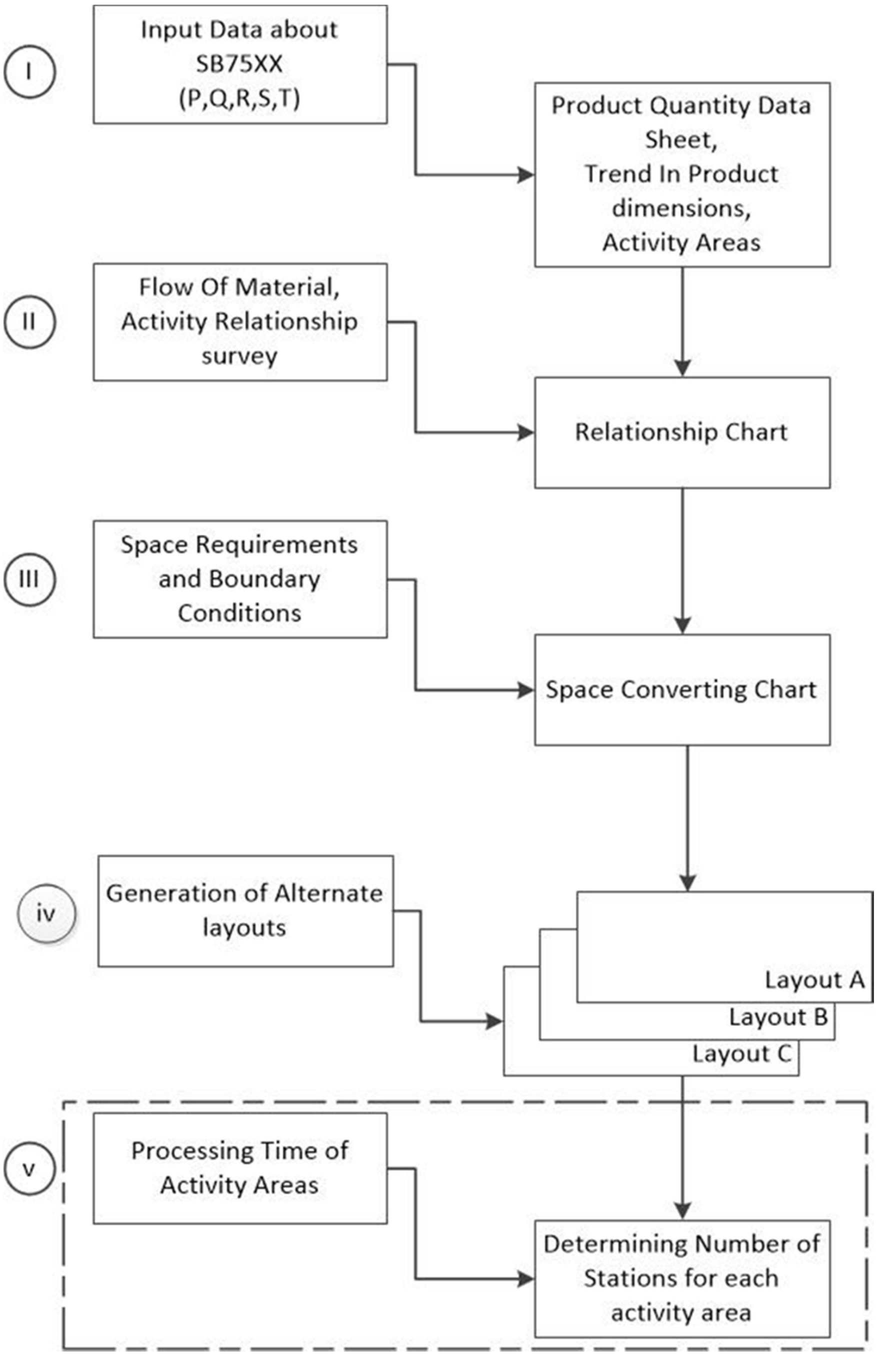

Figure 23 Desired output for each step of SLP adapted for SBT

Step I: Data collection

The initial step involves data collection SB7XX blades. The balde SB7XX is in the design phase at SBT. Hence the data collected is referred to as design data. We collected the product data (dimension and the weight of the blade), expected production targets, product configuration, and the sub-components from the design documents. We observed that the data required for this step was spread across different department documents. By implementing this step of SLP will ensure an integrated information source for the SBT layout planning. With data collected, we learnt about the blade production tasks and the subtasks in detail. Along with the production design team, we grouped the subtasks into the activity areas. Activity areas can be defined as the aggregation of operations with a similar flow of materials and workers sharing. We identified a total of 17 main activity areas identified.

We obtained the design cycle time (DCT) for each of the subtasks from the SBT team. The cycle time is referred to as design cycle time as we do not have real-time processing times of subtasks as SB7XX is not yet in the production run. The blade manufacturing process predominantly consists of the processes which involve surface area operations. Through the trend, we analyzed that the lengths and the chord dimensions of the blades have always increased. The trends have been shown in Figure 24 and Figure 25. We calculated the DCT for SB7XX from the DCT of earlier generation blades with a multiplication factor. The multiplication factor is a function of the surface area of the blade. We have represented the multiplication factor for the blade generations in Figure 26. The exact DCT for the activity areas cannot be specified in the report thus we represent it with reference to a previous generation blade (SB54).

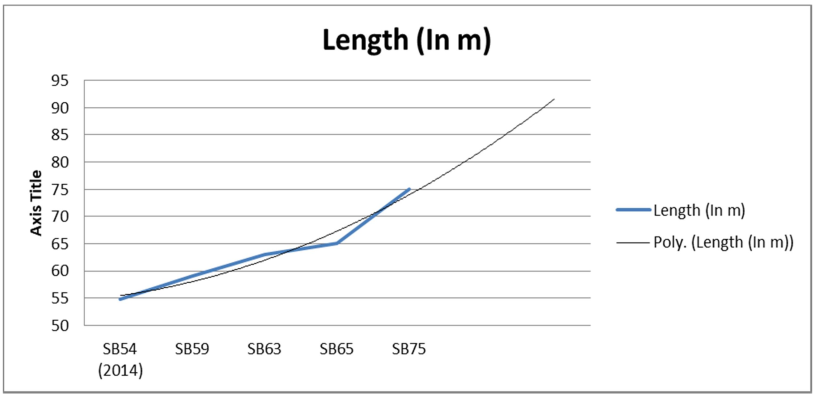

Figure 24 Length trend across blade generations

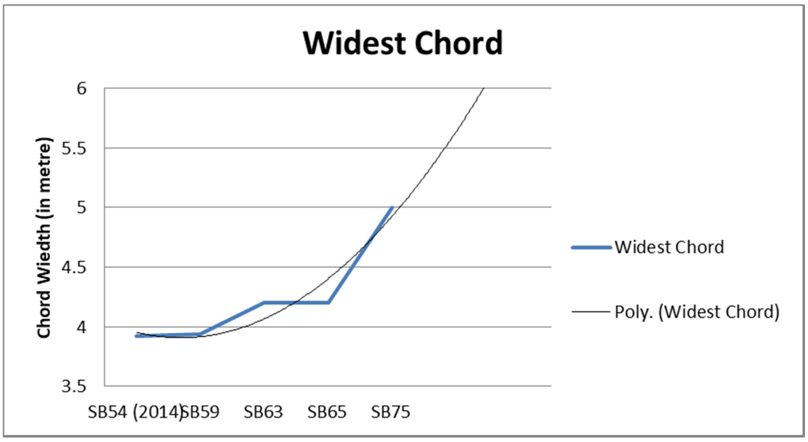

Figure 25: Widest Chord trend aross blade generation

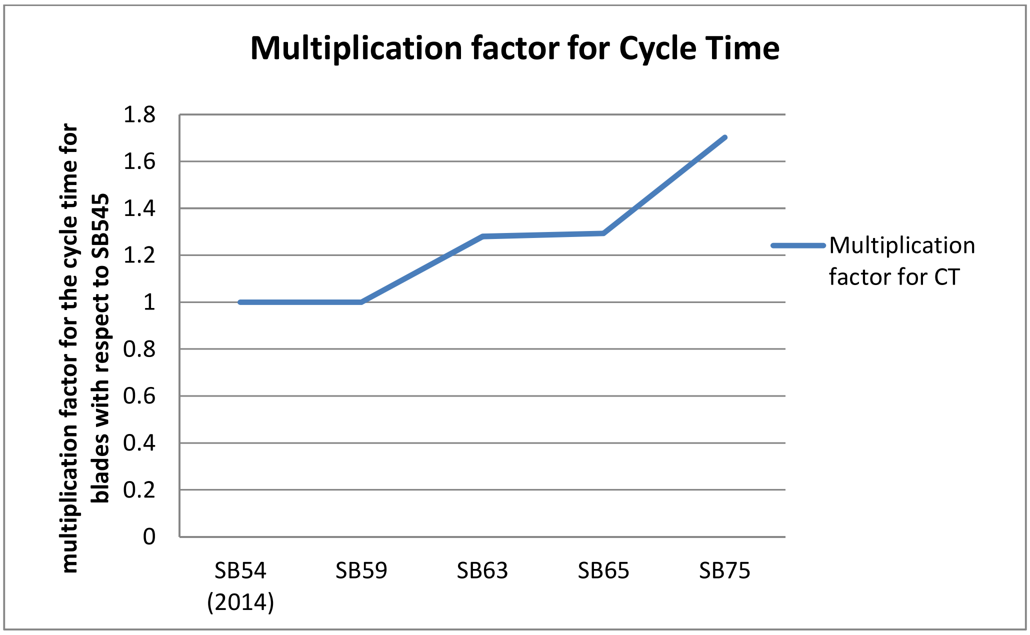

Figure 26: Increase in trend of cycle time with the evolution of blades with reference to SB54 blade

Step II: Flow of Material and Activity Relationship Survey

In this step, we aggregate all the process and material flow between the activity areas defined in the previous step. We executed this step with a survey that involved the participation of SBT members from the design, production, logistics, testing, and innovation departments. Through the survey, we mapped the importance of an actvity area to be placed close to the other activity area considering the operations of departments of the participants of the survey. We aggregated the results in form of a visual chart called 'Activity flow and relationship diagram'. The determination of the activity relationship is a qualitative analysis. Participants from various departments create a validation for this process as we have taken into account all the processes involved in the blade production. The rating for the closeness is done with the help of a linguistic vowel scale as mentioned in Figure 28. For example, the participants of the survey are asked to use the vowel scale rating to answer the question 'how important is it to place the material prep_1 next to component prep_1 for the operations of your department?' The results from this step are aggregated and represented in an illustrative designed by R.Muther (2015). The activity flow and relationship diagram for the SB7XX blade production is shown in Figure 27. Through this step of SLP, the relative positioning of the activity areas can be obtained. For example, from Figure 27 we can interpret that BF_Task 7 must be placed close to the BF_Task 8 activity area for better resource sharing and workflow.

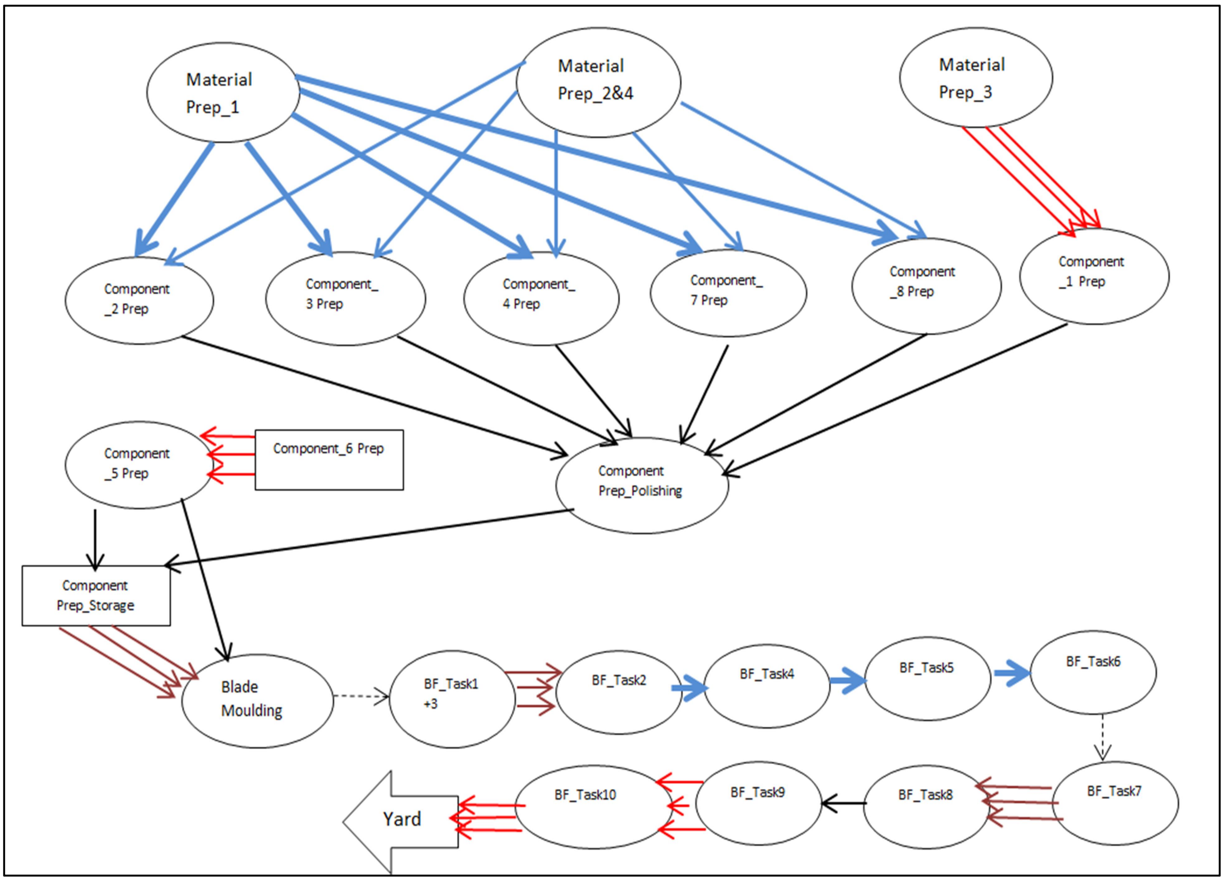

Figure 27 Activity flow and relationship diagram for SB7XX blades

Vowel Code Ratings	Meaning
A	Closeness Absolutely Necessary "Must be next to each other to function effectively."
E	Closeness Especially Important "Need to be very close -- down the hall or aisle"
I	Closeness Important "Need to be on same floor, side or wing."
O	Ordinary Closeness OK "Occasional interaction. Anywhere in Bldg 100 OK."
U	Closeness Unimportant "Infrequent interaction. No significant relationship."
X	Closeness Not Desireable "Keep separate and away."

Figure 28: Linguistic vowel scale used for the relationship survey

Step III: Space Requirement and Boundary Conditions

The geographical arrangements of the activity area can be established only after defining the space requirements for the activity area. In this step of SLP, we collect the area requirement data for the activity areas. The boundary conditions for area requirement are defined as the area required for the tasks performed in the activity area also considering the clearance spaces, the aisle width for the internal transportation, and also considering the safety measures. In this step, we derive the boundary conditions for the activity areas with multiplication factors and the area considerations of the previous generation blades. The multiplication factor is a function of blade dimensions. The parameters considered for the boundary conditions for the SBT case are tool footprints, material handling equipment, worker and work station interaction, and safety factor for operations and future expansion. The boundary conditions for the activity area are converted into scale-down block templates of the activity areas. We used the scale-down block templates in step IV in the alternative generation workshop. The example of the scale-down block templates is shown in Figure 29.

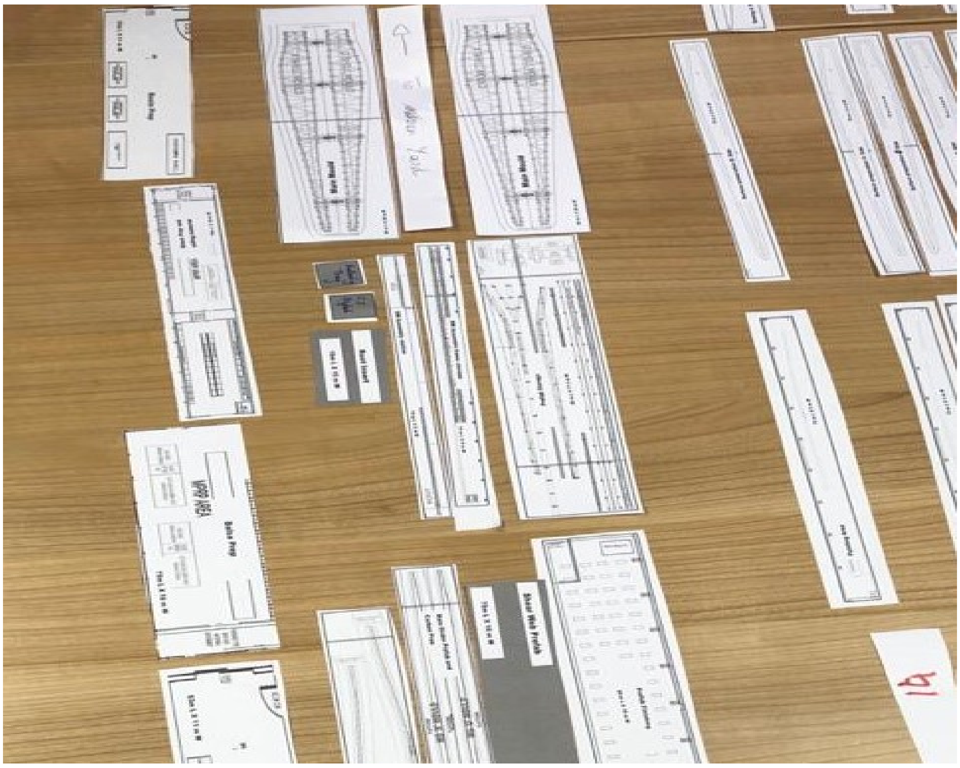

Figure 29 Scaled down 2D block templates of the activity areas from step III of SLP

Figure 30 Outputs from SLP steps represented using a visual display board for the Layout Workshop

Step IV: Generating alternative layouts

An alternative generating process is a qualitative approach as it occurs through a workshop session of professionals from different departments. The layout planning is a Kaizen event as it is a team-based improvement activity. The information from the previous steps is represented in a visual format for easy interpretation of the information related to the manufacturing constraints. The visual display board with all the outputs from the earlier steps of SLP is represented in Figure 30. We developed the alternate layouts by manually placing the activity blocks in specific orientations.

The planning encounters various constraints that need to be considered and adjusted into the plan. Few important considerations are analyzed before the team works on alternative generation:

1. <u>Ease of logical expansion.</u>
   From the previous factory layouts at Suzlon Energy Ltd., the obvious mistake was prevented. The further expansion of the facility was hindered because of its orientation in consideration of the main road. Figure 31 shows a clear view of the orientation of the plant at Bhuj and Ratlam concerning the main road. The Bhuj plant is perpendicular to the main road. This prevented the expansion of the main plant building. Whereas since the Ratlam plant was aligned parallel to the main road the extension of the main plant building was easy.

2. <u>Separated Docks for the inwards and outwards flow in the plant.</u>
   The layout needs to have separate docks for the inward and outward flow as it reduces the complexity of the internal logistics. It is also suitable for large plants where the inwards and outward flows are independent.

Figure 31 Bhuj plant (Left) and Ratlam Plant (Right) orientation concerning the main road (from Google maps)

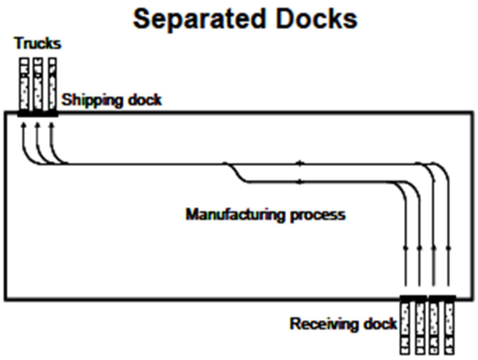

Figure 32 Dock Location representation, (R.Muther, 2015)

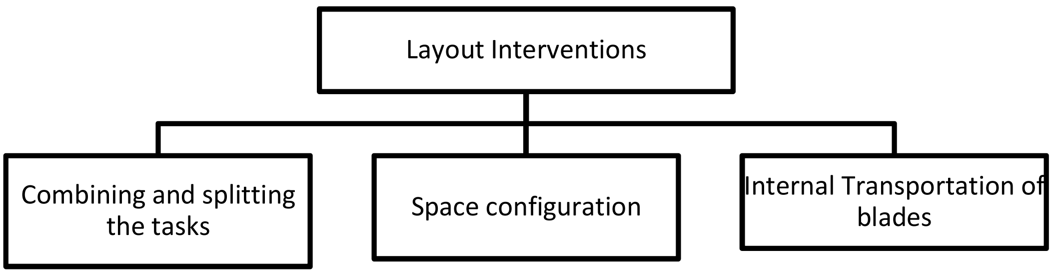

Figure 33 Intervention for layout alternatives

3. Identifying the interventions in the production processes:

   We workshopped with the design team at SBT for identifying the interventions to generate layout alternatives. We identified three interventions that would be interesting to analyze for this study as in Figure 33. Since layout planning is a very complex problem statement. We would be focusing on generating the layout alternatives for the SBT blade manufacturing considering the design interventions given below:

   1. *Combining and splitting of processes to form the activity areas:*
      We analyze and try various combinations of the processes that can be aggregated to perform together in the same stations based on the shared types of equipment and the labor.
   2. *Space orientation of the activity areas:*
      The SBT team wanted to analyze the possibility of placing few activity areas outside the main building. We wanted to analyze the flexibility and ease of operations for these implementations. We were also interested to know the production performances of these alternatives.
   3. *Mode of transportation choose to move the blades between the stations:*
      The SBT team is in the discussion of using new equipment for internal transportation for the blades. We include this intervention when planning the alternative.

Layout Alternative 7: Blade finishing area		
Location	Combining And Splitting of Process	Transporting Equipment
Flexible Temporary Structure	Parking Station	Rotating stand
	BF_Task1 + BF_Task3	
	BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6	
	BF_Task7	
	BF_Task8	
	BF_Task9	
	BF_Task10	
	BF_Task11	

Figure 34 LA_7 configuration for blade finishing operations

4. Planning the Layout alternative:

   We divided the layout for blade production at SBT into two sub layout namely:

   - Material and Component Preparation area + Blade Moulding areas
   - Blade Finishing Area

   Through the workshop sessions, we developed 5 alternative layout plans for the material and component preparation and blade moulding. Three layout plans for the blade finishing operations as represented in Figure 36.

   We planned the layout with the SBT team in the workshop considering the design interventions. The details of the layout alternatives for the blade finishing area are given in Appendix B. For a clear understanding of the process involved in the alternative generation, we explain the process of planning the LA_7 in detail.

LA_7 for blade finishing operation: Considering the increasing trend of dimensions of the future generation blades, the activity area will have an increment in the capacity (no. of stations) and the floor area requirement for the future generation blades. Thus to enable easy future expansion, we placed a few of the activity areas of the blade finishing operation in a flexible temporary structure. The flexible temporary structure is inexpensive for future expansion also easy to implement. From Figure 27 of step III, we know that BF_Task2, BF_Task4, BF_Task5, and BF_Task6 can be aggregated together to be done in the same stations for better workflow and resource sharing. Thus we plan to aggregate these tasks. The production team wanted to assess the effect and the efficiency of the production system with the introduction of new rotating stands for the BF_Tasks. The team wanted to analyze the new rotating stands as this would reduce the waiting time for the cranes to move the blades between the stations. Figure 34 gives the details of the LA_7. The visual template for the LA_7 is represented in Appendix B.

5. Visual representation of the alternatives:

In the workshop, the blocks were arranged for a visual representation of the alternatives as shown in Figure 36. The layout alternatives differed from each other based on the three production interventions. Table 1 explains the layout alternatives 6, 7, and 8 for the finishing area. The finishing operations have 11 tasks. The alternatives have different combinations of the tasks to form the activity area. Later the alternatives also differ in the placement of the activity areas in the main building or the outside area. The internal transportation of the blades is either done using cranes or the telescopic trailer. The use of rotation stands is the introduction of new technology. We want to analyze how these interventions affect the performance of the layouts. Thus, the layouts are evaluated based on qualitative and quantitative characteristics in Chapters 5 and 6.

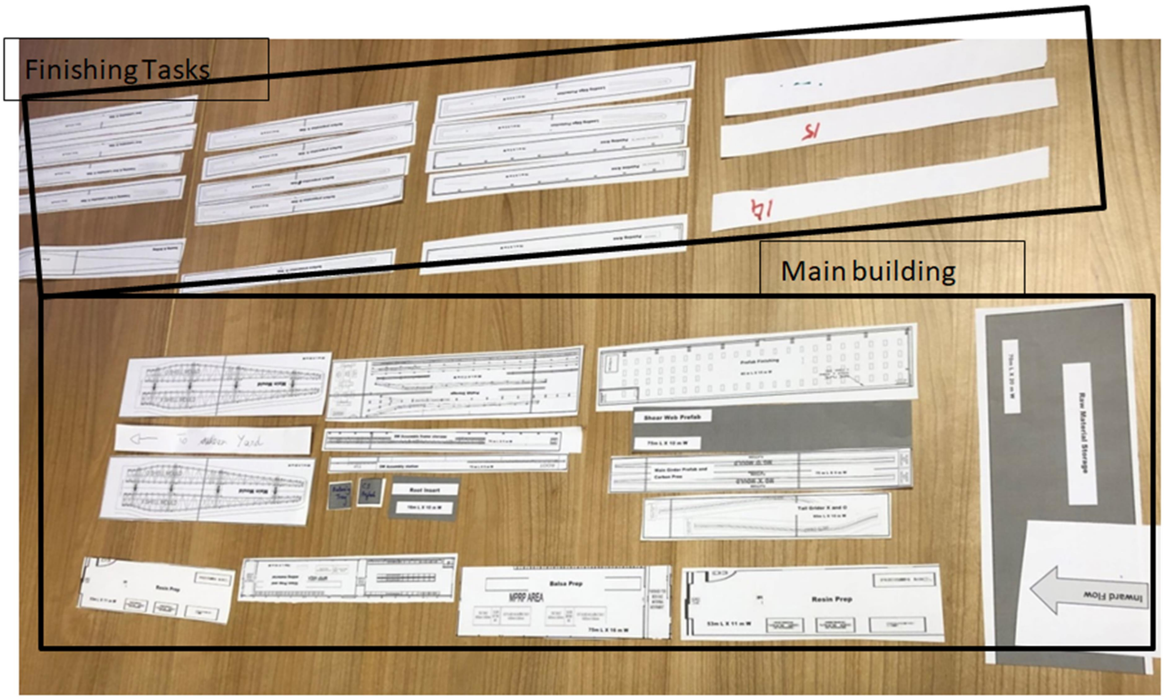

Figure 35 Layout alternative formed with the block templates during the workshops

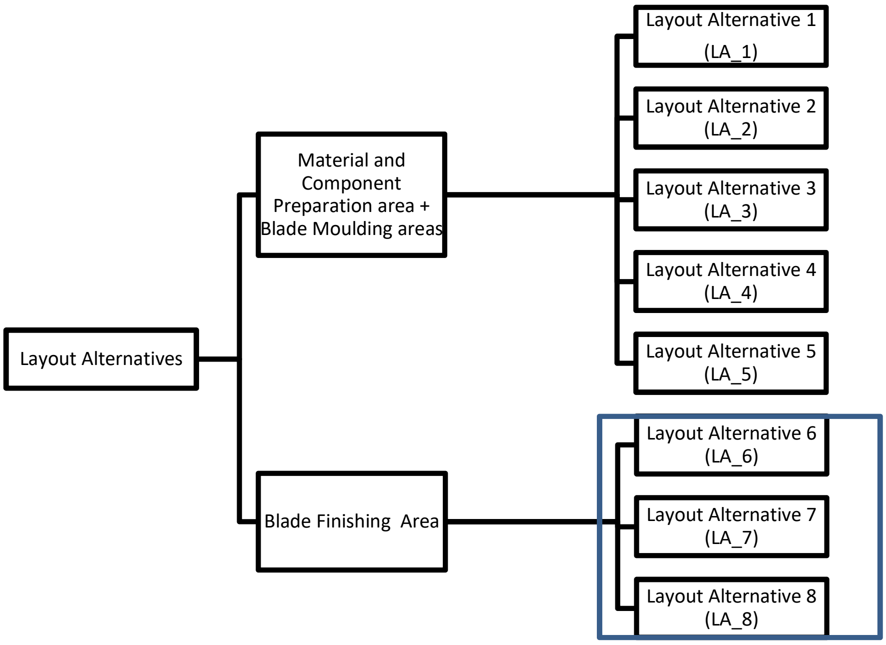

Figure 36: Layout alternatives for SBT case

Table 1 Layout alternatives: Blade finishing area as per the interventions

<table>
<tr><th rowspan="2">Layout Intervention</th><th colspan="3">Layout Alternative: Blade finishing area</th></tr>
<tr><th>LA_6</th><th>LA_7</th><th>LA_8</th></tr>
<tr><td rowspan="8">Combining and splitting of task</td><td>BF_Task1 + BF_Task3</td><td>Parking Station</td><td>BF_Task1 + BF_Task3</td></tr>
<tr><td rowspan="2">BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6</td><td>BF_Task1 + BF_Task3</td><td rowspan="4">BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6 + BF_Task7 + BF_Task8</td></tr>
<tr><td>BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6</td></tr>
<tr><td>BF_Task7</td><td>BF_Task7</td></tr>
<tr><td>BF_Task8</td><td>BF_Task8</td></tr>
<tr><td>BF_Task9</td><td>BF_Task9</td><td>BF_Task9</td></tr>
<tr><td>BF_Task10</td><td>BF_Task10</td><td>BF_Task10</td></tr>
<tr><td>BF_Task11</td><td>BF_Task11</td><td>BF_Task11</td></tr>
<tr><td>Space Configuration</td><td>Some tasks placed outside the main building area</td><td>All tasks outside the main building</td><td>Tasks other than 1,3, 9, and 10 are aggregated at performed outside the main building.</td></tr>
<tr><td>Internal Transportation of blades</td><td>Cranes, Telescopic trailers and Rotating stands with wheels</td><td>No charge for finishing activities, Telescopic trailer, and Rotating stands with wheels needed</td><td>Cranes, Telescopic trailers and Rotating stands without wheels</td></tr>
</table>

Step V: Processing times of activity areas

As already mentioned at the beginning of this section, this step is a modification in SLP methodology for the SBT case. The planned layout should have enough capacity (number of stations) to meet the production demand. The processing times of finishing stations must be quite high. There is a constant rate at which the blades will come out of the main mould stations. The succeeding stations must be available to move the blades from the main mould station to avoid bottlenecks. The number of stations is calculated using a lean tool for line balancing with a chart called Yamazumi chart. The line balancing considers the takt time. Takt time determines the pulse of the production system by linking the pace of customer demand with production activities as defined by Naufal (2016). The safety factor of 20% is considered in case of breakdowns as suggested by the design team. The safety factor includes the uncertainty associated with the production cycle. This will also reduce tight capacity allocation in the stations. From step I, we have the processing time for each activity area. The annual demand for the

SB7XX blades and the total operating hours is known from step I. This is substituted in the Takt time formula given below.

$$Takt\ Time\ with\ safety\ margin = \frac{\text{Total operating hours per month}}{Customer\ demand\ per\ month} X\ (1 - safety\ factor)$$

To determine the number of stations required in the activity areas.

$$Number\ of\ work\ station = \frac{\text{Processing time of activity areas}}{Takt\ Time}$$

Table 2 Line Balancing of the Processes for the LA_7

Sno	Activity Area	No. Of Station	% Utilisation
1	BF_Task1 + BF_Task3	1	90.42
2	BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6	7	81.23
3	BF_Task7	3	66.67
4	BF_Task8	2	69.44
5	BF_Task9	3	59.72
6	BF_Task10	1	81.94
7	Yard	1	
8	Parking Station	1	
	Total No. Of Stations	19	

Takt Time	720
With Safety Margin	576

For a clear understanding of this step, we explain the case of LA_7. We understood from the design team that the number of the station for BF_Task1 + BF_Task3 is to be kept 1 and for BF_Task 9 is to be kept 3 irrespective of interventions due to some production design constraints. So we applied the line balancing technique for the remaining activity areas. We calculate the number of stations for the activity areas using the equation stated above. We consider the takt time as 720 min and safety factor as 20% as given by the SBT team. The number of the station from the calculation for the LA_7 is given in Table 1. The processing time is distributed equally between the station in the activity area and represented in a graph called the Yamazumi chart as shown in Figure 37. Yamazumi chart provides a visual representation of the capacity underutilized at each activity area. Building up a station is a cost to the company, to reduce this extra cost we try to merge the activity areas to see if the unused capacity of the stations can be reduced. The area between the working limit of the station and the takt time is a representation of the stations working beyond the safety margin but within the maximum limit. We follow a similar procedure to obtain the number of stations of the LA_6 and LA_8. The number of station obtained from the line balancing for LA_6, LA_7 and LA_8 is given in Table 1.

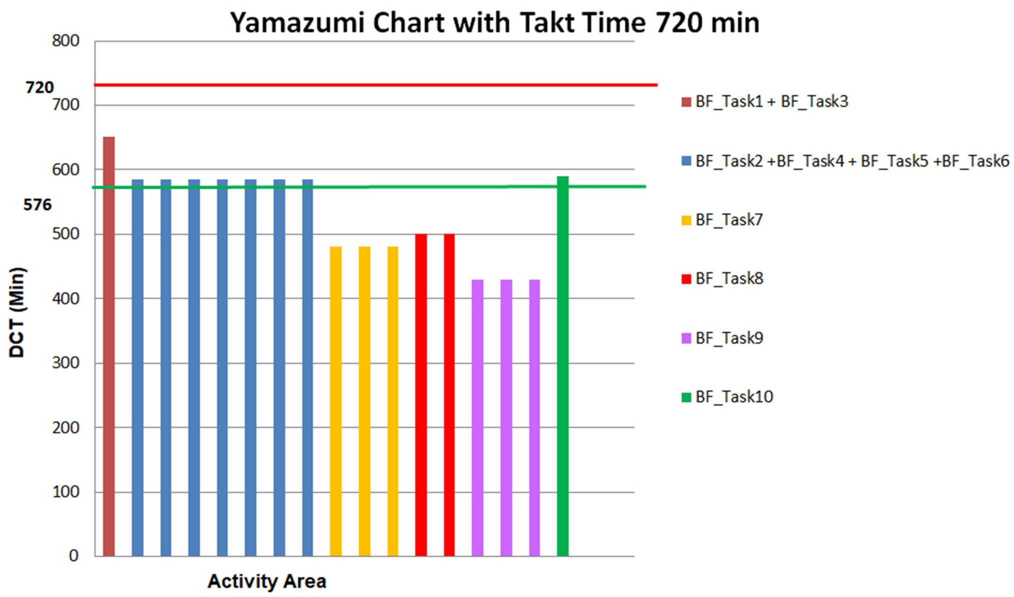

Figure 37 Line balancing using Yamazumi Chart for LA_7

Table 3 Blade finishing area number of stations from line balancing

<table>
<tr><th colspan="6">Layout Alternative: Blade finishing area number of stations</th></tr>
<tr><th>LA_6</th><th>No. of stations</th><th>LA_7</th><th>No. of stations</th><th>LA_8</th><th>No. of stations</th></tr>
<tr><td>BF_Task1 + BF_Task3</td><td>1</td><td>Parking Station</td><td>1</td><td>BF_Task1 + BF_Task3</td><td>1</td></tr>
<tr><td rowspan="2">BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6</td><td rowspan="2">5</td><td>BF_Task1 + BF_Task3</td><td>1</td><td rowspan="4">BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6 + BF_Task7 + BF_Task8</td><td rowspan="4">8</td></tr>
<tr><td>BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6</td><td>7</td></tr>
<tr><td>BF_Task7</td><td>2</td><td>BF_Task7</td><td>3</td></tr>
<tr><td>BF_Task8</td><td>1</td><td>BF_Task8</td><td>2</td></tr>
<tr><td>BF_Task9</td><td>3</td><td>BF_Task9</td><td>3</td><td>BF_Task9</td><td>3</td></tr>
<tr><td>BF_Task10</td><td>2</td><td>BF_Task10</td><td>2</td><td>BF_Task10</td><td>2</td></tr>
<tr><td>BF_Task11</td><td>1</td><td>BF_Task11</td><td>1</td><td>BF_Task11</td><td>1</td></tr>
<tr><td>Total no. of Stations</td><td>15</td><td></td><td>20</td><td></td><td>15</td></tr>
</table>

4.3 Conclusion

In this chapter, we developed a framework that was an integration of the methodologies from the literature study in Chapter 3. The framework can be broadly divided into three stages namely, layout alternative generation, quantitive and qualitative analysis of layout performance, and lastly the integration of the results from both the analysis to select the most suitable alternative for SBT. In Section 4.2, we implemented the steps for the generation of the layout alternatives. We observed that SLP steps involve intensive data collection and organizing it in a usable format. Also, it involves conducting many workshops and surveys. It was observed that it helped in capturing the expert and experienced team member's opinions in form of values that are more usable in decision making. The alternatives generated from this chapter are the results of three design interventions that the SBT team wanted to analyze. From the SLP steps, we obtain the space configuration, capacity (number of stations), mode of internal transportation of the activity areas.

Chapter 5: Quantitative analysis of layout alternatives

The first stage of the framework of layout alternative generation is completed and explained in Chapter 4. The proposed alternatives now have to be compared to see which one performs best. The methodology for selecting the best layout among the proposed alternatives involves quantitative and qualitative analysis. Within our literature study, we choose simulation as a suitable tool for quantitative analysis. In this chapter, we focus on the research question: "*How is the quantitive analysis employed to obtain the production performance data of the alternatives?*" Section 5.1 elaborates on the steps followed while building a validated simulation model. Subsequently in Section 5.2, we discuss the interventions and their implementation in the model to improve the defined performance parameters. In Section 5.3, we prepare the results from the quantitive analysis to be used in the third stage of the framework in Chapter 6.

5.1 Building the simulation model

In this section, we discuss the steps followed from the Law (2015) methodology for simulation modeling as implemented for SBT layout alternatives. The steps are stated below:

1. Problem formulation
2. Data collection and assumptions
3. Validation of the assumptions
4. Construction and verification of the computer program
5. Conducting pilot runs and validating the computer program.

5.1.1 Problem formulation

As discussed in Chapter 1, the production plant for the SB75XX blades does not exist yet. The simulation models of the layout alternatives are paper models that are a virtual representation of the blade manufacturing processes. It is used for obtaining quantitative parameters. The quantitative parameters are the manufacturing KPIs defined by the SBT team. The tasks for the material and component preparation are assumed not to influence the layout performances as the components from these tasks are stocked at the storage units and follow the supermarket logic. Also, the number of stations and the design interventions for material and component preparation is the same for all the alternatives. There is variation in the layout alternatives for material and component preparation only in terms of the space configuration. Therefore, we decide to focus our analysis on the layout alternatives for the blade finishing area (i.e. LA_6, LA_7, LA_8). We first start creating the models in the Tecnomatix Plant Simulation software of the layout alternatives for the finishing area. The layout alternative is explained in Section 4.2. We evaluate layout performance in the deterministic perspective using the design cycle times (DCT) as the plant data for actual processing times (ACT) are not available. We consider triangular distribution with the DCT to study the stochasticity of the system using a simulation model. As discussed in Step V of the Systematic Layout Planning (SLP) in Chapter 4, we evaluated the number of stations for the activity areas using Yamazumi chart representation. This method of dimensioning of stations is a static type of analysis. It does not account for the queuing effect between the activity areas and the delays due to the internal transportation of blades. Thus, we want to include the interventions of the blade arrival rates and the re-dimensioning of the number of stations using bottleneck analysis as experiment scenarios.

According to Law, simulation can be classified as 'terminating' or 'non-terminating. The simulation model for the SBT production system can be categorized as a non-terminating one as we would not want the production line to stop at any point under normal conditions. By definition "non-terminating simulation is one for which there is no natural event to specify the length of the run" (Law, 2015). Secondly, we need to identify if our system is 'steady state' or 'transient state' for better representation of the real system. This is done by understanding the effects of initial system conditions and output analysis of the model. When a system's performance depends on the initial conditions and the run length of the model, then it is identified as a transient system. when the system performance is independent of the initial conditions after a certain run length (i.e., warm-up period) then it is called a steady-state system. We have observed during the experiments that system performance after the warm-up period is steady. The measure of the system performances is defined using the steady-state parameters. The KPIs stated in Section 5.1.1 are the steady-state parameters in this study. The statistical analysis of the steady-state parameters has been discussed in detail in Section 5.2. So to summarize, the simulation study in this thesis is a non-terminating and steady-state type.

We chose the KPIs for the quantitative analysis based on the production targets expected from the plants. The selected KPIs are explained below:

1. <u>The Production Pace (PP) of Blades:</u> It is the time (in days) taken to produce one blade in the manufacturing system. As mentioned earlier in Chapter 4, the manufacturing plant needs to have a target of 0.5 PP (i.e. 12hrs/ blade) to fulfill the expected demand. The layouts must meet this KPI.

2. <u>The Average Throughput (Avg TH) of blades:</u> It is defined as the average time (in days) spent by the blades in the blade finishing. Blade throughput time provides the duration from the time the blade enters the BF_Task1 station till it goes out to the yard. It also accounts for the waiting time of the blade if the successor stations are occupied. The average throughput time is the direct indication of the queueing and bottleneck effect in the production system. An unbalanced production line will have a high value of average throughput compared to a balanced line. There is no target or cut-off value for this KPI. The less Avg TH of blades in the layout alternative is an indication of the system's efficient workflow in the system.

3. <u>The Mediation Time (MT) of the transporting units:</u> It is the sum of the times that the stations were waiting for the assigned transporting units to move the blades to the successor stations. This KPI is essential to analyze the bottlenecks created due to the unavailability of the transportation units. Here the transportation units indicate the cranes and the telescopic trailers. From Table 1, it is evident that the alternatives have a different mode of transportation of blades from one activity area to another. The

MT indicates the duration for which the stations in the layout alternatives are idle and not working as the blade cannot be moved to the successor station due to the unavailability of the crane or the telescopic trailer. This KPI contributes to the non-productive time of the activity areas. Thus, we aim to give more preference to the layout alternative that has minimum MT among the alternatives.

Although the layout planning of a greenfield project involves various factors to be analyzed, through the KPIs defined here we attempt to optimize the system dimension in terms of the number of stations required for each activity. We intend through this analysis to have an overview of the operational KPIs. We aim to improve the capacity planning of the stations and to reduce the risks at the initial stage of layout planning by early proof of concept.

5.1.2. Data Collection and assumptions

For the simulation study, we received the data from the design documents available at the SBT team. As already mentioned in Step I of SLP in Chapter 4, we have obtained the design cycle time for SB7X by using a multiplying factor with the design cycle time of the SB65 blade type. We have determined the number of stations in the activity area from the line balancing and the Yamazumi chart for all the layout alternatives in Step IV of SLP. The number of stations obtained from this step is from the deterministic cycle time as it is from the design data. Due to the lack of plant data for the production times, we tried to fit a probability distribution to represent the blade finishing tasks. We use the probability distribution to get more close to the realistic perspective of plant operation. As a consequence, a triangular distribution was used to represent the cycle times of the blade finishing tasks. The triangular distribution requires three parameters: minimum, maximum, and mode of the processing times for each task. We obtained the values for the min, max, and mode from the design team at SBT. The SBT team evaluated the values for the distribution parameters from their experience with the previous generation blades (SB65, SB63, SB59, SB54) plant data. The percentages are expressed in terms of the design cycle times in Table 4. For example for BF_Task4, the triangular distribution has a minimum and mode value equal to design cycle time and the maximum value is 20% more than the design cycle time.

Table 4 Triangular distribution parameters for Design Cycle Time of blade finishing tasks

S no.	Tasks	Min	Max	Mode
1	BF_Task1 +BF_Task3	DCT	10% X DCT	DCT
2	BF_Task2	DCT	20% X DCT	DCT
3	BF_Task4	DCT	20% X DCT	10% X DCT
4	BF_Task5	DCT	10% X DCT	DCT
5	BF_Task6	DCT	10% X DCT	DCT
6	BF_Task7	5% X DCT	5% X DCT	DCT
7	BF_Task8	DCT	10% X DCT	DCT
8	BF_Task9	DCT	15% X DCT	DCT
9	BF_Task10	DCT	15% X DCT	DCT

One of the differentiating factors between the layout alternatives is the mode of transportation of blades between the activity areas. The overhead cranes and the telescopic trailers are used in the plants for the previous blade generations also. The research team at SBT wants to introduce a new technology intervention for the mode of transportation in this study. The intervention is the use of rotating stands with wheels. The details of which mode of transportation are assigned for moving the blades between specific activity areas are mentioned in Appendix B. We have considered the time taken to move the blades from one activity area to the other as 30 min as suggested by the design team. The transportation modes are shared between the activity areas. Through the simulation runs, we aim to study the waiting time of the blades for the crane and the telescopic trailer. Crane and telescopic trailer are the resources that are shared between the This is accounted for in the simulation study with the KPI 'Mediation time of the Transportation Equipment '. Figure 38 gives a summarized representation of the input data used while modeling at each level. The model construction of the layout alternatives has been explained in Section 5.1.4.

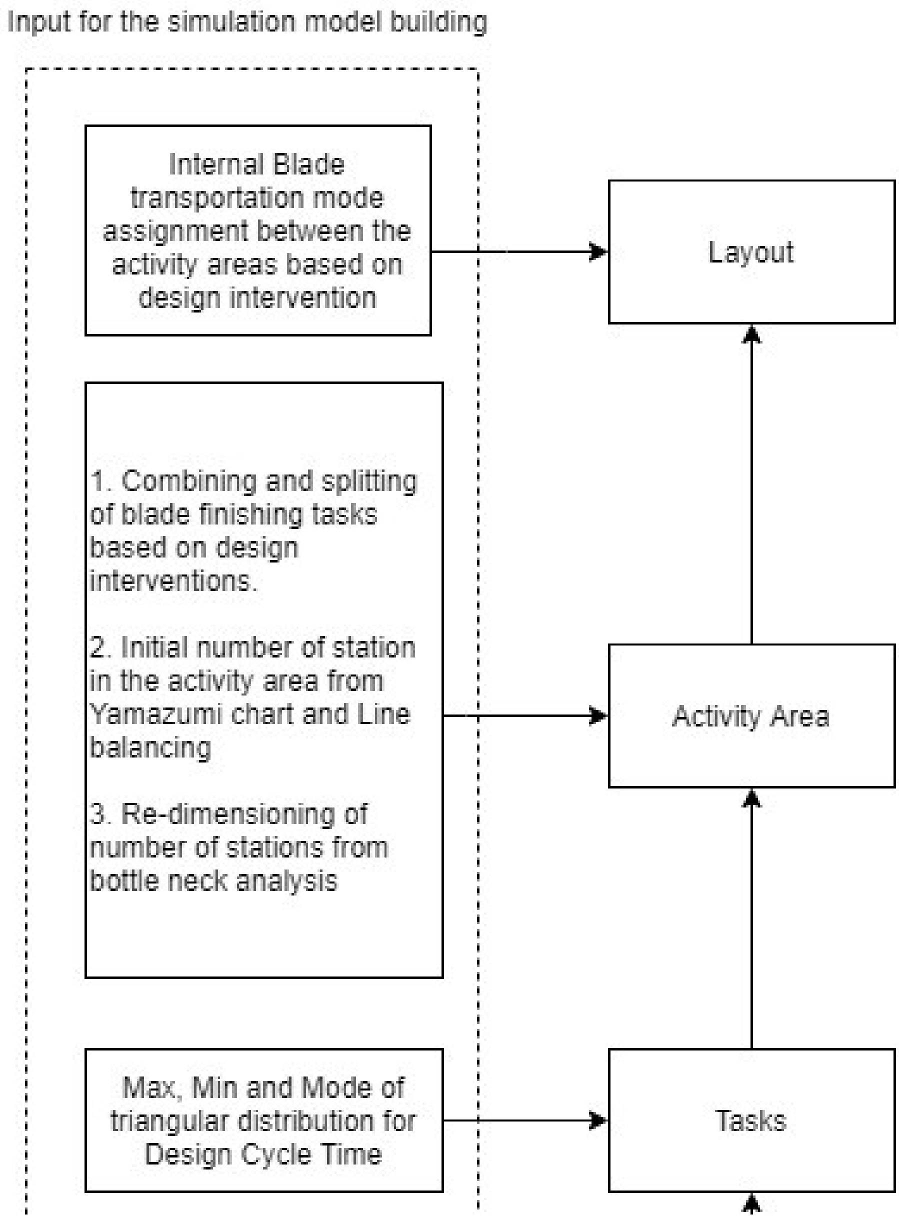

Figure 38 : Flow chart representing the Inputs to the simulation model

When defining a system using a simulation model it is necessary to define the assumptions to reduce the complexity of the problem. The set of assumptions were verified with the production design team at Hengelo. The assumptions considered for building the simulation model are stated below:

1. The quantitative analysis of layout alternatives is considered only for the blade finishing tasks. The reason behind this is because the process before these tasks is the main blade modeling which has more or less constant cycle time.
2. There is no starvation of the stations in the activity areas.

3. The blade's arrival to the blade finishing area is considered to be at a constant interval.
4. The setup times for tasks are not considered separately, as in real life the calculation for the task preparation and set up times are accounted together with other sub-tasks to form one main task.
5. The operating hours are 8 hours per shift and there are 3 shifts per day.
6. The factory operates 288 days per year. The remaining days are assigned for maintenance work.
7. There are no breakdowns of machines during the operating hours. Tooling and operators have an availability of 100%.

I. *Outputs from the simulation run:*

The final outputs from the simulation runs are used for decision-making. The outputs are defined as KPIs in Section 5.1.1. The KPI values are the aggregated outputs at each level. The KPI Mediation Time (MT) at the layout alternative level, is the addition of the waiting time for the transportation equipment to move the blade to the proceeding station at the processing station level. The Average Throughput Time of the alternative is the average of the MU attribute namely Blade Throughput time for each simulation run. Whereas the production pace (PP) is obtained by the count of the blades coming out of the system fully finished. Figure 39 is the representation of the outputs obtained at each level of the simulation model.

During the experiment runs for the bottleneck analysis, the percentage utilization of the processing station at the activity area level is calculated. It is the direct representation of the stations being occupied by the blade during the production period. Based on the overutilization of the stations at the activity areas, the re-dimensioning of the number of stations at that station is done. The procedure for the bottleneck analysis for the re-dimensioning of stations is explained more elaborately in Section 5.2.

II. *Transporting Equipment:*

The transportation of blades between the activity areas can be done using three types of equipment namely, telescopic trailers, overhead cranes, and the rotating stand. The assignment of the transportation equipment type between each station is according to Table1. We use the KPI ‘Mediation Time (MT) of the transporting units’ to analyze the effective resource sharing between the activity areas.

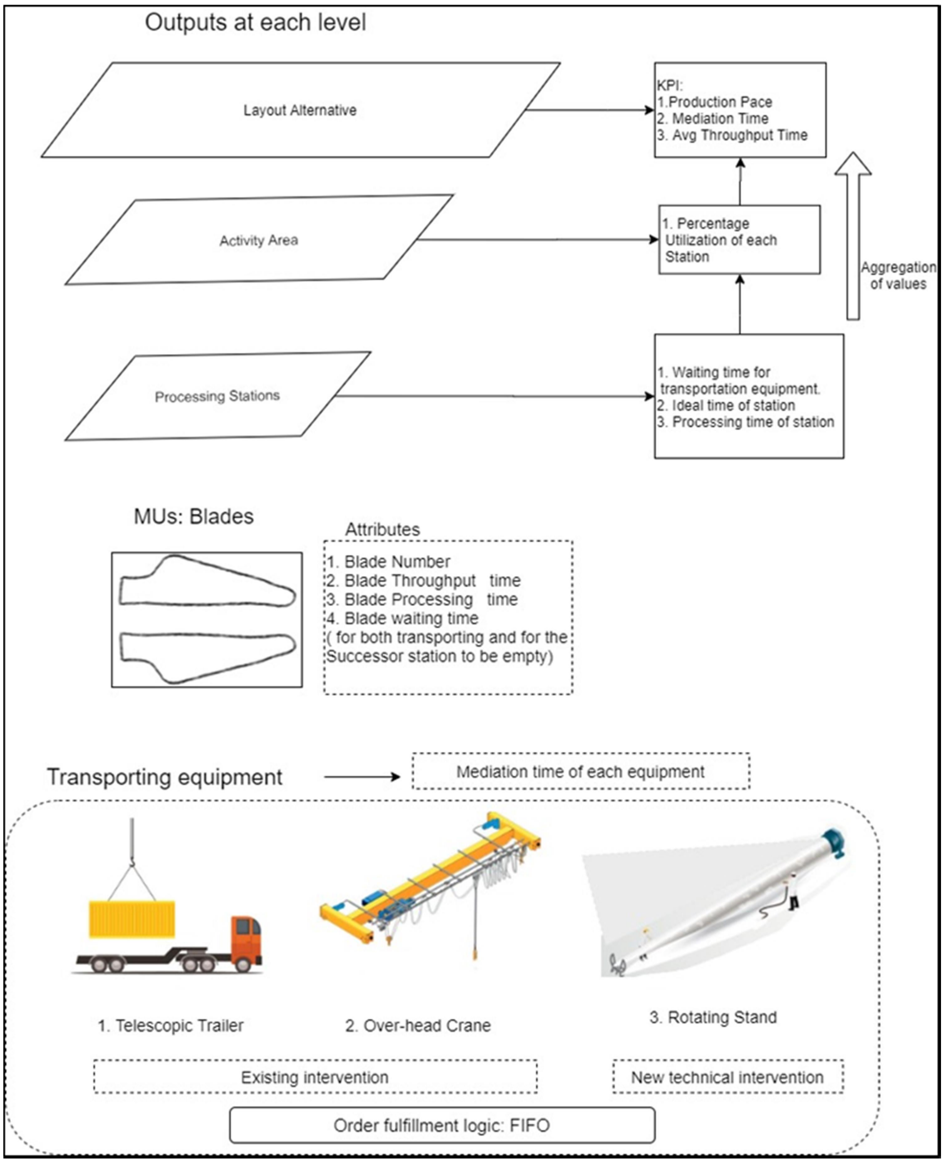

Figure 39: Conceptual model representing the output of the simulation

5.1.3. Validation of the assumptions

Before the construction of the simulation model with the Tecnomatix software, the set of assumptions stated in the above section were discussed and validated with the production team at SBT through series of meetings. We validated the set of assumptions before the coding step of the simulation modeling to improve the credibility of the model. We have considered the set of assumptions common for all the layout alternatives.

5.1.4. Construction and verification of the computer program

We have used the bottom-up approach to build the simulation model. The bottom-up approach for modeling is a method of piecing together the sub-systems to give rise to the final system. This strategy involves making the “seed” model and then combining them to obtain the final complex model. We have implemented this concept in the simulation model building of the layout alternatives. We have first made the basic processing station frame as the seed model. The process flow chart for the simulation model of the processing station is given in Figure 41.

The processing station receives the blades from the precedent activity area stations. Once the blades are done processing, they are listed in the table named ‘Blades in Queue’ of the successor activity area. The blades enter the activity area with the FIFO logic and are assigned to the station that gets available first. Once the blade is assigned to the station in the succeeding activity area, the availability of the assigned transportation equipment is checked and moved to that station. The waiting time of the blades is accounted for due to two scenarios. First, one being the unavailability of the station and the second one is due to the unavailability of the assigned transporting equipment. Both of these waiting scenarios directly increase the throughput time of the blade in the station. The processing station carries out the set of sub-tasks aggregated as per the layout alternative intervention. The sub-tasks are aggregated as a single main task in the software with new parameters of the triangular distribution. We use the parameters for the triangular distribution (min, max, and mode) for the input as the processing times for the processing station from Table 4.

The frame of the processing station in the Tecnomatix software is shown in Figure 42. The frame of the processing station is used to build the activity areas. Figure 40 shows the activity area built by eight stations of rotating stands in LA_8. The activity areas are then aligned to build the layout alternatives. All stations in a particular area use the same type of transportation equipment. The assignment of the transporting equipment to move the blades from the stations in the activity area is done based on the FIFO logic.

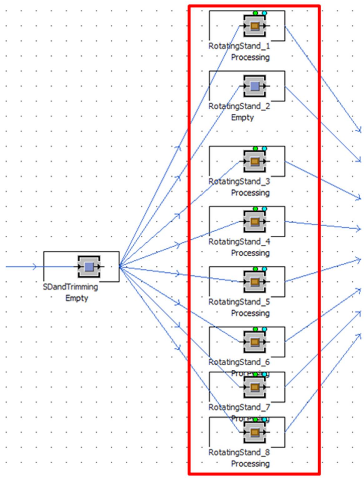

Figure 40 The activity area aggregated using processing station frame

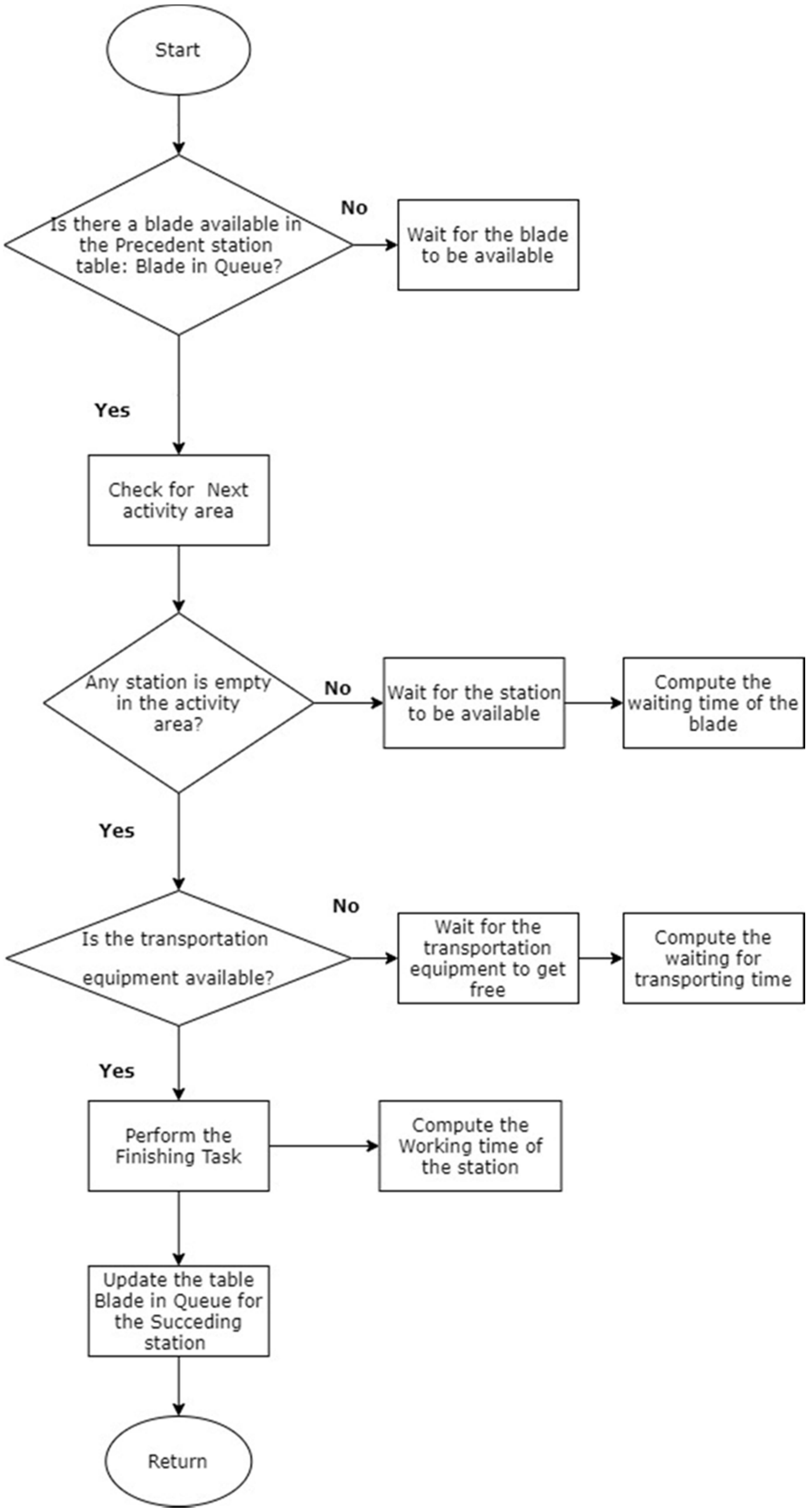

Figure 41 Flowchart of the Processing Station

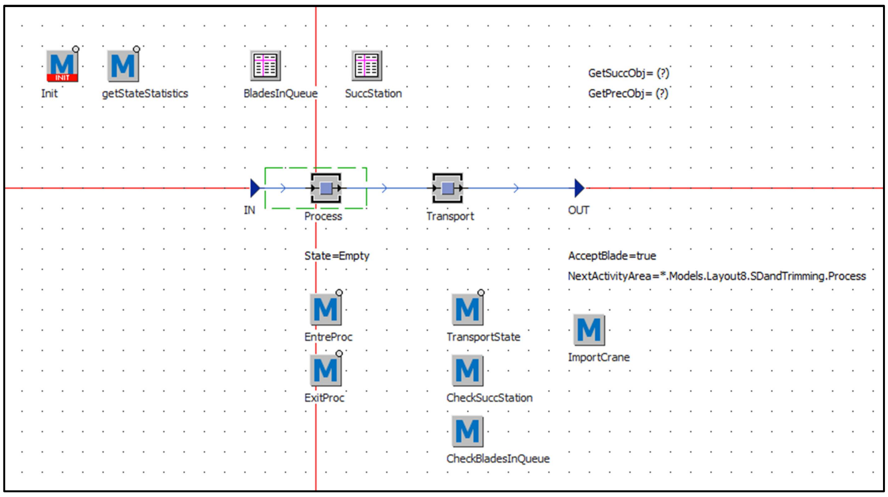

Figure 42 The frame of the basic processing station 'seed model' used in building the layout in the software

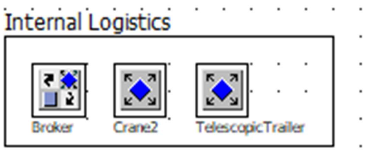

Figure 43 Internal logistics frame

The simulation runs for the predefined run length. The overall plant statistics are calculated after the simulation run stops. The control panel for the simulation model is presented inFigure 44. The control panel includes the station configuration and the pictorial representation of the layout alternative. The outputs of the experiments in the panel for easy comparison between the alternatives.

The verification of the codes in each module was done simultaneously while programming to avoid an extensive debugging process at the end. The simulation model uses design cycle time (DCT) and the results were then discussed and verified with the design team.

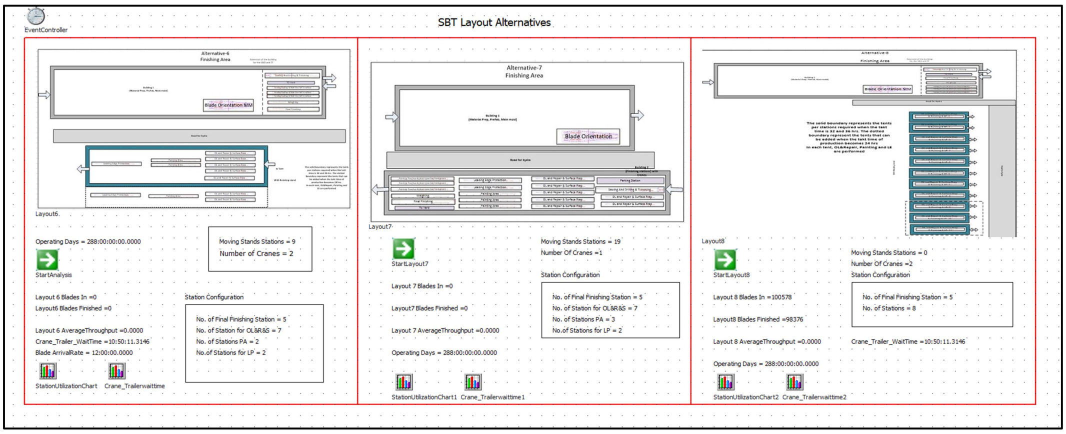

Figure 44 Control panel for the simulation experiment

5.1.5. Conducting pilot runs and validating the computer program

The model was created after various iterations of programming and verification. The model being of the greenfield project the credibility of the model highly depended on the feedback from stakeholders from the production and process design team. The output from pilot runs of the model was extracted activity-wise and compared with the analytical data with the engineers at SBT.

We built the simulation model for the new SBT blade manufacturing plant using Law's (2015) methodology. We performed the steps of problem formulation, data collection, and construction of the model followed by its validation and verification. After these steps, we carry out the experiments for the various interventions to obtain the quantitative parameters of the layout alternatives to be used in Chapter 6.

5.2 Experiments for the Quantitative Data

In this section, we discuss experiments to obtain the production KPIs for the quantitative analysis. Following the steps discussed in Section 5.1, we build the simulation model of the layout alternatives for the blade finishing tasks. The simulation models for the layout alternatives with the software are shown in Appendix B. In this section, we want to analyze which set of input parameters, and which model specification would affect the performance measures and would lead to optimal performance. According to the experimental design terminology, the input parameters are called the factors, and the output parameters are called responses. We do not compare the layout alternatives (LA) in this section; rather we decide on what system configurations for the same LA have to be simulated. Then we also decide on how to evaluate and compare their results. The factors that lead to the optimal performance of the LA are considered as the configuration of the LA that is to be used for analysis in Chapter 6.

5.2.1 Interventions for the experiments

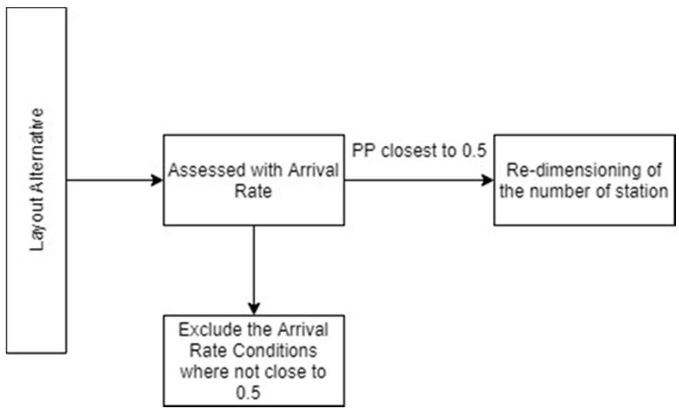

Figure 45 Interventions for the experiments

The interventions are used for designing the experiments. The interventions decide on the factors that are to be used for the simulation and experiment. The objective is to obtain the best configuration of inputs for the LA performance. The input factors that are of our interest are discrete quantitative variables. The LA performances are analyzed for two interventions suggested by the SBT team based on their experience. The factors used in the interventions are the blade inter-arrival rate and the number of stations in the activity areas. The interventions for the experiments are stated below:

a. Varying the blade arrival from the moulding station
b. Re-dimensioning the station numbers in the activity areas

The intervention of the different blade arrival rates is used as a screening process before getting into the re-dimensioning of the stations. We only consider the blade arrival rate for the layout when the performance is closest to the required target. Through the first intervention, as a screening process, we try to reduce a large number of alternatives that are to be simulated. We find the value of the factor through the simulation that shows the best response or performance among the alternatives. Figure 45 gives a clear idea of the interventions to carry out experiments.

a. <u>Blade Arrival from the moulding station (BA):</u>
The existing manufacturing facilities for SEL have either one or two moulding stations. The SBT team wanted to have an overview of the performance of the layout based on the number of blade moulding stations. This would directly influence the decision of the number of stations for blade moulding operations required to meet the demand. We define blade arrival as the inter-arrival time of the blades from the moulding stations into the finishing process stations. The processing time at the moulding station is 24 hours (design data) and 36 hrs (design data with expected delay). The BA values for the experiments are obtained from the process design team. The experiment runs are carried for the following BA values: 12 h, 18h, 24h, 36h. We experiment with the BA values to determine the number of moluding stations to attain the targeted PP of 0.5 days/ blade (12hrs/ blade). The BA values of 12 hrs and 18 hrs are used for the experiment to analyze the layout alternative performance when two moulding stations are used in the production system. 12 hrs is the design data and the 18 hours is design data with the expected delay based on the experience from the production of the previous generation blades. Table 5 is the representation of the BA values used for the experiments for the layout alternatives.

Table 5 Configuration for the experiment with the Blade arrival rate.

Layout Alternative	Input: Blade arrival (hr/blade)			
	12	18	24	36
LA_6	confi_1	confi_2	confi_3	confi_4
LA_7	confi_5	confi_6	confi_7	confi_8
AL_8	confi_9	confi_10	confi_11	confi_12

b. Re-dimensioning numbers of stations

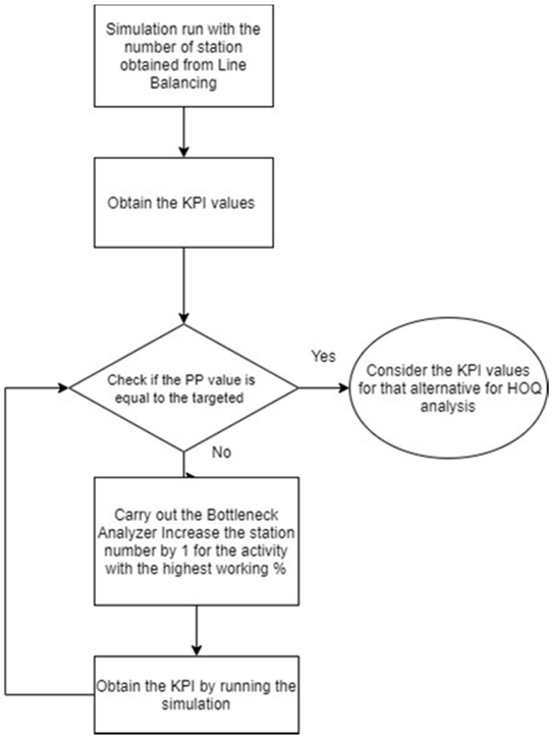

Figure 46 Method followed for Re-dimensioning of the stations in activity areas using Bottle-neck analysis

The number of stations required using line balancing. The value of the number of stations obtained is tabulated in Table 3. The determination number of stations is a layout problem as it directly influences the dimension of the built-up area required for the layout. Secondly, as discussed in Section 1.2 we aim in obtaining the layout that would help in attaining the production targets. Thus the determination of the station numbers is capacity planning of the production system. We implemented line balancing to determine the number of stations in step V in section 4.2. Line balancing is a static analysis of the production system. It does not account for the queuing and the bottleneck effect. In this intervention, we experiment for different station numbers in the activity area to obtain the configuration that leads to the best performance when stochasticity is considered. We use bottleneck analysis for deciding on which activity area should have an increment in the working station. The bottlenecks in the production systems are the blockages that stall the production. There are many ways to identify bottlenecks in a system. For this study, we use the utilization percentage of the stations in the activity area. We identify the stations that are being over-utilized which can lead to a high idle time of the downstream station. The other stations apart from the bottleneck stations are forced to operate at a lower capacity. Identifying and removing the bottlenecks in the system will improve the output performances of the production systems. The experiment methodology for this intervention is an iterative approach to increment the number of stations. The methodology is presented in a flow chart in Figure 46. The initial configuration with which the experiment starts is the result of the first intervention for the LA. The simulation runs are used to analyze the activity area with the most utilized station. The high percentage utilization of the activity area indicates that the stations in the activity area are the bottleneck in the process as they are being over-utilized. The response used in this experiment is Production Pace (PP), which can also be considered as the stopping criteria for the experiment method. The simulation run is stopped once we obtain the targeted PP value, i.e., 0.5 days/ blade (12hrs/ day). The configuration of the station numbers in the activity area is considered the best performing factor in the intervention. We then use the KPIs of these configurations of the LA for analysis in Chapter 6. The statistical analysis of the model performed is elaborated in the next section.

5.2.2. Statistical Analysis

In this section, we determine the warm-up period, run-length, and the number of replications for the simulation experiment. The initial values of the production parameters near the beginning of the non-terminating simulation model are subjected to bias due to the initial conditions. To determine the warm-up period, a graphical procedure by Welch (1981) is employed. The goal of using this technique is to obtain a warm-up period. Here, the model is run for n independent replications for a run length m. The run-length needs to be sufficiently larger than the expected warmup length. The resulting data for the same blade unit over different replications from the simulation run is averaged out. The averaged value of blade units is then plotted in a graph with moving averages with different window sizes. The aim of carrying out moving averages for the simulation runs is to obtain a smooth curve so that the warmup period can be visualized in the graph. The estimated warmup period for the layout alternatives is listed in Table 6.

Table 6 Warmup period estimated for the layout configuration using Welch's approach

Run-length	No. of replication	w	Configuration	Warmup period (days)
288 days	5	w= 3 w=5 w= 10 w= 20 w= 25	LA_7	24
			LA_8	12
			LA_6	48

For the warmup period estimation, we decided to run the model for 288 days as that is equivalent to one production year at SBT. The number of replications is considered to be 5 for this analysis. Welch's graph was plotted for each of the models for the layout alternatives to identify the point k where the moving average cover smoothens out. Figure 47 is Welch's graph for layout alternative 7. We choose blade number k =33 as the correspondence to the steady-state for the KPI. We simulated for multiple replications to obtain the time it takes to complete the production of k=33 blades. Through this, we would estimate the time required by the production system to attain stability. So that we would start calculating our KPIs after the model reaches the warm-up period to the simulation end time. Eventually, we choose the warm-up period as 24 days for LA_7. The graph for the warmup period determination of the layout alternatives 6 and 8 has been shown in Appendix C. The arrows in the graphs indicate the warm-up period selected for the experiment.

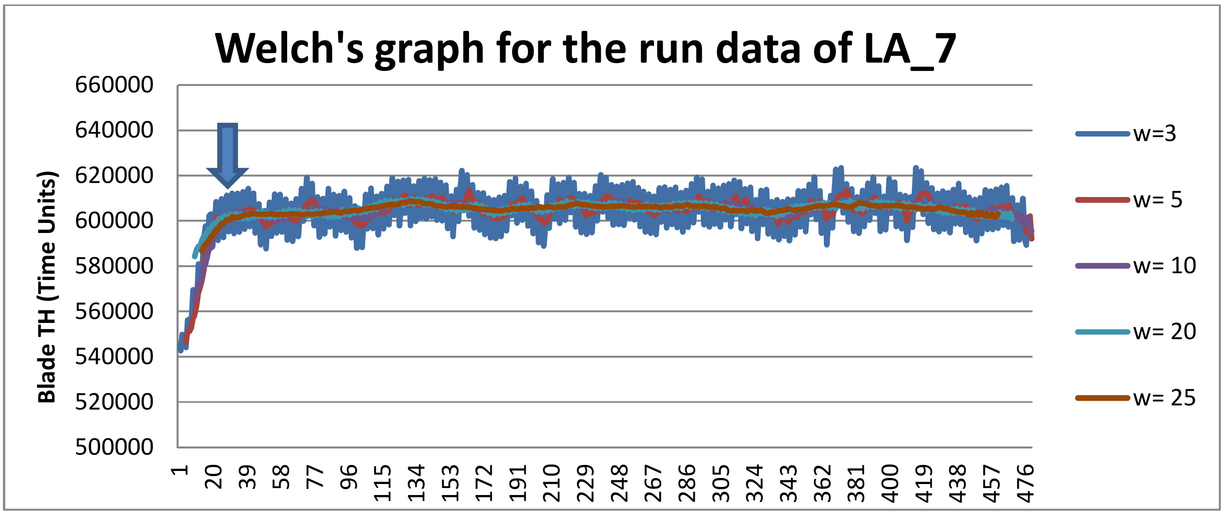

Figure 47 Welch's graph for LA_7

We consider the run length as the number of days the factory operates annually. Thus, we consider the run length as 288 days for the experiment runs. For the determination of the number of replications for the simulation run, we choose to give statistical confidence of 95% with a relative error of less than 0.05. As suggested by Law (2015) the replication/ deletion technique for means is used as it is the easiest to implement and is used to compare different system configurations. The number of replications for each of the layout alternatives is given in Table 7. The results from this statistical analysis for determining the warm-up period, run-length, and the number of replications are used in the simulation experiments.

Table 7 Number of replications for the simulation model of alternatives

	Configuration	Number of Replications
Confidence Interval 95% and a relative error of 0.05	LA_6	5
	LA_7	3
	LA_8	3

5.2.3. Experiment Runs and Results

In this section, we assess the different blade arrival rates for the layout alternatives as explained in Section 5.2.1. and then we compare interventions. The experiment results help in analyzing the plant layout performance against the blade arrival rate perspective.

a) <u>The experiment runs and results with BA values: 12 h, 18h, 24h, 36h</u>

The simulation models of the layout alternatives (LA) are run with the dimensioning of the activity area as obtained from the line balancing of blade finishing processes as stated in Table 2. As already explained in Section 5.2.1, the number of stations in the activity areas for the layout is a static analysis using line balancing. Configurations 1,2,3, and 4 are for the LA_6 with BA 12, 18, 24, and 36 respectively. The results from the first simulation are tabulated in Table 8. From the results, we see that the layouts do not perform to attain the targeted PP of 0.5 days/blade for any of the arrival rates. Even it is observed that the average throughput times for the simulation runs are high. Thus we can infer from the results that the number of the stations in the activity area using the static analysis would not be sufficient to attain the targets. We compare the results of these configurations from the simulation run of the LA_6 model. We observe the Confi_2 performs better and hence we select the arrival rate of 18 h/blade for further experimentation of the LA_6. Similarly, we select the configuration for LA_7 and LA_8. The selected configurations are highlighted with bold text in Figure 48**Error! Reference source not found.** and Table 8. From the results, we can interpret that layouts will require 2 molding stations for better performance of the layout alternatives.

Table 8 Experiment run results with the number of stations in activity areas from line balancing for blade arrival intervention

Layout	Experiment Number	Configuration	Arrival Rate (h/blade)	Avg Throughput (h)	PP (day/ blade)	MT (time unit)
6	1	Confi_1	12	498.4	0.8	0.0
	<u>2</u>	**Confi_2**	**<u>18</u>**	**<u>408.9</u>**	**<u>0.8</u>**	**<u>0.0</u>**
	3	Confi_3	24	174.2	1.0	0.0
	4	Confi_4	36	186.1	1.5	0.0
7	1	Confi_5	12	256.0	1.9	6.9
	<u>2</u>	**Confi_6**	**<u>18</u>**	**<u>170.4</u>**	**<u>0.8</u>**	**<u>1.6</u>**
	3	Confi_7	24	176.6	1.0	1.1
	4	Confi_8	36	188.8	1.5	0.6
8	**<u>1</u>**	**Confi_9**	**<u>12</u>**	**<u>179.7</u>**	**<u>0.6</u>**	**<u>90.3</u>**
	2	Confi_10	18	167.2	0.8	50.7
	3	Confi_11	24	173.5	1.0	29.4
	4	Confi_12	36	185.6	1.5	1.6

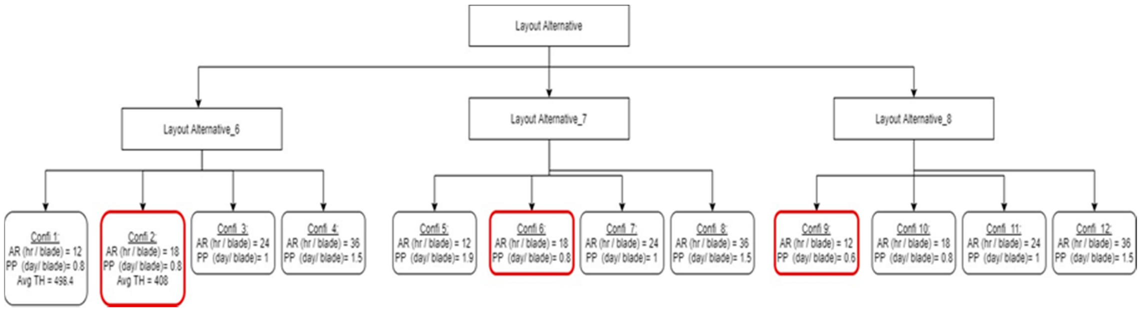

Figure 48 Flow chart representation of different configuration with the highlighted configuration that is selected for the layouts

b) <u>The experiment runs and results for re-dimensioning of stations using Bottle-neck analysis</u>

In the second intervention for the experiments, we try to identify the over-utilized stations and improve the performance by removing the bottlenecks. The high working percentage from the bottleneck analysis suggests that the activity area is blocking the blades from moving to the successor operation areas. The stations are not sufficient to cater to the blades arriving which is leading to the blades waiting for the stations to get available. To improve the flow of the blades, the stations in the activity area with the highest utilization percentage are increased by 1. We observed that by increasing the operating stations at those activity areas the KPI values also improved.

The second intervention for the experiment is implemented for all layout alternatives. The iteration results of the simulation run in terms of station working percentage for layout alternative 6 are shown in Table 9. The terminology used in the table for the resource column is explained for better understanding using Figure 49

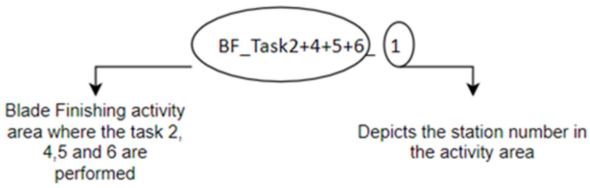

Figure 49 Representation of terminology of the resources in the simulation analysis

Table 9 Layout alternative 6 bottleneck analysis iteration of resource working percentage.

Sno	Resource	Line Balancing	Bottleneck analysis iteration1	Bottleneck analysis iteration2	Bottleneck analysis iteration 3	Bottleneck analysis iteration4
1	BF_Task8	92.5	62.1	90.2	90.6	50.0
2	BF_Task2+4+5+6_1	76.1	97.6	81.1	81.6	92.1
3	BF_Task2+4+5+6_2	75.7	97.3	80.9	81.1	90.8
4	BF_Task2+4+5+6_5	75.6	97.1	79.7	80.0	89.5
5	BF_Task2+4+5+6_3	75.4	97.0	79.1	79.8	87.2
6	BF_Task2+4+5+6_4	75.1	96.7	78.0	78.4	82.5
7	BF_Task7_1	64.7	85.1	94.2	63.2	68.1
8	BF_Task7_2	64.3	84.9	94.0	62.9	67.9
9	BF_Task1+3	60.6	78.0	87.8	88.2	93.5
10	BF_Task9+10.P1	23.9	32.1	35.1	35.2	38.6

For a clear understanding of how we did the bottleneck analysis, the procedure for layout alternative 6 is described in detail. Table 9 shows the working percentage of the stations obtained after every iteration. The layout performance with the station number obtained using the line balancing shows that BF_Task8 is used exhaustively. Thus, the number of stations for that activity area is increased by 1. Simultaneously it can be visualized that there is an improvement in the PP which can be visualized by the graph shown in Figure 51. Then we proceed with the simulation run with increment in the station number at activity area BF_Task8. For each iteration, the activity area that is overutilized is highlighted in Table 9. The simulation run is terminated once the PP value reaches 0.5. The configuration of the stations with increased numbers is considered the final configuration for this study. Figure 50 shows the percentage utilization of each activity area after every iteration of the bottleneck analysis. Subsequently, the same steps are followed for the LA_7 and LA_8. The percentage utilization of the activity areas and KPI values after every iteration for LA_7 and LA_8 is shown in Figure 52 and Figure 53 respectively.

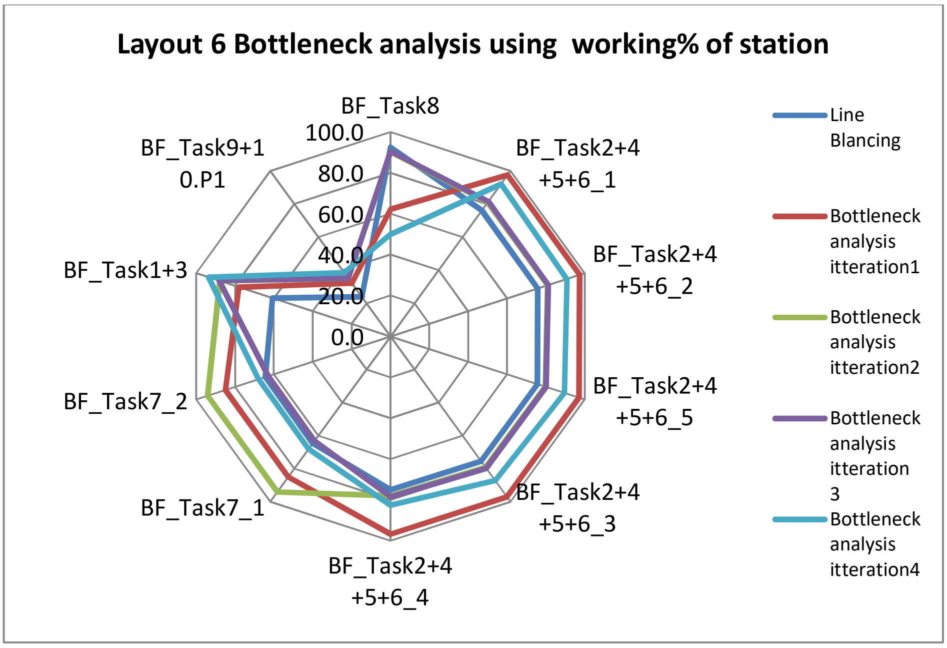

Figure 50 Percentage utilization of station in LA_6 for each iteration

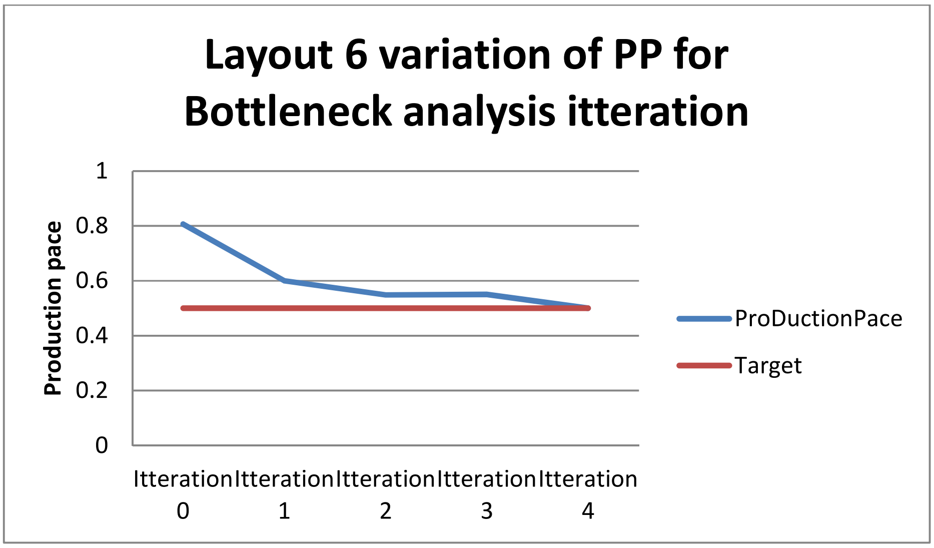

Figure 51 Variation in PP after every iteration for LA_6

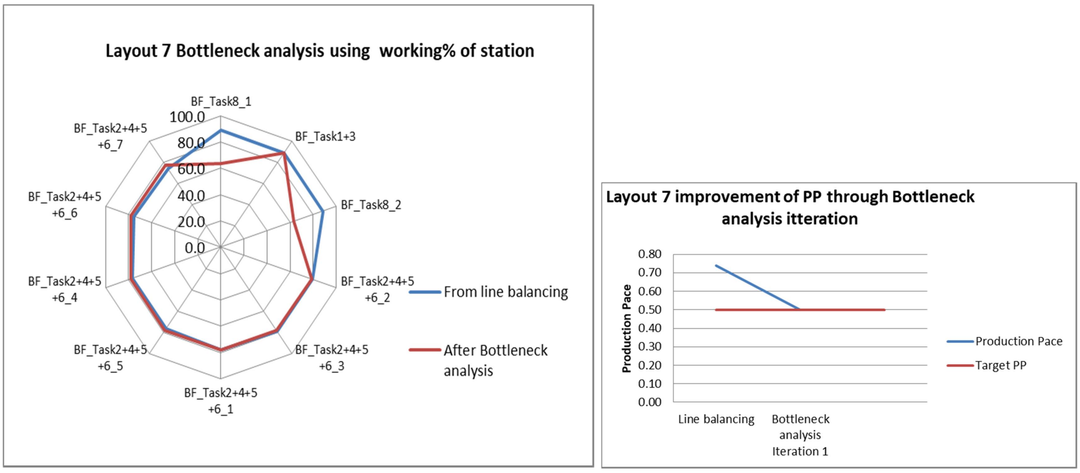

Figure 52 Working percentage of the station in the activity area for each bottleneck iteration and the variation in PP for LA_7

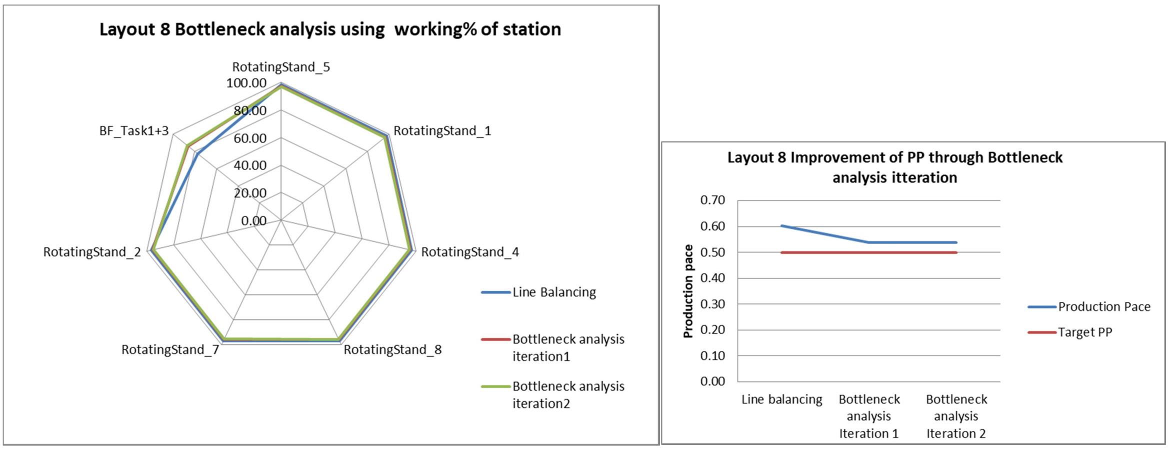

Figure 53 Working percentage of the station in the activity area for each bottleneck iteration and the variation in PP for LA_8

The bottleneck analysis leads to improved KPI values for the layout alternatives compared to the one before the analysis. The layout performance for the quantitative parameters is obtained and is shown in Table 10. The number of stations for the layout alternatives has also increased suggesting that the number of stations obtained from the line balancing of the production system would have been insufficient to have the desired production targets. The number of stations of the activity area for all the alternatives considered for the final decision-making process is shown in Table 11. The underlined values in the table indicate the activity area that has visualized increment in the station numbers.

Table 10 KPI values for layout alternative after station dimensioning from bottleneck analysis

Layout	Avg Throughput (h)	Production Pace (Day/ Blade)	Mediation Time of Trailer and Crane (Time Units)
6	161.78	0.501	0.000
7	164.22	0.499	11.247
8	174.88	0.539	120.214

Table 11 Number of the station for each activity area of layout alternative from quantitative analysis

<table>
<tr><td colspan="6">Layout Alternative: Blade finishing area number of stations after bottleneck analysis</td></tr>
<tr><td>LA_6</td><td>No. of stations</td><td>LA_7</td><td>No. of stations</td><td>LA_8</td><td>No. of stations</td></tr>
<tr><td>BF_Task1 + BF_Task3</td><td>1</td><td>Parking Station</td><td>1</td><td>BF_Task1 + BF_Task3</td><td>1</td></tr>
<tr><td rowspan="2">BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6</td><td rowspan="2">7</td><td>BF_Task1 + BF_Task3</td><td>1</td><td rowspan="4">BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6 + BF_Task7 + BF_Task8</td><td rowspan="4">11</td></tr>
<tr><td>BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6</td><td>7</td></tr>
<tr><td>BF_Task7</td><td>3</td><td>BF_Task7</td><td>3</td></tr>
<tr><td>BF_Task8</td><td>3</td><td>BF_Task8</td><td>3</td></tr>
<tr><td>BF_Task9</td><td>3</td><td>BF_Task9</td><td>3</td><td>BF_Task9</td><td>3</td></tr>
<tr><td>BF_Task10</td><td>2</td><td>BF_Task10</td><td>2</td><td>BF_Task10</td><td>2</td></tr>
<tr><td>BF_Task11</td><td>1</td><td>BF_Task11</td><td>1</td><td>BF_Task11</td><td>1</td></tr>
<tr><td>Total no. of Stations</td><td>20</td><td>Total no. of Stations</td><td>21</td><td>Total no. of Stations</td><td>18</td></tr>
<tr><td>Earlier Station Number</td><td>15</td><td>Earlier Station Number</td><td>20</td><td>Earlier Station Number</td><td>15</td></tr>
</table>

5.3 Quantitative data preparation for the multi-criteria decision making

In this section, we focus on data preparation of the quantitative result for making it usable in this next step of our methodology. The results obtained from the quantitative analysis using simulation software are tabulated in Table 10. The values obtained from the experiments need to be normalized before using the results for multi-criteria decision-making. To interpret and give relative weights to each criterion, it is necessary to normalize the results. The normalization is made by dividing each value by the total column value. The normalized values of the KPIs are tabulated in Table 12.

$$Normalised\ Avg\ Throughput = 1 - \frac{Avg\ Throughput}{\sum Avg\ Throughput\ for\ all\ layouts}$$

$$Normalised\ Production\ Pace = 1 - \frac{Production\ Pace}{\sum Production\ pace\ for\ all\ layouts}$$

$$Normalised \text{ Mediation Time} = 1 - \frac{Mediation\ Time}{\sum Mediation\ Time\ for\ all\ layouts}$$

Table 12: Normalized quantitative parameters for layout alternatives

Layout	NormAvg Throughput (H)	NormProduction Pace (Day/ Blade)	NormMediation Time Trailer and Crane (Time Units)
6	0.6770	0.6746	1.0000
7	0.6721	0.6757	0.9144
8	0.6509	0.6496	0.0856

5.4 Conclusion from quantitative analysis

We followed the methodology suggested from the literature review for the quantitive analysis. We used the methodology by Law (2015)to build the simulation model of the layout alternatives. The simulation model helped in involving the stochasticity to the production system of the layout alternative. From the simulation experiments for the blade arrival rate, all the three layout alternatives performed better with the BA values 12 and 18hrs. We can conclude that there is a requirement for 2 moulding stations for the production of B7XX blades to attain the production targets. The configuration of the station numbers for the activity areas obtained from the line balancing in the SLP step in Section 4.2 is observed to be insufficient to obtain the targeted KPIs. We observed the overutilization of stations in the activity area which lead to bottlenecks in the system. Hence we incorporated bottleneck analysis in the simulation experiments to obtain the optimized station for the production pace of 12 hrs/ blade. Table 13 shows the KPIs before and after the bottleneck analysis for the LA. We observed that increment of 5 stations in the LA_6 lead to an improvement in the KPI by around 38%. The LA_6 does not have any waiting time to move the blades between the stations. LA_6 uses rotating stands as the internal transportation equipment. The production design team at SBT was very keen on analyzing this new design intervention for the greenfield project. The quantitative analysis provides proof that using a rotating stand can lead to layout planning with a better workflow. The increment in 1 station leads to around 37% improvement in the LA_7's performance. Increment in 3 stations has led to an improvement in LA_8 performance by 10%. But when we analyze the total number of stations LA_7 requires the 21 stations to achieve the PP of 0.5 days/ blade which is the highest number when compared to the other layouts. The more number of stations will directly influence the more floor area required to build the layout. We can conclude from the quantitative analysis of the alternative that LA_6 is a better performing alternative as it has the desired production KPIs with the least number of stations (i.e. 20 stations).

Table 13 Improvement in the KPI PP after the bottleneck analysis

Layout	Initial Production Pace (Day/ Blade)	Production Pace (Day/ Blade) after Bottleneck analysis	Improvement %	Increment in the overall station numbers
6	0.81	0.501	37.91	5
7	0.79	0.499	36.82	1
8	0.60	0.539	10.11	3

Table 14 Final station numbers after bottleneck analysis

Layout Alternative: Blade finishing area number of stations before and after bottleneck analysis					
LA_6	No. of stations	LA_7	No. of stations	LA_8	No. of stations
Earlier Station Number	15	Earlier Station Number	20	Earlier Station Number	15
Total no. of Stations after Bottleneck	20	Total no. of Stations after Bottleneck	21	Total no. of Stations after Bottleneck	18

Chapter 6: Qualitative Analysis and Multi-criteria Decision Making

This chapter describes the steps that are taken for the implementation of the methodology chosen from the literature for the qualitative analysis and multi-criteria decision making. Section 6.1 describes the steps and the results of the qualitative analysis. In Section 6.2, the required steps for combining the results from the quantitative and qualitative analysis are described.

6.1 Qualitative Analysis

Qualitative analysis involves parameters that are subjected to conflicting opinions. Thus from the literature review, we choose to implement Analytical Hierarchical Process (AHP) for our case study. The AHP uses weight estimation techniques in the selection and decision-making process (Vaidya, 2006). The qualitative analysis reflects the various intangible factors of the layout apart from the production and monetary factors. In this section, we focus on answering the research question *"How can we employ AHP in our case to obtain the qualitative performance of the alternatives?".* We followed the below steps for the qualitative analysis of the alternatives using AHP:

1. Parameter definition
2. Determination of the absolute weights of the qualitative parameters
3. Determination of aggregated and normalized integrated judgment of qualitative parameters
4. Layouts' performance analysis based on qualitative parameters

6.1.1 Qualitative parameter definition

Qualitative parameters can be defined as intangible and requisite layout characteristics. We identified five qualitative parameters that the SBT team will be interested in evaluating. The parameters are stated and explained below:

1. Ease of Implementation: How easily can the layout be adopted and implemented in Suzlon. Also the degree of ease in terms of approval for the sanctions of plan and infrastructure requirement.

2. *Flexibility* (To permanent and Temporary Changes): Ability of the layout to adapt to new products, design changes, changes in capacity, and new process. The ease of accommodating in the layouts as planned without changes (normal or emergency) in, and variety (or number) of, items like the following: Operation sequence, Material dispatching procedure, Rework procedures, Standby equipment, Type or classification of employees.

3. *Ease of Operation*: The effectiveness of sequenced working operations or steps-without unnecessary back-tracking, cross flow, transfers, long hauls-of materials, paperwork, or people.

4. *Safety of Operators*: The effect of the layout and its features on accidents or damage to employees and Machine facilities.

5. *Maintainability*: The extent to which the layout will benefit or hinder maintenance work, including building and machine repair as well as day-to-day.

6.1.2 Determination of the absolute weights of the qualitative performance

In this section, we determine the absolute weights of the qualitative parameters that are defined in the above section using the AHP methodology by Saaty (1980). The parameters defined are not of equal importance in our case study. We construct a matrix expressing the relative importance of the set of attributes. For example, what is the relative importance of 'Ease of Implementation' with other attributes, 'Flexibility', 'Ease of Operation', 'Safety', and 'Maintainability'? We obtained the value for the comparison matrix through the discussion with the SBT managers across various teams. For this evaluation, a standard linguistics scale was used as shown in Figure 54. The use of the linguistic scale can be explained with an example, the SBT team was asked to choose whether 'Flexibility' is of great importance, rather moderately more important, and as equally important, and so on down to moderately less important, than 'Ease of Implementation' for SBT layout performance analysis? The team anonymously agreed that 'Flexibility' is moderately more important than 'Ease of Implementation' thus a value of 5 is assigned in the comparison matrix. These pair-wise comparisons are carried out for all factors to be considered and shown in Table 15. In the next step, we obtain the absolute weights of the parameter by adding the normalized relative importance of that parameter. From our study, we observed that 'Safety' is considered as one of the prime important judgment criteria for the layout analysis as it has the highest absolute weight. 'Ease of Operation' constitutes nearly 22% of the importance for qualitative analysis. Followed by 'Flexibility' and 'Maintainability' contributing to 9.94% and 7.09%. The parameter 'Ease of implementation' is only considered as 3% important when evaluating the qualitative layout performance.

Possible Values:
1 = equally important;
3 = sightly more important;
5 = moderately more important;
7 = greatly more important;
9 = esxtremely more important;
0,33 = slighlty less important;
0,20 = moderately less important;
0,14 = greatly less important;
0,11 = extremely less important.

Figure 54 Linguistic scale equivalence to arithmetic values (adapted from Saaty (1980))

Table 15: Determination of the absolute weights of the qualitative parameters

Contingent comparison matrix																
	Operational Performances															
Possible Values: 1 = equally important; 3 = sightly more important; 5 = moderately more important; 7 = greatly more important; 9 = esxtremely more important; 0,33 = slighltly less important; 0,20 = moderately less important; 0,14 = greatly less important; 0,11 = extremely less important. *Operational Performances*	Ease of Implementation	Flexibility	Ease Of Operation	Safety	Maintainability	*Normalized Column*					Absolute Weight	***Weight %***	***Weights% X Operational performance***	λ	λmax
Ease of Implementation	1.00	0.20	0.14	0.11	0.20	*0.04*	*0.01*	*0.01*	*0.08*	*0.01*	0.15	**2.98%**	**0.16**	5.31279	**5.90**
Flexibility	5.00	1.00	0.14	0.11	3.00	*0.19*	*0.06*	*0.01*	*0.08*	*0.16*	0.50	**9.94%**	**0.51**	5.09708	
Ease Of Operation	7.00	7.00	1.00	0.11	5.00	*0.26*	*0.40*	*0.10*	*0.08*	*0.27*	1.11	**22.10%**	**1.56**	7.0404	
Safety	9.00	9.00	9.00	1.00	9.00	*0.33*	*0.51*	*0.86*	*0.69*	*0.49*	2.89	**57.88%**	**4.68**	8.08427	
Maintainability	5.00	0.33	0.20	0.11	1.00	*0.19*	*0.02*	*0.02*	*0.08*	*0.05*	0.35	**7.09%**	**0.28**	3.98469	
Total	27.0	17.5	10.5	1.4	18.2	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	5.00	**100.00%**	**7.18**		

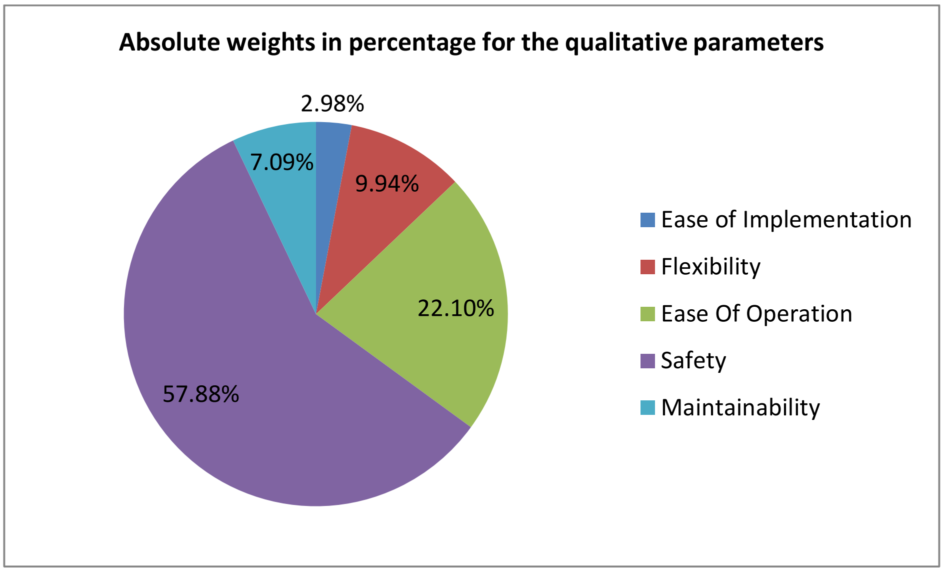

Figure 55 Pie Chart representation of qualitative parameters absolute weights

6.1.3 Determination of aggregated and normalized integrated judgment of qualitative parameters

We surveyed to determine the layout alternatives' performance values. The participants of the survey scored the layouts based on their expectations and experience towards qualitative parameters. Figure 56 is the representation of the survey form that was used for this study. All the individuals' scores are considered of equal importance while integrating the results. The individual scores are aggregated to obtain the value that is to be used for the AHP.

Qualitative survey

Note: The alternate layout are configured for areas: Material Prep, PreFab and Main Mold and for Finishing stations. Rate the layouts based on the below parameterts on the scale of 1 to 5. Where 1 being the least favorable and 5 being most favorable. The criteria for the assessment of the layouts have been defined below. Each criteria doesnt have equal importantance in the evaluation.

		Material prep, Prefab, Main Mold					Finishing area		
Sno.	Alternatives / Criteria	1	2	3	4	5	6	7	8
1	Ease of Implementation	4	2	3	3	4	3	4	4
2	Flexibility	3	2	3	3	3	4	3	4
3	Ease Of Operation	4	2	3	3	3	4	4	3
4	Safety	4	3	4	4	4	4	4	4
5	Maintainability	3	3	4	4	4	4	4	3

Scale	Rating in terms of fulfillment of the crieria
1	Very poor
2	Poor
3	Fair
4	Good
5	Excellent

Defination of critira:

1. Ease of Implementation : How easily can the layout be adopted and implemented in Suzlon. Also degree of ease in terms of approval for the plan and sanctions, infrastructure.

2. Flexibility : (To permanent and Temporary Changes) Ability of the layout to adapt to new products, design changes, changes in capacity, and new process.The ease of accommodating in the layouts as planned (without changes (normal or emergency) in, and variety (or number) of, items like the following: Operation sequence, Material dispatching procedure, Rework procedures, Standby equipment, Type or classification of employees.

3. Ease of Opertaion: The effectiveness of sequenced working operations or steps-without unnecessary back-tracking, cross flow, transfers, long hauls-of materials, paper work, or people.

4. Safety of Operators and Machines : The effect of the layout and its features on accidents or damage to employees and facilities

8. Maintainability: The extent to which the layout will benefit or hinder maintenance work, including building and machin repair as well as day-to-day

Figure 56: Qualitative Survey Form for SBT layout from Employee_01

According to Forman (1997), individual judgment is aggregated using the geometric mean. Hence our AIJ (Aggregated Individual Judgment) for the layout performance is the geometric mean of all the participant's survey. Then, the normalization of the AIJ is done to change the values of numeric columns in the dataset to a common scale for easy comparison. The results of AIJ and Normalized AIJ are tabulated in Table 16. From this step, we obtained the parameters in which the LA fared well and in which it was lacking. For example, from the results, we can infer that LA_7 is less maintainable but is easy to implement and operate and is also flexible.

Table 16: Aggregated and normalized integrated judgment of qualitative parameters

		Aggregation of Integrated Judgement								Normalised AIJ							
		Material prep, Prefab, Main Mold					Finishing area			Material prep, Prefab, Main Mold					Finishing area		
Sno.	Alternatives / Criteria	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1	Ease of Implementation	4.18	2.99	3.95	4.13	3.73	3.57	3.95	4.32	0.23	0.20	0.21	0.22	0.22	0.20	0.21	0.23
2	Flexibility	3.57	2.86	3.37	3.52	3.52	3.78	3.95	4.37	0.19	0.19	0.18	0.19	0.21	0.21	0.21	0.23
3	Ease Of Operation	3.78	2.99	3.73	3.52	2.83	3.78	4.00	3.37	0.20	0.20	0.20	0.19	0.17	0.21	0.21	0.18
4	Safety	3.48	2.55	4.00	3.57	3.37	3.78	3.78	3.29	0.19	0.17	0.21	0.19	0.20	0.21	0.20	0.18
5	Maintainability	3.52	3.37	3.78	3.78	3.57	3.37	3.29	3.29	0.19	0.23	0.20	0.20	0.21	0.18	0.17	0.18
	Sum	18.53	14.76	18.82	18.51	17.00	18.26	18.96	18.63	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

6.1.4 Layouts' performance based on qualitative parameters

We now integrate the weights of the parameters and the layout performance on the hierarchical model. **Error! Reference source not found.**, is the visual representation of the AHP for the SBT case to get a more clear picture of how much each parameter contributes to final decision making. By aggregating the weights of the parameters with the values of layout performance, AHP helps in identifying the alternative that has more probability of attaining the targeted goal. The value in the AHP table is obtained by multiplying the criteria weights with the alternative performance for that criteria. It is tabulated in Table 17. Each of the alternatives is observed to have certain characteristics likely, LA_7 is considered to be the safest and maintainable among the three alternatives. Whereas LA_8 has the highest rank in the ease of implementation and flexibility. But when considering all the criteria, LA_7 is more likely to attain better quality targets as it performs consistently well in all the parameters.

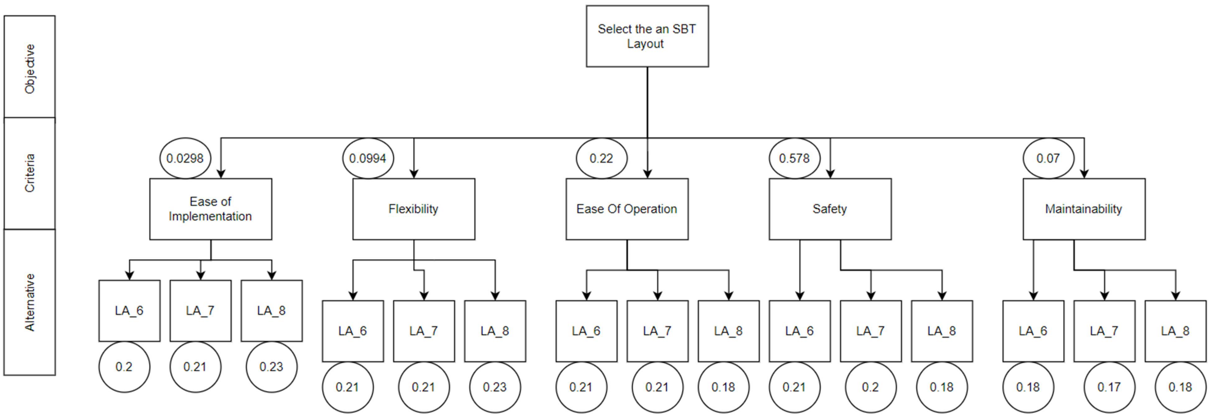

Figure 57 The AHP hierarchy for SBT layout for qualitative analysis of the finishing area

Table 17 Qualitative performance of the layout alternatives

Aggregation of Integrated Judgement										
			Material prep, Prefab, Main Mold					Finishing area		
Sno.	Alternatives / Criteria	Weight %	1	2	3	4	5	6	7	8
1	Ease of Implementation	0.0298	0.0067	0.0893	0.1178	0.1232	0.1112	0.1064	0.1178	0.1288
2	Flexibility	0.0994	0.0191	0.0193	0.0178	0.0189	0.0206	0.0206	0.0207	0.0233
3	Ease Of Operation	0.2210	0.0451	0.0448	0.0438	0.0420	0.0367	0.0457	0.0466	0.0399
4	Safety	0.5788	0.1088	0.1000	0.1230	0.1115	0.1146	0.1197	0.1153	0.1021
5	Maintainability	0.0709	0.0135	0.0162	0.0142	0.0145	0.0149	0.0131	0.0123	0.0125
		Score	0.1932	0.2695	0.3166	0.3101	0.2980	0.3054	0.3127	0.3067

6.2. Multi-criteria decision making

The layout planning problem is identified as the Multiple Criteria Decision Making (MCDM) problem from the literature study. In this section, we answer the research question *'How are the results combined of qualitative and quantitative analysis to select the best performing layout?'* The methodology selected from the literature study is Quality Function Deployment (QFD) using a tool called House of Quality (HoQ). This section provides the steps and results of implementing this method.

According to Shahin (2008), QFD is a systematic approach where customer needs are defined and are translated as product features. HOQ is a tool used for the QFD to translate customer requirements in terms of engineering design values by creating a relationship matrix. The HoQ for the SBT case has been implemented based on these five elements:

1. Customer needs (Whats): The 'Whats' for the HoQ matrix are the qualitative parameters and the quantitative KPIs. The parameters are the SBT requirements that are to be realized in the final layout for the manufacturing of SB7XX blades.
2. Design requirements (Hows): The 'Hows' are the layout alternatives that are the translation of the design interventions namely LA_6, LA_7, and LA_8.
3. The relative importance of the customer needs: The criteria (quantitative and qualitative) do not have equal importance in decision making. We conducted the stakeholder survey to determine the relative importance of the 'Whats' in a similar method we obtained the weights of the parameters in the qualitative analysis. The resultant weights for the parameters are visualized as a pie chart in **Error! Reference source not found.**. The criteria 'Safety' and 'Avg Throughput' and 'Production pace' were ranked the most important. Followed by 'Ease of Implementation' and 'Mediation time'.

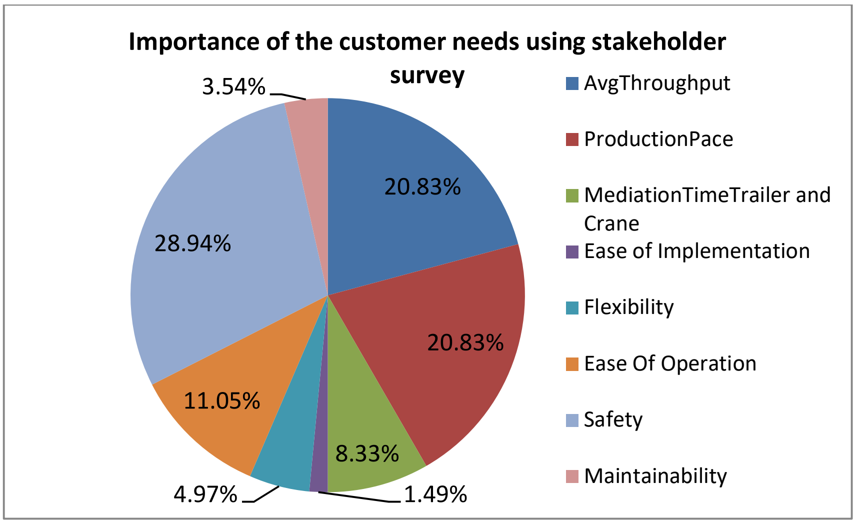

Figure 58 Weights of 'Whats' obtained from the survey

4. Relationships between 'Whats' and 'Hows': The simulation results obtained from the quantitative analysis and the normalized integrated judgment of alternatives from the

qualitative analysis form the elements of the matrix as shown in **Error! Reference source not found.**. Again the matrix values were normalized in the scoring table dividing each element by the sums of the rows. Normalization of data helps in an easy comparison between the alternatives. Table 18 is the required output of this step with the normalized relationship value between 'Whats' and 'Hows'.

Table 19 Layout performance values from qualitative and quantitative analysis

	Layout	6	7	8	Sum
From Normalized quantitative parameters	AvgThroughput	0.677	0.672	0.651	2.000
	ProDuctionPace	0.675	0.676	0.650	2.000
	MediationTimeTrailer and Crane	1.000	0.914	0.086	2.000
From Aggregated and normalized integrated judgment of qualitative parameters	Ease of Implementation	0.195	0.208	0.232	0.635
	Flexibility	0.207	0.208	0.235	0.650
	Ease Of Operation	0.207	0.211	0.181	0.598
	Safety	0.207	0.199	0.176	0.582
	Maintainability	0.184	0.173	0.176	0.534

Table 20 Normalized Relationship value between 'Whats' and 'Hows'

Layout	**6**	**7**	**8**
AvgThroughput	0.339	0.336	0.325
ProDuctionPace	0.337	0.338	0.325
MediationTimeTrailer and Crane	0.500	0.457	0.043
Ease of Implementation	0.307	0.328	0.365
Flexibility	0.318	0.320	0.361
Ease Of Operation	0.346	0.353	0.302
Safety	0.355	0.342	0.303
Maintainability	0.345	0.325	0.330

5. <u>Overall priorities of the design requirements:</u> In this step, the relationship between customer needs and the design requirements are combined with the weights of the 'Whats' is established. To obtain the matrix value, we calculated the product of each weight of 'Whats' and the value of the relationship between 'Whats' and 'Hows'. The final HoQ for the SBT case is shown in Table 21. The overall priority of the layout alternative is the sum of the column values. The alternative constituting the highest overall priority value indicates that it performs better than other options designed when the relative importance of the evaluation parameters is also considered.

Table 21 HoQ matrix for the evaluation of SBT Layout Alternatives

Hows (Alternative) / Whats (Criteria)	LA_6	LA_7	LA_8	Weights of Whats
Avg Throughput	0.3385	0.3361	0.3254	0.2083
Production Pace	0.3373	0.3379	0.3248	0.2083
Mediation Time	0.5000	0.4572	0.0428	0.0833
Ease of Implementation	0.3074	0.3278	0.3648	0.0149
Flexibility	0.1034	0.3205	0.3612	0.0497
Ease Of Operation	0.3456	0.3525	0.3019	0.1105
Safety	0.3551	0.3420	0.3030	0.2894
Maintainability	0.3451	0.3246	0.3303	0.0354
Overall Priorities of How	0.3454	0.3488	0.2952	

From the results of the HoQ analysis, we could gather the performance of the layouts based on the criteria that were required to be satisfied at the planning stage itself. HoQ has helped us to identify the best feature of each of the layout alternatives. Also, we could see that layout alternative 7 has performed best considering all the criteria. It can also be observed that the performance of the layout alternative 6 is also very close to alternative 7. Hence with some improvements in LA_6, the expected targets can be easily met. Though alternative 8 is easy to implement and is the most flexible layout, the other criteria are not scored better than the rest.

6.3 Conclusion

6.3.1. Qualitative Analysis Conclusion

In this case study, the qualitative analysis was proposed to consider the decision makers' subjective judgments. It also aimed to reduce the vagueness and uncertainty in the decision process. Thus, this section provides the steps and results of the qualitative analysis of the layout performance using AHP. The surveys conducted helped in capturing the opinions of the experts based on their experience and knowledge. The AHP analysis helped in identifying the positive and the negative attributes of the layout designs. From the qualitative analysis, we can conclude that LA_6 has the highest score for safety and easy maintainability. LA_8 scores the highest for factors like flexibility and ease of implementation. Though LA_7 scores the highest only in one factor i.e. ease of operation but is observed to perform the best when all the factors are considered.

6.3.1. MCDM Conclusion

We have shown in this section the steps for integrating the qualitative and the quantitative results. We employed the HoQ tool for this decision-making process. The results from the HoQ can be used as the feedback loop for the designing team to improve the layout alternative. The HoQ is also a good presentation format for the management as it highlights the best and worst features of the layout designs. From HoQ we can evaluate the relative importance of the parameters for layout evaluation as required by SBT. We observed that the SBT team members' prime requirement from the layout planning was that the facility layout needs to be safe for the employees and the machines in the plant. Followed by their requirement to meet the production targets like production pace and Avg Throughput. We also observe that LA_6 can also be a good choice for the implementation as it scores very closely to LA_7. The difference between the score of LA_6 and LA_7 is only 0.003, which can be considered as a negligible difference. From Section 1.2, the flexibility of the layout for future expansion and modification is considered as one of the important factor for layout assessment considering the design evolution of wind turbine blades. But LA_6 score is very less for the flexibility factor, which would suggest that LA_6 would not be a favorable choice. From the MCDM technique for the layout assessment, we would suggest SBT implement LA_7 for finishing operations of the SB7XX blades.

Hows (Alternative) **Whats (Criteria)**	**LA_6**	**LA_7**	**LA_8**	**Weights of Whats**
Avg Throughput	0.3385	0.3361	0.3254	0.2083
Production Pace	0.3373	0.3379	0.3248	0.2083
Mediation Time	0.5000	0.4572	0.0428	0.0833
Ease of Implementation	0.3074	0.3278	0.3648	0.0149
Flexibility	0.1034	0.3205	0.3612	0.0497
Ease Of Operation	0.3456	0.3525	0.3019	0.1105
Safety	0.3551	0.3420	0.3030	0.2894
Maintainability	0.3451	0.3246	0.3303	0.0354
Overall Priorities of How	0.3454	0.3488	0.2952	

Chapter 7: Conclusions, Recommendations, and Further Research

The goal of this research study is obtained successively by answering the research questions defined in Section 1.3. The questions are answered sequentially in Chapters 2 to 6. In Chapter 2, the introduction into the blade manufacturing at Suzlon is given. It also provides information about the conventional layouts used for the production systems. Chapter 3, is a review of the available literature for the layout assessment methodologies. Chapter 4 describes how we adapted the framework from the methodology available in the literature for our case study. Chapter 5 describes the process of creating the simulation model of the alternatives for obtaining the production KPIs. In Chapter 6, we describe the implementation of the methodology selected for the qualitative analysis and the final decision-making process for the selection of the layout using the results from both qualitative and quantitative analysis. In this chapter, we provide conclusions on our research. Section 7.1 focuses on the conclusion and the recommendations based on the obtained results. In section 7.2, we elucidate on the future research for this study.

7.1 Conclusion and Recommendations

The goal of our research was to '***develop a methodology for facility layout planning for Suzlon Energy Limited and investigate the characteristics of layout alternatives for a new generation blade concerning qualitative and quantitative criteria.'***

We have developed a framework that is adapted from integrating methodologies available in the literature. The framework also acknowledges the gaps that were identified in the methodology in literature and were modified for the SBT case. The adapted framework can be used as a systematic procedural approach to attain the research goal. Table 22 is a compilation of the purpose and the approach of the methodologies that constitute our framework.

Table 22 Compilation of the methodologies adopted for the framework

This Research	Approach	Methodology
Alternate Generation	Systematic Layout Planning	R.Muther, 2015
Evaluation tools for quantitative criteria	Discrete Event Simulation	Law (2015)
Evaluation tools for qualitative criteria	AHP (Analytical Hierarchy Process)	Saaty (1980)
Evaluation tool for combining qualitative and quantitative criteria	QFD (Quality Function Deployment)	HoQ (House of Quality)

Since the research is for a greenfield project, we had to generate alternatives before proceeding to the analysis part. The SLP methodology used for this purpose was a systematic approach that had multiple iterations as we received feedback from the SBT team. We have seen how the data available from the existing production system can be migrated for the new production system. The SLP methodology by Muther (2015) has three phases in layout planning called the conceptual phase, the detailed phase, and the installation phase. In our study, we have focused on the first phase of SLP i.e. the conceptual phase. The conceptual phase of the layout design focuses on the factors like

- Sequencing of the operations
- Space configuration
- Capacity Planning (Number of stations)

We modified and adapted the alternative generating method for the SBT case by incorporating 'Static Line Balancing' for the determination of the station numbers required to attain the production targets. This makes a small step towards the integration of SLP with capacity planning. We also incorporated new design interventions that the design team wanted to evaluate before suggesting them to the management. Hence making our methodology relevant for the strategic decisions making tool for the production system.

The layout selection is done using the multi-criteria decision-making (MCDM) technique. Criteria selected for the SBT layout assessment were a mix of quantitative and qualitative factors. The quantitative factors are identified as the production KPIs namely: Production pace, Average Throughput, and Mediation Time. The qualitative factors are the desired attributes of the layout that are important but cannot be quantified. The qualitative factors selected for our research are namely: Ease of implementation, Safety, Ease of operation, Flexibility, and Maintainability.

The framework uses simulation for obtaining the alternate quantitative performance data. We built the simulation model for the alternatives and validated it. The simulation models of the alternatives were used to identify the bottlenecks in the production system as their initial performance did not match the SBT targets. We have used the bottleneck analysis as an intervention to re-dimension the number of stations in the layouts. We saw improvement in the KPIs for nearly 10% to 35% among the alternatives after the bottleneck analysis. This also indicates that the quantitative results have accounted for the capacity planning, queuing effects, and logistical resource management. The bottleneck analysis also helped in improving the Avg Throughput values for the blade in the production system. The LA_7 has a reduction in Avg TH by 46 hours (approx. 2 days) which is a very big improvement for a production system. Hence we would suggest that it is an essential step in the layout planning to do bottleneck analysis. This would ensure planning the layout with appropriate capacity to meet the demand. The average throughput for the layouts varies between 161 to 174 hrs. The improvement in Avg Th for the layout alternatives is tabulated in Table 23.

Table 23 Reduction in Avg Th of blades after Bottleneck analysis

Layout Alternative	6	7	8
AvgThroughput after Static balancing (hrs)	167.8	210.7	179.6
After Bottleneck (hrs)	161.5	163.9	174.7
Reduction In Avg TH (hrs)	6.2	46.8	4.9

We implemented the AHP methodology for obtaining the qualitative results. We were able to capture the subjective judgment of the experienced SBT members through this methodology. We also quantified the relative importance of the qualitative attributes used to assess the layout in the selection process. The results from the AHP can be used to identify the alternatives that perform best in any one or more parametric analysis. For the assessment of the layout performance combining both the qualitative and quantitative analysis results, we built a relationship matrix as per the HOQ methodology. The HoQ helped in clear visualization of the alternative performance individual as well as overall parameters.

We observed that LA_7 had the highest priority number in the HoQ. Also, the LA_6 was scored very close to the LA_7. The production KPIs are But as can be visualized from Figure 57, LA_6 scores very poorly in the flexibility parameter. Thus suggesting that LA_6 cannot be easily adapted for future generation blades and also not flexible to new technology introduction and capacity increment in the future. If only quantitive analysis had to be considered, it would have been more logical to suggest the implementation of the LA_6 for blade finishing operations as it performs well in those parameters and requires fewer station numbers. But when having a holistic view of both quantitative and qualitative parameters we can conclude, that LA_7 would be the best performing layout for the SBT case.

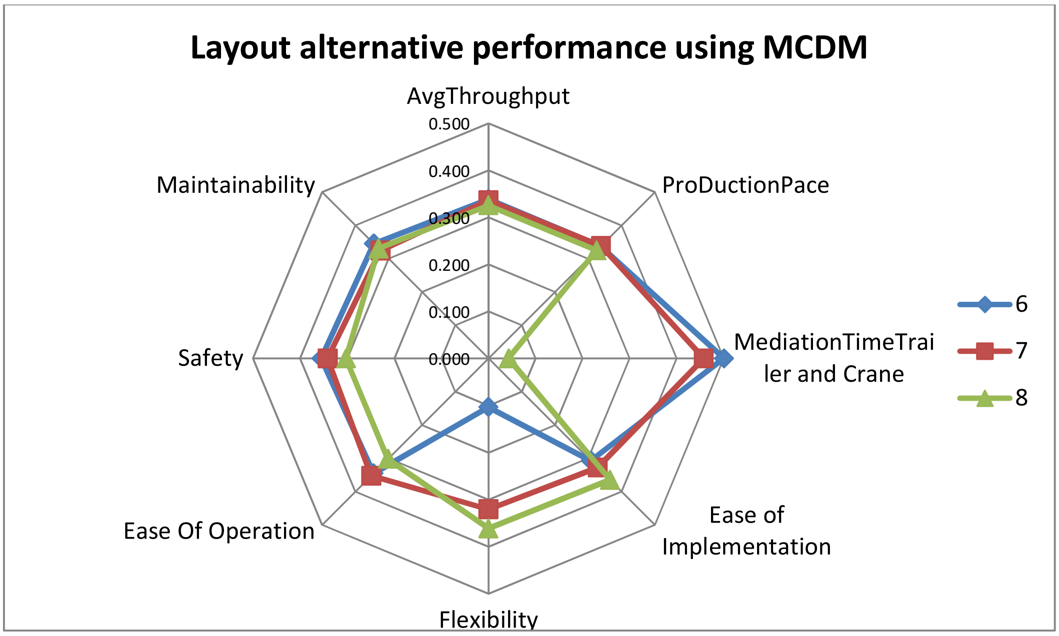

Figure 59 Results from layout assessment for blade finishing operation at SBT

Overall, in this study, the development of a decision-making methodology system with system performance improvement approaches was described to support management in assessing the production KPIs and qualitative attributes. Although the proposed methodology examined only a few design interventions, with some modifications it can be incorporated for more types of interventions like technological, logistical, etc.

7.2 Future Research

The methodology presented in this research is an initial step for facility layout planning and its performance assessment as a decision-support tool. Here we accounted for the production processes, capacity planning, space configuration and stochasticity of the system, new design, and technological interventions, and optimal sequencing of the tasks.

We constructed a simulation model for the analysis of the alternatives generated through the SLP methodology by Muther (2015). The simulation model can be constructed with more details for a more detailed study of the layout planning stage. The model also included the blade finishing processes, for future study the material and component preparation and blade moulding operations can also be included.

We developed a framework of methodologies from the literature study in Chapter 4. We have implemented the framework up to the HoQ step in this research. For a more structured selection process of the layout from the designed alternatives, we suggest implementing the TOPSIS methodology suggested by Shahin(2011). It will help in identifying to identify the best alternative (which has all the criteria at the desired level) and the worst alternative (which has criteria with tolerable levels). While defining the framework we identified two gaps:

1. In the quantitative analysis, the procedures are very subjective and are based on individual opinions.
2. The qualitative and the quantitative analysis are mutually exclusive and are not self-sufficient for a holistic view.

Hence we would suggest further research to fill the gaps observed in the framework. Also, the cost is an important parameter for the layout selection. Due to insufficient data, the cost analysis could not be performed but we would suggest incorporating it to have a more efficient decision-making strategy.

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Appendices

Appendix A: Frameworks from the literature review for the methodology

1. **Z. Zhang (2019)**

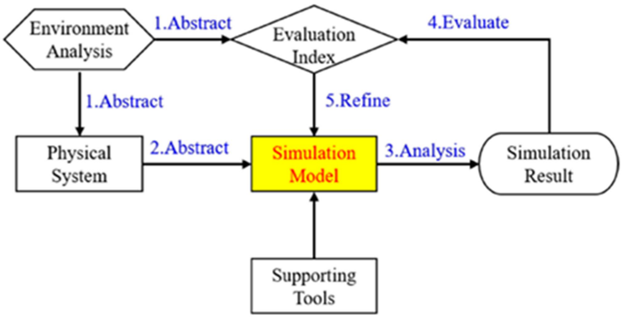

Figure 60 Z.Zhang (2019) Meta Model Of Simulation-Based Approach

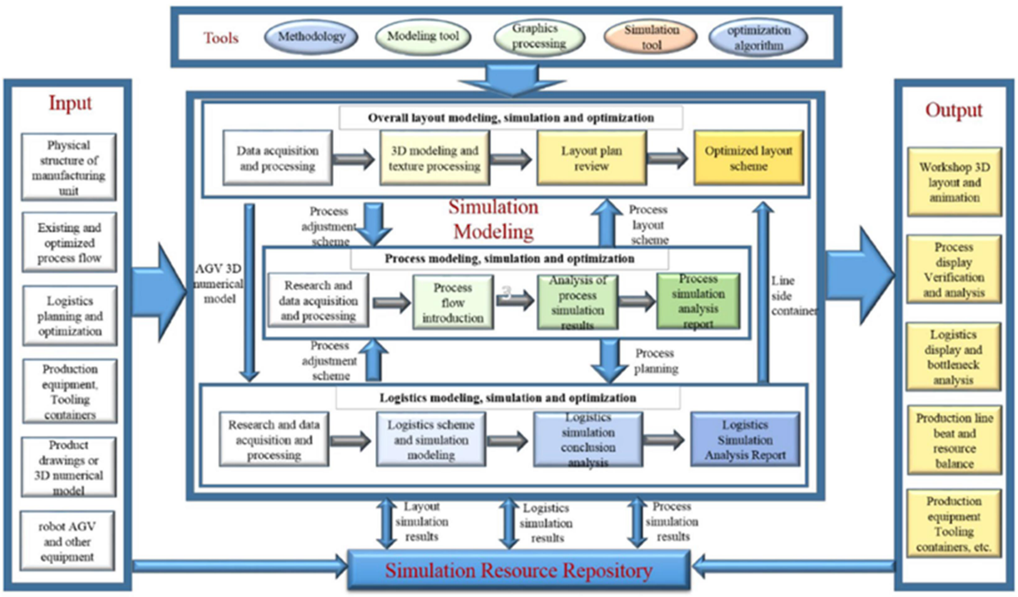

Figure 61 Z.Zhang (2019) System architecture of simulation-based lean layout and production planning

2. A. Shahin (2011)

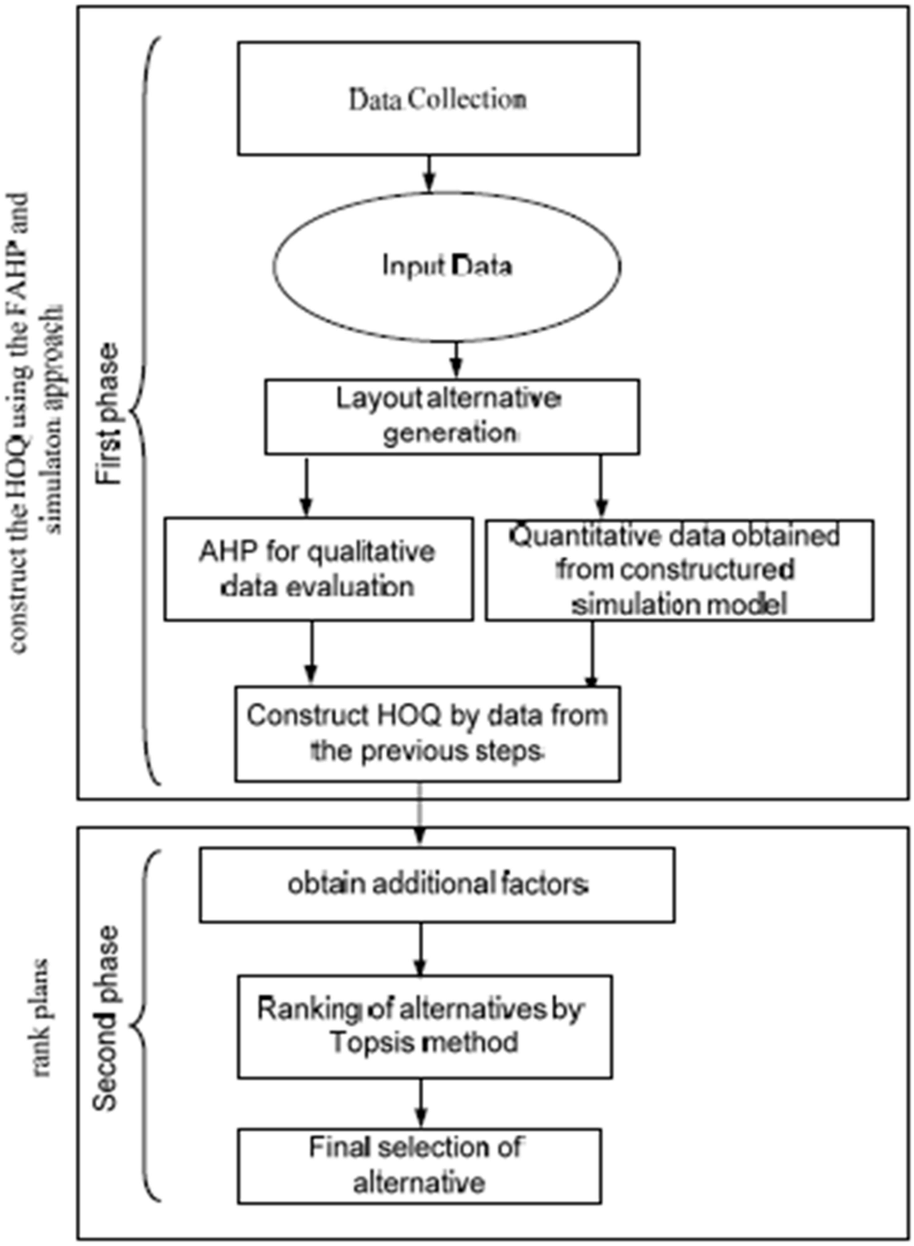

Figure 62 A. Shahin (2011) Proposed methodology with quantitative and qualitative analysis

3. M.Gangal (2009)

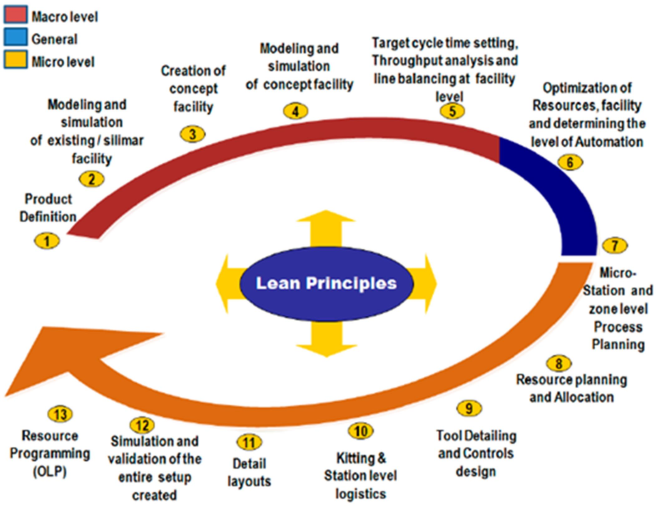

Figure 63 M.Gangal (2009) Plant Design Framework using the lean principle

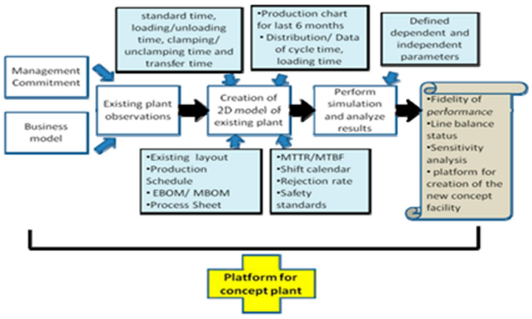

Figure 64 M.Gangal (2009) Approach to model and simulate an existing facility

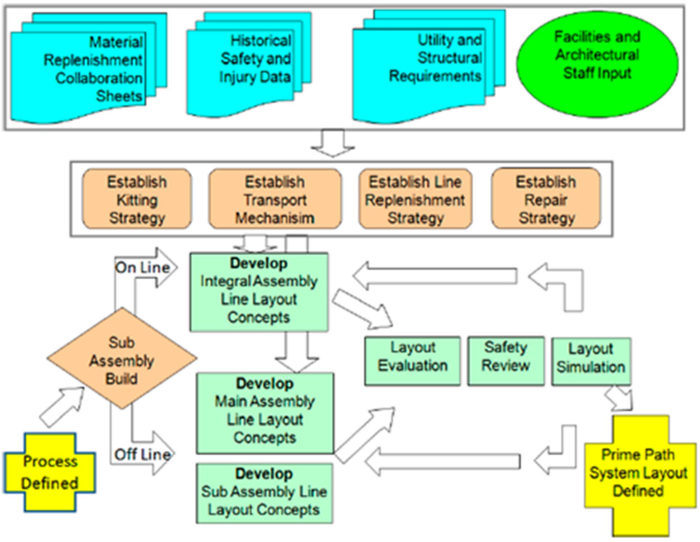

Figure 65 M.Gangal (2009) Approach to create Macro Level Prime system layout

4. C.Kuo (2003)

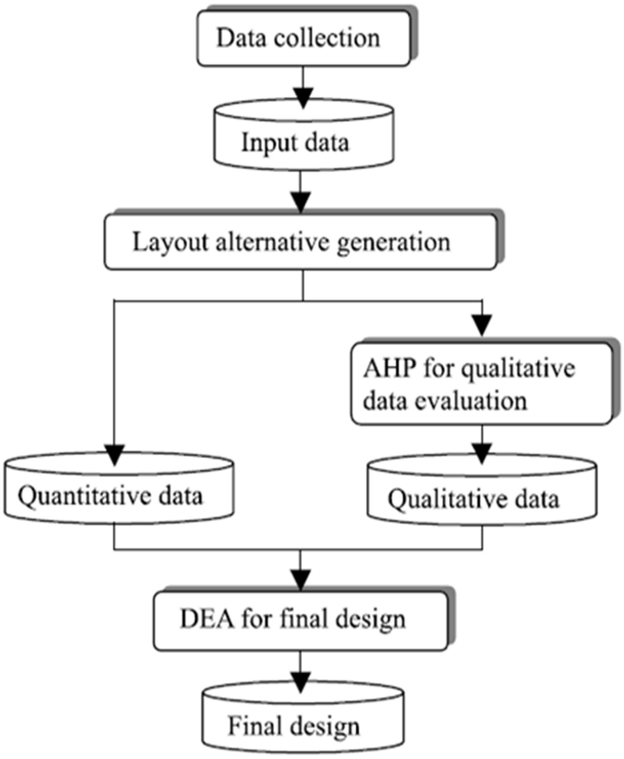

Figure 66 C.Kuo (2003) A hierarchical AHP/DEA methodology for the facilities layout design problem

5. J.E.Branstrator. (1989)

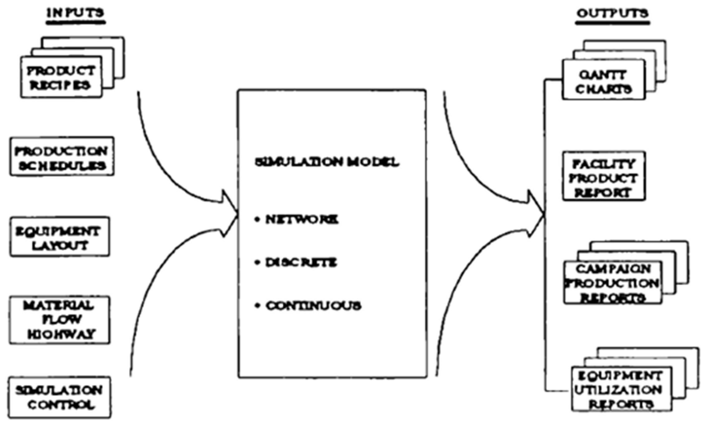

Figure 67 J.E.Branstrator (1989) Flexible Simulation Model design

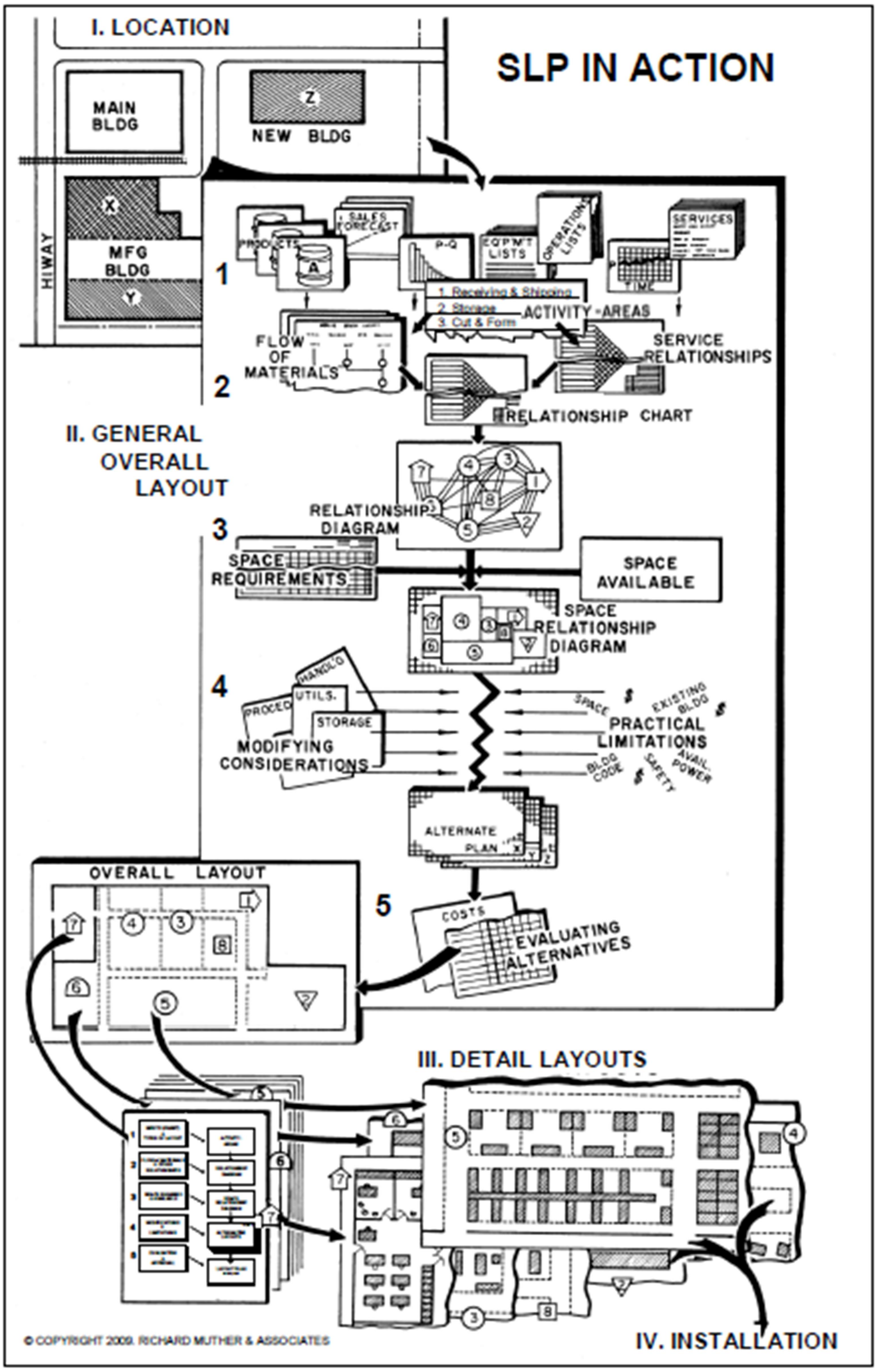

Figure 68 Muther(2015) Phases in Systematic Layout Planning

Appendix B: Layout Alternatives

The layout alternatives are generated Using the SLP methodology by Muther (2015).

Table 24 LA_6 design intervention

Layout Alternative 6: Blade finishing area		
Location	**Combining And Splitting of Process**	**Transporting Equipment**
Main Building	BF_Task1 + BF_Task3	Telescopic Trailer
Flexible Temporary Structure	BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6	Rotating stand
	BF_Task7	Rotating stand
	BF_Task8	Telescopic Trailer
Main Building	BF_Task9	Crane
	BF_Task10	
	BF_Task11	Crane

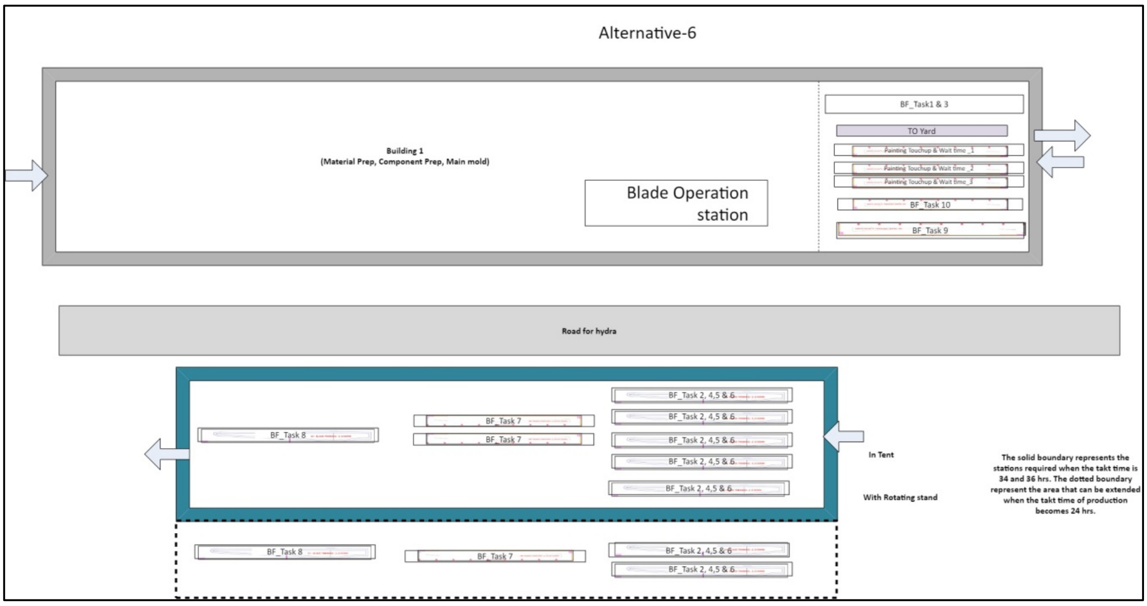

Figure 69 Layout Template for LA_6

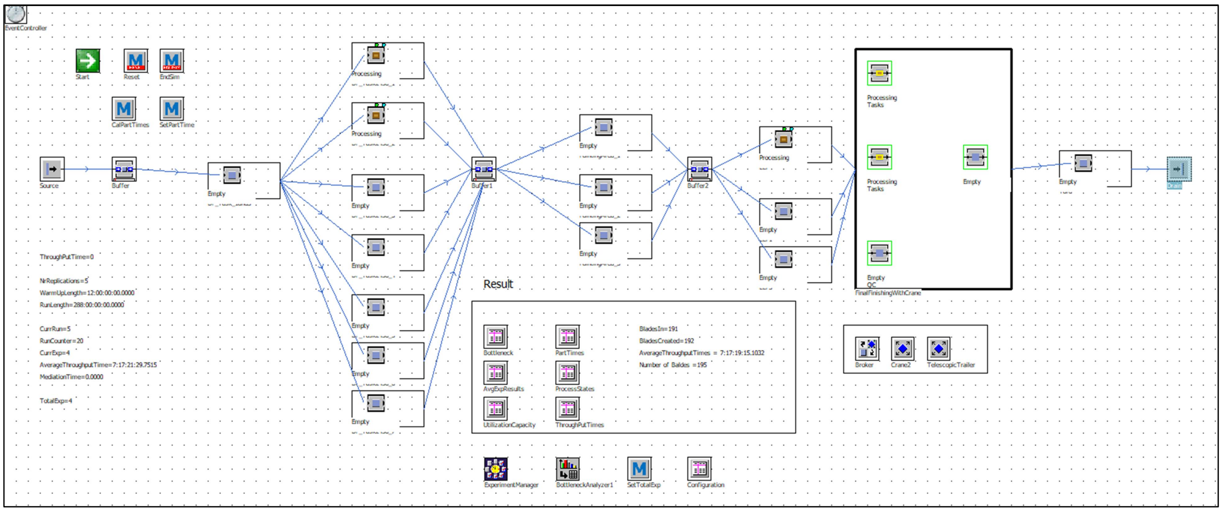

Figure 70 Simulation frame for LA_6

Table 25 LA_7 design intervention

Layout Alternative 7: Blade finishing area		
Location	Combining And Splitting of Process	Transporting Equipment
Flexible Temporary Structure	Parking Station	Rotating stand
	BF_Task1 + BF_Task3	
	BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6	
	BF_Task7	
	BF_Task8	
	BF_Task9	
	BF_Task10	
	BF_Task11	

Alternative-7

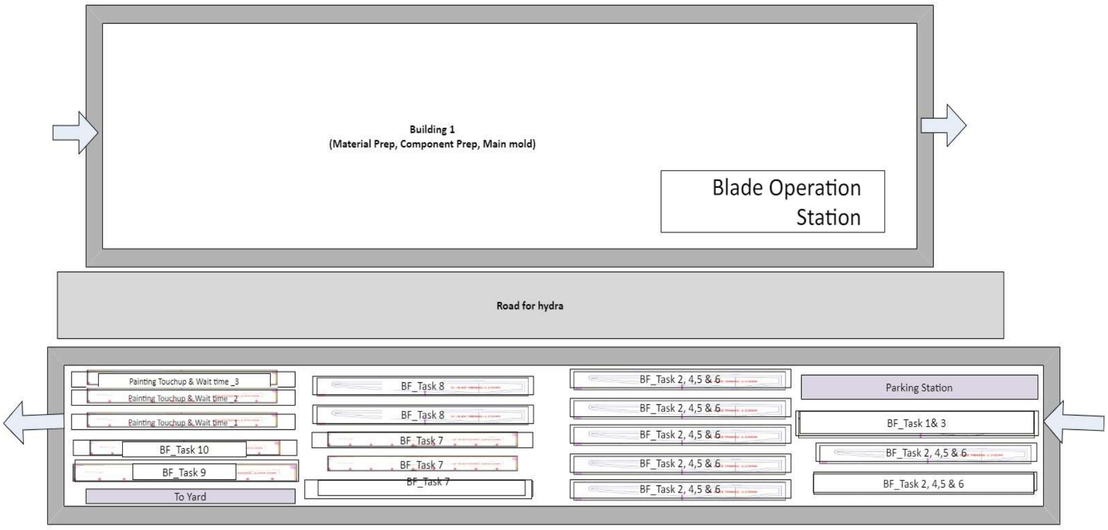

Figure 71 Layout Template for LA_7

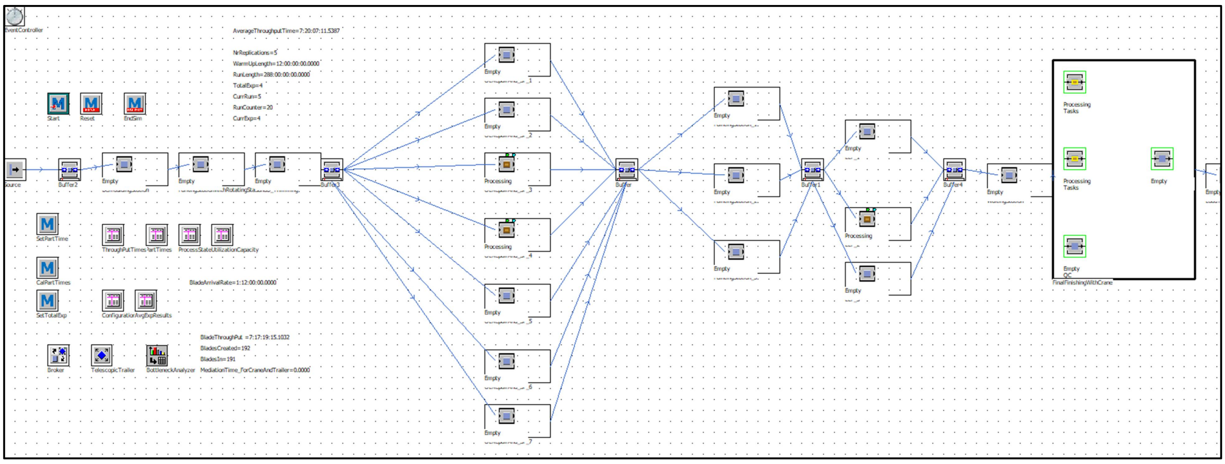

Figure 72 Simulation frame for LA_7

Table 26 LA_8 design intervention

Layout Alternative 8: Blade finishing area		
Location	Combining And Splitting of Process	Transporting Equipment
Main Building	BF_Task1 + BF_Task3	Telescopic Trailer
Flexible Temporary Structure	BF_Task2 +BF_Task4 + BF_Task5 +BF_Task6 + BF_Task7 + BF_Task8	Telescopic Trailer
Main Building	BF_Task9	Crane
	BF_Task10	Crane
	BF_Task11	

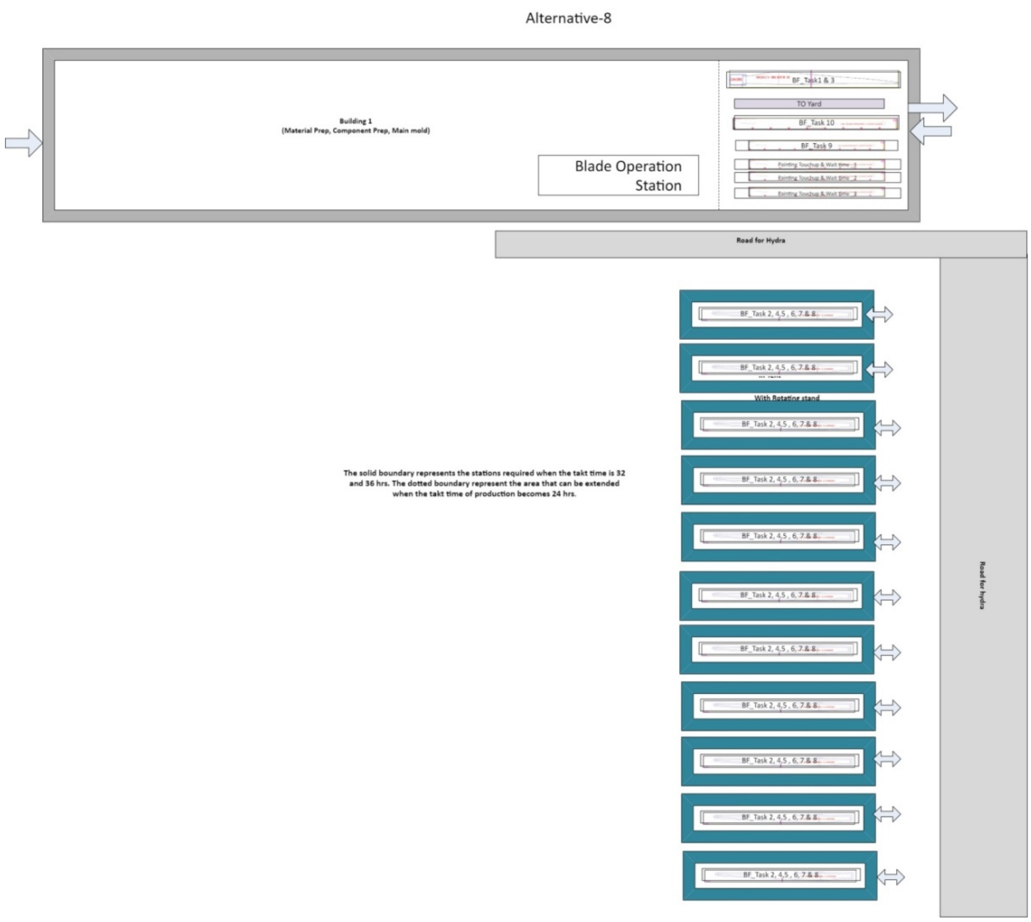

Figure 73 Layout Template for LA_8

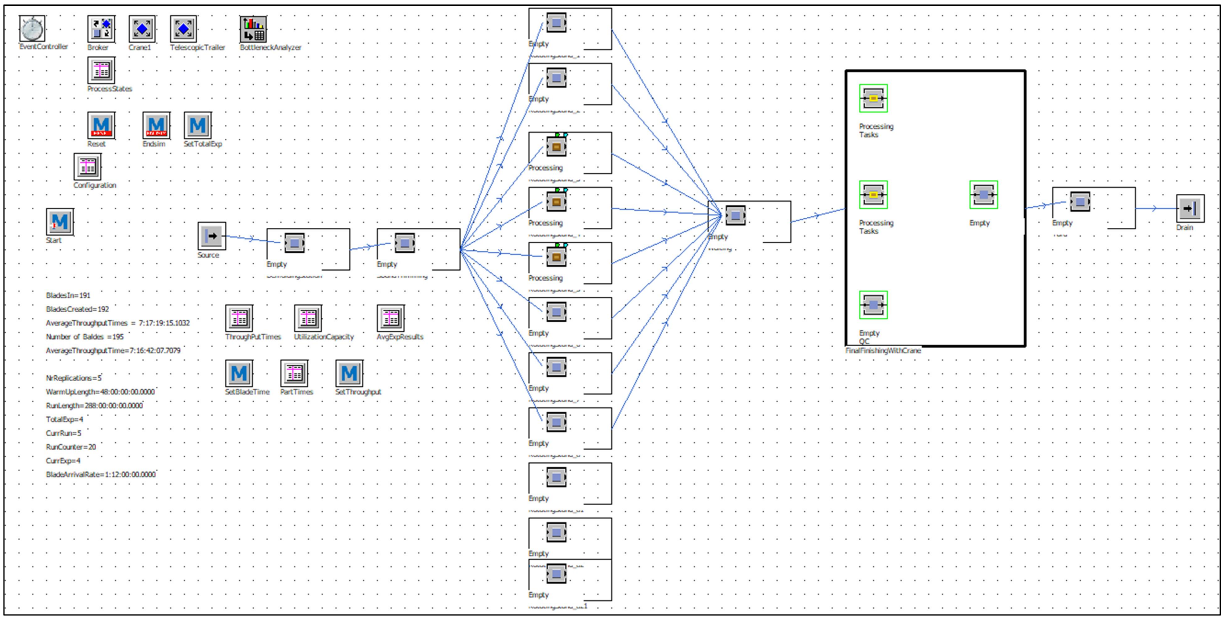

Figure 74 Simulation frame for LA_8

Appendix C: Statistical analysis for the simulation model

Welch's graph for the run data of layout alternatives:

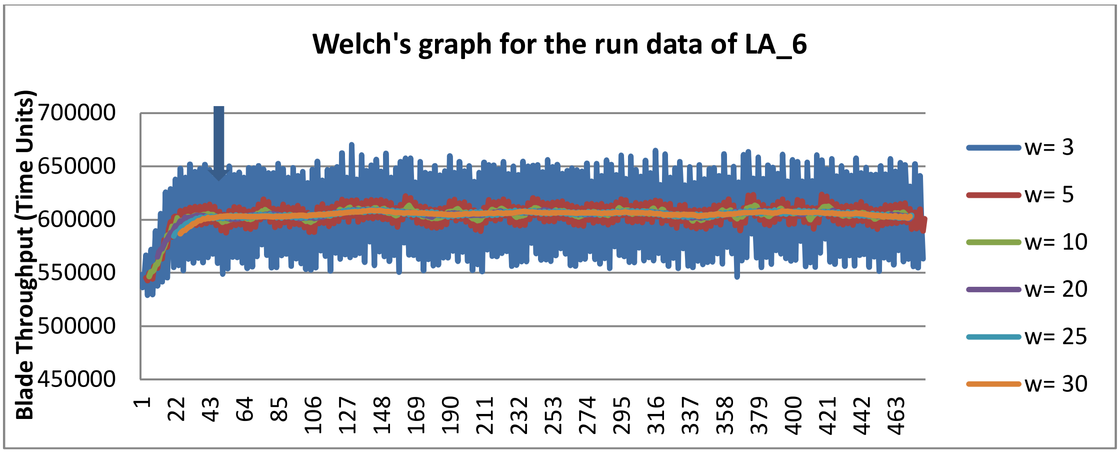

Figure 75 Welch's graph for the run data of LA_6

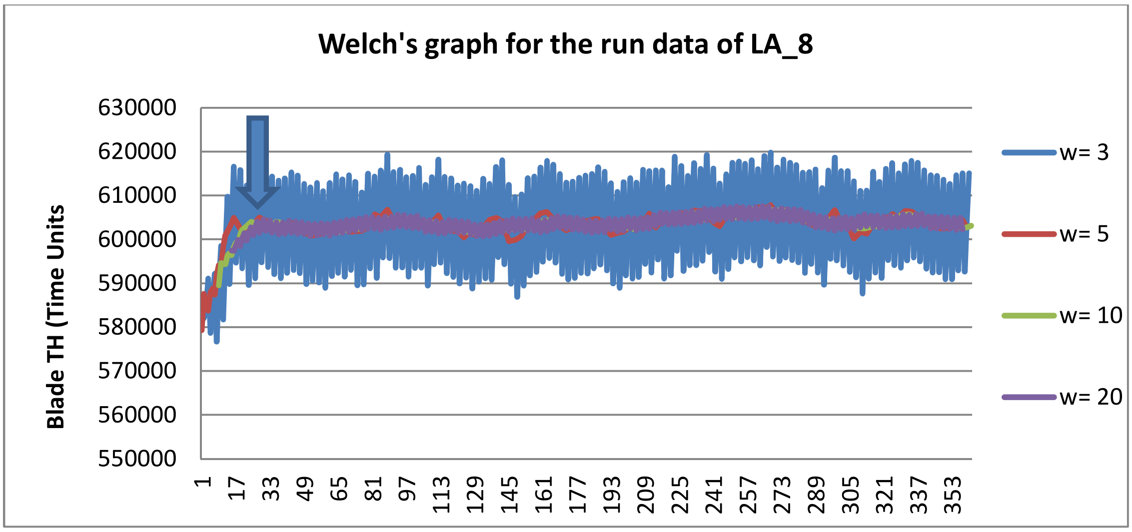

Figure 76 Welch's graph for the run data of LA_8