UNIVERSITY OF TWENTE

Applying simulation to wind rotor blade manufacturing

Process alignment in an international environment

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Industrial Engineering & Management

Master Thesis

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SUZLON
POWERING A GREENER TOMORROW

Preface

The report laying before you summarises my accomplishments in improving the way Suzlon Blade Technology Nederlands can understand, test, and advance blade production processes that are performed at a distance of eight thousand kilometres, in Ratlam, India. Completing an assignment during an internship of six months is a necessary achievement to graduate at the master program Industrial Engineering & Management of the University of Twente, but it shouldn't be seen as requirement, rather it should be seen as the fulfilment of a long route, as the proof of what we can do when putting knowledge and passion together.

That is right, students should experience these mandatory assignments as exciting periods of their life, and I believe most of us do. We are always told to choose a topic we feel passionate about, but sometimes this requires courage. During the master program, I came across simulation and was mesmerized by its practical approach as well as the sturdy theoretical framework behind it, but I was also intimidated by its complexity and unexpected difficulties.

I would like to thank Suzlon Blade Technology Nederlands for the opportunity they've given me with this assignment, it allowed me to morph my feelings of awe towards simulation to an enthusiastic respect and eagerness. Furthermore, I would like to thank all of the colleagues of Suzlon I had contact with, be it because of a quick chat at the coffee machine, sharing of data and production concepts, or a meeting call across continents. I sincerely appreciate your help and the warmth everyone is exuding.

On a separate note, I would like to thank my internal supervisors at Suzlon Nederlands, Alberto Maria de Crescenzo and Sandro Di Noi. Your help in understanding blade production was invaluable, the constant support and discussions allowed me to experience what working in a team feels like, but above all I'd like to thank you for recreating a part of Italy in a foreign – and marvellous – land.

Next, I would like to thank my university supervisors, Martijn Mes and Marco Schutten, in helping me to cross the bridge from simulation theory to practice, and for their most useful feedback on my thesis. Without your help, my report would probably be obscure and incomprehensible to the most acute of the readers.

Lastly, I would like to thank my family and friends, both close and far, for their support. These last two years in the Netherlands have been astonishing and full of new experiences, for which I am immensely grateful. I am grateful to my family for sustaining me without ever asking anything back, even though they've been the ones mostly affected by my distance. I am grateful to my friends in Italy, for always keeping in touch and treating me as if I had never left. I am grateful to all the new friends I've bonded with while in the Netherlands and to a specific group of friends, whose cute name I will omit. You have contributed to making this Dutch experience of mine as rich and eye-opening as it could be.

I hope this thesis will kindle a spark within you all, up to you to decide its course.

Matteo Brunetti *Hengelo,* 30^{th} *of September 2019*

Management Summary

Suzlon Blade Technology Nederlands (SBT-NL) is a R&D and product support company for wind turbine blades located in Hengelo, they are a branch of the international wind turbine company Suzlon Energy Ltd. Their goal for this project was to assess the value of simulation, and more specifically Discrete Event Simulation (DES), as a strategic decision tool in the field of wind turbine blades production.

Production processes have a story of being optimised as standalone entities, without considering integration between operations, queuing effects, stock outs, and production flow. Because of this traditional approach, SBT-NL struggles with obtaining a clear understanding of the effects of newly designed interventions in the production plant and to achieve reliable quantitative analysis. By implementing DES, the company aims to structure their research process regarding potential improvements of their production lines, obtain statistically validated results, and experiment with different scenarios in a risk-free environment.

To answer their question, we compared various simulation methodologies from the literature and selected one, then proceeded to perform a simulation study following said methodology on one of their standard sized plant, the plant in Ratlam, India. We collected data, defined a conceptual model, translated it into 2D and 3D computer simulation models, and tested various interventions proposed by the engineers of the research department.

Two types of interventions were proposed for the testing phase:

- Operation Optimisation on processing times, comprising the Component Optimisation and the Blade Optimisation.
- Layout re-dimensioning through task rescheduling and stations balancing.

The first focuses on reducing processing times for each moulding operation at components and blades moulding stations, by redesigning the work procedure and removing inefficiencies, where possible. The second takes into account the overall processing time for each station and aims to lower it below a reference Takt time for the plant, which we estimated using lean manufacturing tools. To reduce bottlenecks and increase productivity, we changed the layout (shifting of equipment and different space allocation), substituted the batch formation logic with a standardised weight class logic, and redistributed tasks between stations.

Furthermore, we identified a gap between the plant operational standards and the expected performance by design standards. This gap is due to assumptions made at SBT-NL when analysing the systems and on completed projects that have never been finalised at the plant. The gap greatly reduces the accuracy of design estimations, prevents reliable analyses and is a significant performance loss for the plant.

At the end of our research, we evaluated simulation as a powerful and useful tool, obtained a suggested schedule to implement interventions at the plant, quantified the standards gap between plant and design, and extrapolated recommendations on how to overcome this gap and increase the reliability of analysis performed by the R&D office.

In this thesis, we showed the applicability of DES as a strategic decision tool for SBT-NL. We summarize the following benefits.

- It allowed for testing of both major and minor process changes to the system and in risk-free scenarios.
- It allowed for a more accurate representation of stochasticity inherent to the real production system.
- It returned us reliable stochastic results for each intervention and allowed for proper and quantitative comparison of alternatives.
- It allowed to aggregate knowledge spread over documents and employees at the R&D department and at the plant in India, in the form of conceptual models, computer models, and data sets, which are readily accessible and that ease the understanding of interactions between processes.

Moving forward, the suggested schedule of implementations at the plant is as follows:

1. Rescheduling & Balancing.
2. Reduction of the intervention backlog.
3. Full Operation Optimisation.

Each step of the implementation will improve the performance of the system by reducing the blade lead time in the Finishing area or increasing the productivity of the plant. The expected performance of the system is shown in Table 1 using a confidence interval of 99%, with a 1% relative error. The collected KPIs are:

- FLT, Finishing Lead Time for blades, calculated in hours.
- PP, Production Pace, as in number of hours between the release of two subsequent blades at the end of the production line.
- CSO, Components Stock Outs, as in monthly average of stock outs.
- MSO, Materials Stock Outs, as in monthly average of stock outs.

When simulating the Ratlam plant including all the new interventions and the reduction of the backlog, the lead time of blades could be reduced on average by 57%, productivity could increase by 48%, and there should be no stock outs of components or materials.

Table 1: Performance of system at each implementation step, for reduction of Blade Finishing Lead Time and increase in productivity

	FLT (h)	PP (h/blade)	CSO	MSO	Reduction of Blade Finishng LT	Increase in productivity
Default system	275.28	19.76	0.00	0.00	-	-
1st step	126.92	14.51	0.00	0.00	-53.9%	26.6%
2nd step	116.24	11.14	0.00	0.00	-57.8%	43.6%
3rd step	117.82	10.25	0.00	0.00	-57.2%	48.1%

We have further recommendations on how to implement the interventions and to increase the accuracy of design estimations:

- We advise to implement the two parts of the Operation Optimisation intervention concurrently, the one on components and the one on blades, as it will pool costs for training of employees and tooling, and because implementing only the Blade Optimisation would lead to frequent components stock outs in the system.
- We advise the R&D office in Hengelo to improve the procedure to account for queueing effects, delays and interactions on the production line. These assumptions make up 77 hours of the gap between design and plant standards. Simulation has proved to be an effective tool to include the interactions on the production line, thus we suggest its use.
- Lastly, we advise SBT-NL to model cranes in the 3D environment only for larger sized plant where more blades need transportation concurrently. In the standard sized Ratlam plant, cranes were actually underutilised and the required transportation time is overestimated by just several hours, which is not enough of a discrepancy to justify the significant coding and modelling effort required to represent the crane logic in 3D.

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Chapter 1: Introduction

1.1 Background description

Suzlon Energy Ltd. is an Indian company that designs, produces and installs wind turbines all around the world, but mostly in India, as that is a growing market for wind energy and also where most of their wind rotor blade production plants are situated.

The company branch located in Hengelo, Suzlon Blade Technology Nederlands (SBT-NL), is one of several research departments in northern Europe. Its responsibility is to design and optimize both the wind rotor blades and their production process. Being assigned to the Innovation & Strategic Research department, which studies and improves production processes, our focus is on the process design, rather than on the blade design.

The company is experiencing an increase in wind turbine orders and foresees this to be a trend that will continue in the future. Therefore, the current main goal of SBT-NL is to increase the production of wind rotor blades to align with the expected high market demand, while striving to contain costs regarding new equipment and investments.

Due to difficulties in assessing alternative interventions for the wind rotor blade plants and the economical unfeasibility of performing real life experiments for all of them, SBT-NL decided to implement Discrete Event Simulation (DES) software as a strategic tool to support decision-making and evaluate costly interventions in a virtual environment.

1.2 Project goal

The goal of this master research is to help the company in assessing the potential of simulation in the wind turbine sector with regards to operations. We want to do so by providing them with an adapted simulation methodology from the literature and a general conceptual model of their production plants. A production plant is chosen to apply the methodology and create detailed 2D and 3D digital models. Moreover, few plant intervention proposals from the R&D department are tested in digital models to serve as a first experience and guideline with simulation in the company to evaluate the methodology.

1.3 Problem context

Prior to the start of the thesis project, the company conducted a study on the actual production rate of the plant that we use as a case study in this research, namely the plant in Ratlam, India. The company noticed that this production rate is lower than the achievable potential rate, considering the current equipment and workforce.

We selected the Ratlam plant as a case study for this research project because it is one of the standard sized factories and its production is currently halted, allowing for layout and process changes to be implemented more rapidly. After the project, the company plans to extend the knowledge and methodology applied during this assignment to other plants, as it is felt many factories are affected with the same productivity issues. Each plant is dedicated to one type of blade only and for the Ratlam plant this blade is one of the 2 MW blades platform. We provide more details on the blade type and its production process in Chapter 2, let us now focus on the perceived reasons for the low production rate.

The discrepancy between actual and potential production rate is due to many factors: operational inefficiencies, misalignment between process designers and plant managers, layout inefficiencies, communication problems, etc. In Figure 1, we present a problem cluster to better convey the factors and their relationships. We identified four topic areas that influence productivity:

1. Design.
2. Layout.
3. Operations.
4. Improvement procedure.

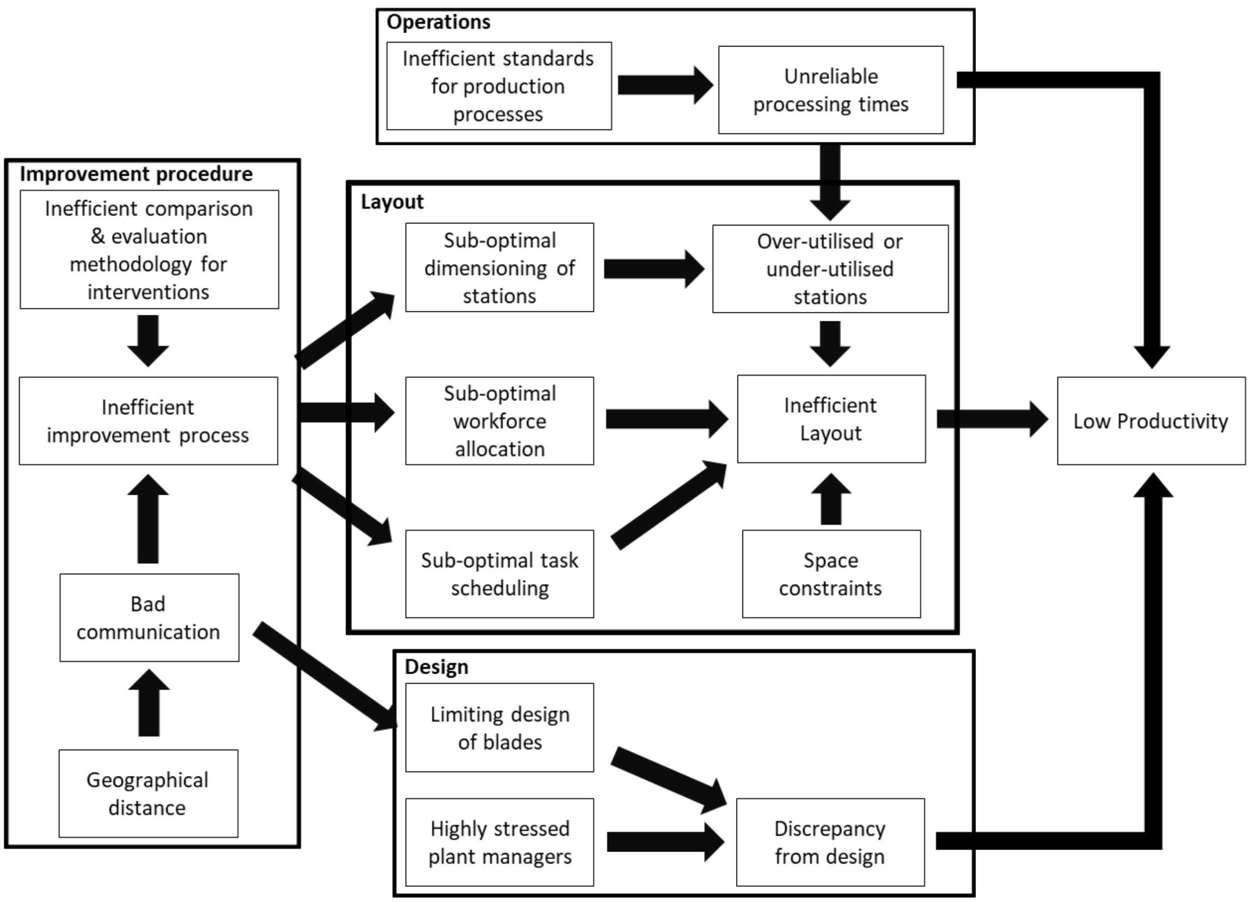

Figure 1: Problem cluster divided in topic areas

In the first area, related to blade design, it was reported that the designers' documents given to the manufacturing plants limit the maximum productivity, which pushes plant managers, highly stressed by the low production, to follow their own schedule and resort to firefighting, leading to even lower performances.

In the second area, related to plant layout, it was reported that the overall manufacturing process is not balanced, some stations are over-utilised and others are under-utilised. A reason for this is the insufficient capacity of the over-utilised stations compared to their blade processing time. The problem cannot be easily solved by adding extra capacity, because of space constraints and the desire of the management to reduce costs, also considering the aforementioned analysis on the current equipment untapped potential. Therefore, to increase the capacity of an over-utilised station, it would be preferable to reallocate resources from an under-utilised station in the plant. Another problem regarding the layout is the workforce allocation, both related to congestion, when working at some specific stations, like the moulding area, and to the unknown real number of employees required by some tasks compared to the one written in the design documents. Lastly, task scheduling is considered to be sub-optimal because there is a feeling that potential lead time reductions could be achieved by shifting the sequence of tasks in the procedure. This is considered as a layout problem because shifting the tasks can require shifting the location of the stations responsible for those tasks.

In the third area, related to operations, it was reported that the real lead time of a wind rotor blade is unknown or at least very unpredictable. This is due to a high variability in processing time of tasks in the final phase of blade manufacturing, unforeseen repairs to the blade and a general lack of operational standards for the production processes.

In the fourth area, related to the improvement procedure, we understood there is a communication problem that influences the follow-up in India of decisions taken in Hengelo, due to geographical distance and culture, which also creates a “grey” area where accountability is easily lost. This communication problem also affects data gathering, the knowledge available on the actual process, and the discrepancy from design projects. On the other hand, the structure in place for process improvement projects is felt as lacking when it comes to evaluating operations and layout interventions, as the focus has been mostly on studying each process separately without considering their relationships and the cascade effects of disruptions, which makes evaluation or comparison of alternatives difficult.

1.4 Core problem selection

Together with the company supervisors, we discussed the four problem areas and identified one relevant core problem, highlighted in Figure 2, which we could influence and properly address within the time of a master assignment:

“The inefficient comparison and evaluation methodology for alternative interventions”

To justify our decision, we refer again to the four topic areas and describe the reasoning that led to narrow the choice to a single core problem:

Design. This topic area was excluded because the blade design itself is out of scope for an IEM thesis.

Layout. The space constraints cannot be solved by expanding the building in Ratlam due to the goal to reduce costs, therefore we should focus on the stations dimensioning, on the workforce allocation or on the re-scheduling of the tasks. Dimensioning was deemed important as the company would like to achieve a balanced production process as soon as possible, to increase the productivity without new investments. Next, workforce is quite cheap in India, so less economically relevant than the stations dimensioning or task re-scheduling. Moreover, this would not be a long term planning but something the plant manager can hopefully improve with daily management. Finally, task re-scheduling is considered easy to achieve, a responsibility of the process designers, and influencing the dimensioning of the stations.

Ultimately, stations dimensioning and task re-scheduling were seen as potential problems to be tackled by the Innovation & Strategic Research department. However, they can be approached by researchers already employed at SBT-NL whom also have more experience with the processes, but in turn have no knowledge on simulation. Therefore, we agreed on letting the senior researchers focus on interventions for the stations dimensioning and task re-scheduling, while we would prioritize our work on another problem area.

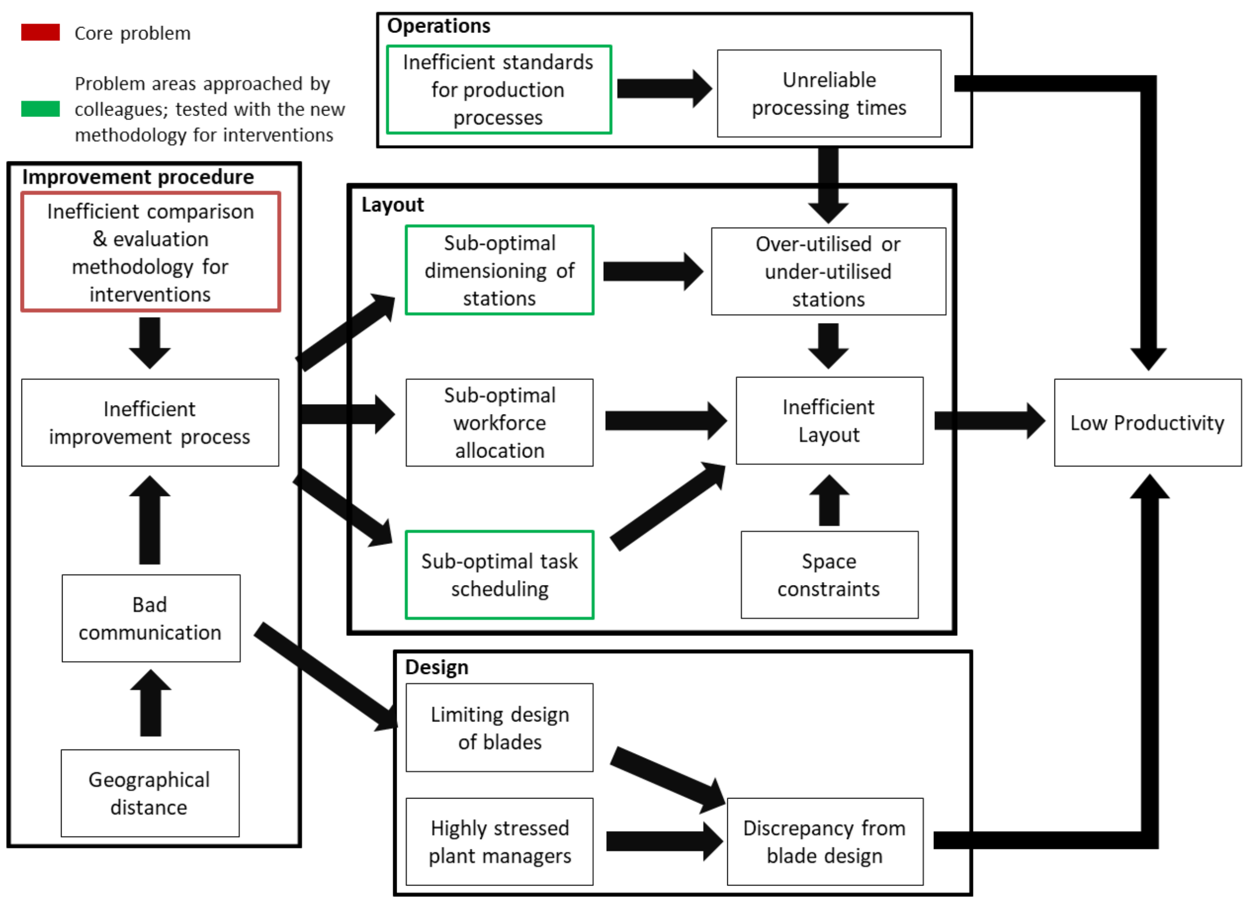

Figure 2: Problem cluster with highlighted core problem and problem areas approached by Suzlon

Operations. This topic area was also excluded, because the operational standards for the production processes are already being approached at the production plants in India with the lean methodology. Similarly to the workforce allocation, these type of projects are at a deeper detail level of the operations, also categorized as Process Kaizen, while the research department should focus on the high level improvements project in the production, also categorized as Flow Kaizen, to obtain the best results from its effort (Rother et al. 2003). In other words, the research department should not focus on mapping and selecting all the hand movements an operator will perform, but rather suggest the best location for the workstation where the operator will perform these movements.

The improvement procedure. Both geographical distance and bad communication are issues that cannot be easily influenced in six months' time and which, again, are out of scope for a master assignment in IEM. Furthermore, the costs and benefits achievable by solving these problems are very hard to define due to the difficulty in achieving organizational culture change. On the other hand, the comparison and evaluation methodology for alternative interventions is something which we can influence and indirectly impacts geographical and communication obstacles, something which is felt as important by the decision-makers, and which will allow for future savings since it eases the way for further improvements.

The core problem we are going to tackle requires an analysis of the current intervention procedure, an analysis of the production plant, and a procedure to test the proposed interventions and compare them. Therefore, to be deemed a useful strategic tool, simulation should help us to structure the research process at the company, to represent the plant environment in detail, to create various scenarios based on the interventions and to virtually test them, since they are too costly to be tested at the real plants. This is the link between our project goal and the core problem highlighted at the company.

Now, we discuss whether simulation is a proper tool to analyse Suzlon's plants or not, as a negative answer would lead us to change our project. When studying real systems, it must be checked whether there is an actual need for a simulation study and not for another approach. We perform this check by following the guidelines from Law (2015), see Figure 3.

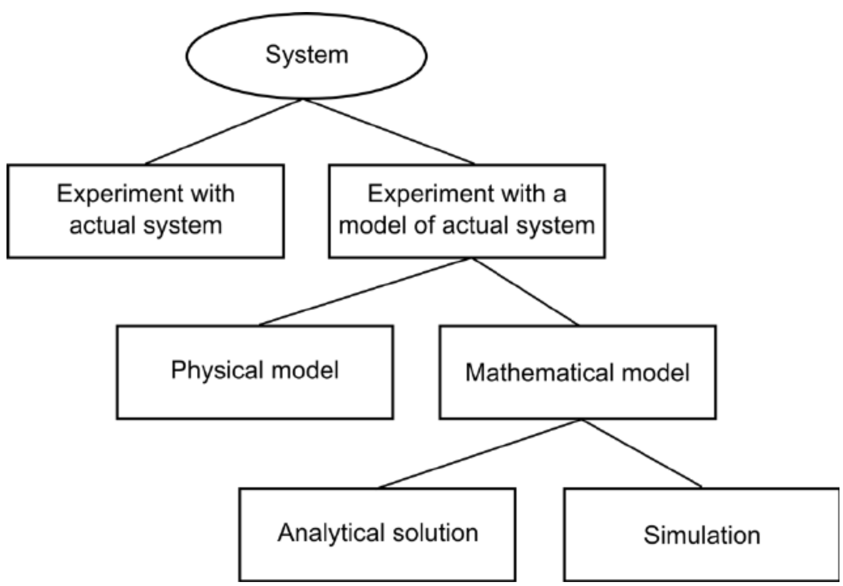

Figure 3: Ways to study a system (Law 2015).

The first choice is to experiment with the actual system or with a model of it. The equipment in the processing plant is very expensive and completely implementing interventions takes a long time due to aforementioned organisational and geographical inertia. Furthermore, the lead time for a single blade to be produced is definitely long. Therefore, it is not possible to experiment with the actual system as it would be too costly, both considering experimental time and capacity changes for the stations. We conclude that a model of the actual system is required.

Due to the same reasons and to the complexity of the full production process that we want to model, it is impractical to create a physical model and to obtain data from it in reasonable time. Thus, in our case a mathematical model is a cheaper and faster tool to conduct an analysis, compared to real life manufacturing and testing.

A simple analytical solution is already being used at SBT-NL to analyse the production, but the actual system is very complex and requires the inclusion of uncertainties, e.g., shortage of materials, delays due to overlapping calls of the handling equipment, variance in processing times. A simulation model will allow for an easier integration of the large amount of data from the production plant environment, blades, raw materials, components and cranes.

After the choice for a simulation model is made, we must determine which kind of simulation approach to use: since the model exemplifies a system that evolves over time with stochastic processes, it can be considered a dynamic and stochastic model. Also, the model can be defined as discrete, because the flow of time can be represented by discrete events that occur at scheduled points in time and that may change the state of the system. This discrete-event representation allows us to better analyse the interaction between entities, e.g., blade or component movements, stock outs, queueing effects and cascade delays.

Finally, the guidelines provided by Law in selecting how to study a system support the company's choice for DES.

1.5 Research questions

After selecting the core problem to analyse, a main research problem has been formulated together with the company:

"How can Discrete Event Simulation (DES) support Suzlon Blades Technology Nederlands in its R&D process, with respect to the analysis of interventions in blade production plants through detailed digital models?"

The research problem is going to be tackled by dividing it in multiple research questions (Qs) and sub-questions that can be answered separately:

Q1: What is the process of creating wind turbine rotor blades?

- What are the trends in the wind rotor blades market that will influence the production process?
- What is a wind rotor blade?
- What type of blade are we focusing on and what is the general procedure to manufacture it?

- What is the current procedure to evaluate and compare interventions for layout and process improvement at SBT-NL?

Q2: What simulation methodology best fits SBT-NL improvement process and how can we adapt it?
- What simulation methodologies are currently present and most relevant in the literature?
- What are the most important criteria to compare methodologies for SBT-NL?
- How should the chosen methodology be adapted to the company's improvement procedure?

Q3: How has simulation been used in practice?
- What is written in the literature regarding wind turbine field and simulation?
- What are examples of DES simulation studies performed in similar fields?
- What can be applied in our study?

Q4: What information do we need to create a detailed model of the manufacturing plants?
- What does the chosen simulation methodology suggest?
- What specific information do we need for 3D models?
- What level of detail is necessary?
- What is the current layout at the chosen plant?
- What are the processing times for each task at the chosen plant?
- How much resources (materials, components, handling equipment) are needed for each task at the chosen plant?
- Which distributions should we use to represent the processing times of tasks?
- Which scenarios will be represented or researched by the model?
- Which KPIs should we measure in the model?

Q5: How should we experiment with the interventions?
- What interventions do we want to experiment with?
- What is our Design of Experiments (DOE)?
- What does the chosen simulation methodology suggest?
- What extra data is needed?

Q6: Which interventions can be implemented at Suzlon's manufacturing plant?
- Which intervention performs best according to the selected KPIs?
- What is our suggested implementation schedule?

1.6 Research approach and outline

Here we describe the approach of the thesis research and assign each research questions to chapters.

To answer Q1, we firstly present important market trends influencing the blade production. Afterwards, we describe the wind rotor blades structure and their production process for the specific blade type produced at the Ratlam plant. Lastly, the current procedure to evaluate and compare interventions for layout and process improvement is introduced with its major issues. Chapter 2 is the introductory chapter used for Q1.

Moving forward to Q2, knowledge on the simulation methodologies in literature is gathered by means of a literature review, while criteria for comparing simulation methodologies are gathered from employees and managers at the research department during kick-off project meetings. This information is then used to adapt the chosen methodology to SBT-NL. The answer to Q2 is presented in Chapter 3.

Q3 is answered searching for similar case studies in literature where DES was applied to wind turbines industry and to manufacturing processes in general. The results increase our confidence in using simulation as a strategic decision tool in the wind turbine industry from a practical perspective. We also gather insights and recommendations on what can be applied to SBT-NL and how to implement it in the company IT infrastructure. Q3 is also presented in Chapter 3.

For Q4, choices on the level of detail of the model and performance KPIs are discussed together with the company supervisors and other stakeholders for the project. More detailed data regarding layout, processes, and resources is obtained by reading into the company data (i.e., Design Cycle Time documents and other required specifications) and by means of interviews to experts on the real processes, whom are working at the selected plant. Then, the collected data is statistically analysed, e.g., through distribution fitting. The modelling phase and all the relevant knowledge from Q3 is described in Chapter 4.

As mentioned before in the core problem selection, the senior researchers from SBT-NL produced ideas for interventions at the plant on the layout and the operations. On the other hand, our task is to implement these interventions in the simulation model, considering the necessary extra data and model recoding, and experiment with a proper DOE. These steps answer Q5 and are presented in Chapter 5.

Q6 is answered in two steps. First, an analysis and discussion on the experimental results following the simulation methodology guidelines. Then, a ranking and evaluation through AHP, based on the outcome of internal presentation to company stakeholders and decision makers about the features of different alternative interventions. Q5 is described in Chapter 6.

The final chapter, namely Chapter 7, provides conclusions on our achievements, recommendations, and topics for further research.

Chapter 2: Wind turbine industry and blade production process

In this chapter, we first briefly describe wind turbines and their market trends, which relate to Suzlon's choice to increase production. Then we focus on blades and their components. We present the general blade production process divided in macro phases and a layout for the standard plants. Lastly, we will introduce the current situation in Suzlon Blade Technology Nederlands with regards to R&D activities for layout and process improvements and data management. This knowledge will suffice to answer Q1:

"What is the process of creating wind turbine rotor blades?"

2.1 Wind turbines and market trends

Suzlon is a producer of the dominant three-bladed Horizontal-Axis Wind Turbines (HAWTs). This type of turbine is roughly composed of three main parts, shown in Figure 4: the rotor hub and blades, the nacelle, and the tower structure.

- The rotor includes three blades and a hub to let the blades turn and tilt based on wind direction and speed.
- The nacelle contains the generator, the gearbox (or direct-drive mechanism), the shafts, and most of the electronic components of the turbine.
- Lastly, the tower structure can be made up of different basements and tower types, ranging from tubular steel towers to floating jackets for off-shore locations. It also contains the yaw motor and drives to turn the whole upper part of the turbine based on wind direction.

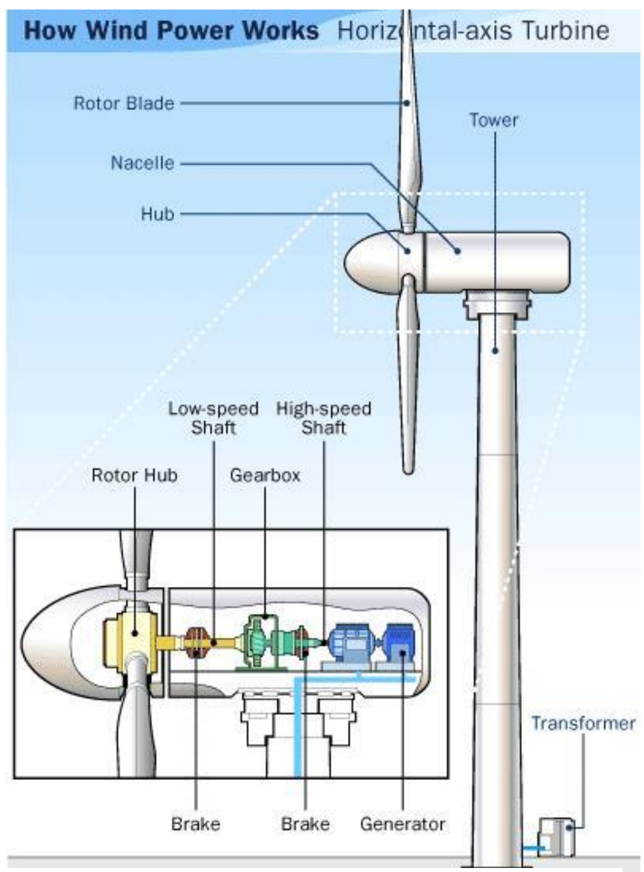

Figure 4: Horizontal-Axis Turbine (Layton, 2006)

Suzlon plans to increase the production of wind turbines, and consecutively of blades, to align with the upward trend in wind energy installed capacity, as in both the worldwide and the Indian market, this value is expected to at least quintuplicate in the period from 2020 to 2050, as shown in Figure 5 and Figure 6 respectively. The four scenarios used in the analysis of the GWEC (2016) represent the level of enforcement and impact of green policies by world governments. They scenarios are displayed in ascending level of enforcement and impact, from left to right.

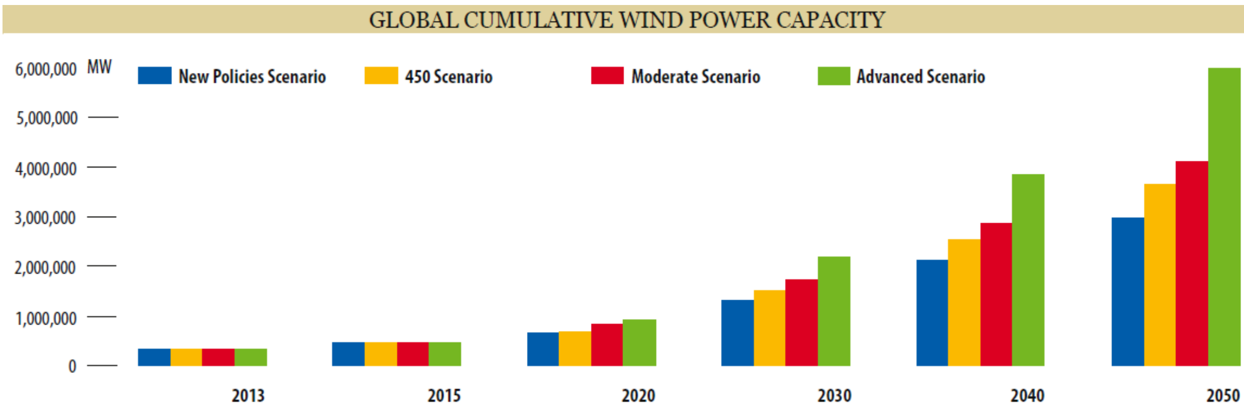

Figure 5: Global wind power capacity based on four future scenarios (GWEC 2016a).

INDIA							
Total Capacity in MW	**2013**	**2014**	**2015**	**2020**	**2030**	**2040**	**2050**
New Policies Scenario	20,150	22,465	25,088	50,063	111,938	184,838	256,789
450 Scenario	20,150	22,465	25,088	67,098	155,736	254,827	358,314
Moderate Scenario	20,150	22,465	25,088	44,734	116,257	227,137	372,830
Advanced Scenario	20,150	22,465	25,088	56,297	163,473	294,184	452,197

Figure 6: Projections for installed capacity in MW in India based on four future scenarios (GWEC 2016b).

Similarly, Figure 7 shows the average length of blades, alternatively measurable as half the rotor diameter length, that is also following an upward trend, leading Suzlon Blade Technology to focus on longer blades. We want to optimise the production of one of the 2 MW blades platform and we can see this choice is aligned to the demand trends for India, which is Suzlon's main market, because the 2 MW platform has also been following the trend of length increase. The 2 MW blades platform is shown in Figure 8 and is used for wind turbine S88 to S120.

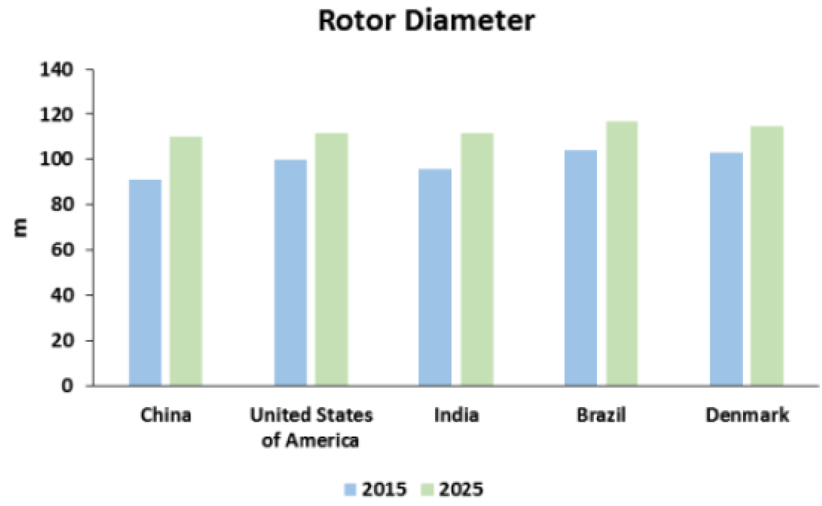

Figure 7: Historical and projected rotor diameters in selected markets (WEC 2016).

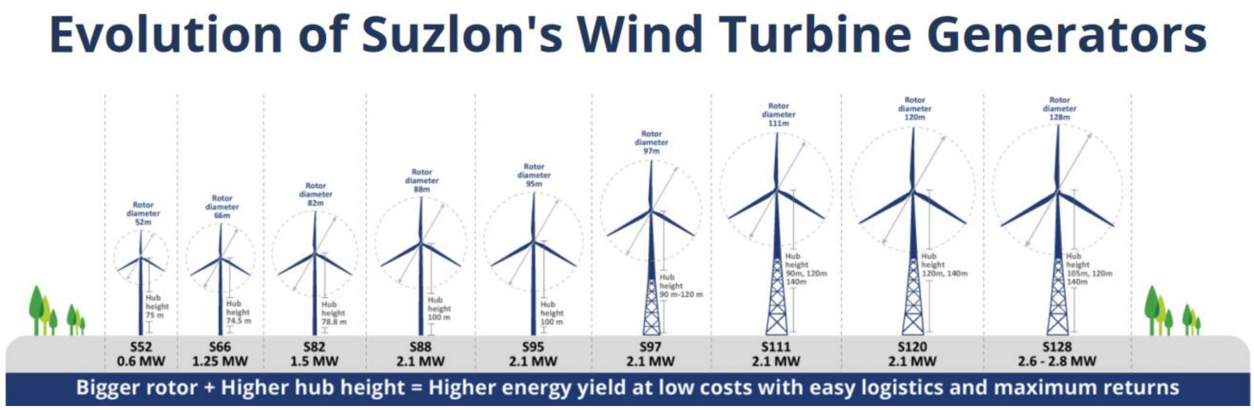

Figure 8: All Suzlon's Wind Turbine Generators, including the 2 MW blades platform

We will now move to the blade structure and production, as this is the area where SBT-NL operates.

2.2 Blade structure and components

A blade is commonly referred to as having two sides, the lower side and the upper side, as visible in Figure 9. The lower side withstands high pressure and low speed, vice versa the upper side withstands lower pressure but high speed. This pressure difference generates a lifting effect on the blade perpendicularly to the air flow and turns the rotor, while also generating a dragging effect. The goal of blade design is to maximize the lift and minimize the drag, to reach the maximum speed and thus harvest more kinetic energy from the wind, while ensuring structural integrity for the long lifetime of the blade.

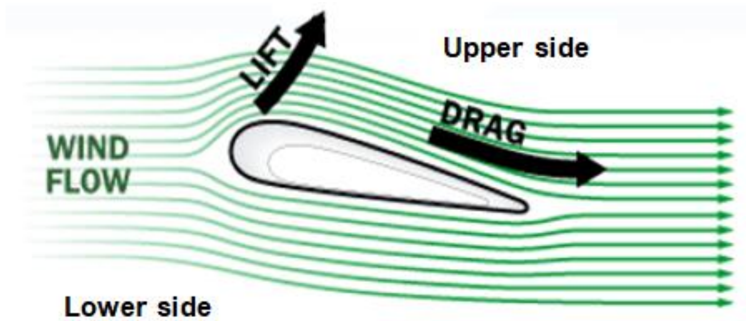

Figure 9: Lift & Drag, courtesy of SBT-NL

While this reasoning applies to all blades, each blade specific model is composed of different artefacts, layers of materials, and follows a different production process, based on its design and the producer. The production plant which is the subject of our study operates for a single type of blade from the 2 MW blades platform. Its production requires eleven unique components, few raw materials to create the core body of the blade, and several aiding materials.

The raw materials are used also to create the core body of the eleven components, thus the raw materials department must satisfy the aggregate demand of the main blade and the components. The aiding materials have not been included in this project due to time constraints and the relatively low cost of these commodity items, which are bought from external suppliers.

2.3 Blade production process

Blade production can be roughly represented with four macro phases, namely Material Preparation (MP), Components Preparation (CP), Blade Moulding (BM), Blade Finishing (BF), and details on the stations, handling equipment, and shifts. Moreover, we can define the Blade Lead Time (*BLT*) for the manufacturing plants as a function of the processing times for the blade moulding phase (*DMT*), blade finishing phase (*FLT*), crane movements (*CM*) to transport blades between stations, crane delays (*CD*), and repair delays (*RD*).

$$Blade\ Lead\ Time_{(DMT,FLT,CM,CD,RD)}$$

We now guide the reader through each macro phase of the general blade production process and represent it on a general layout in Figure 10.

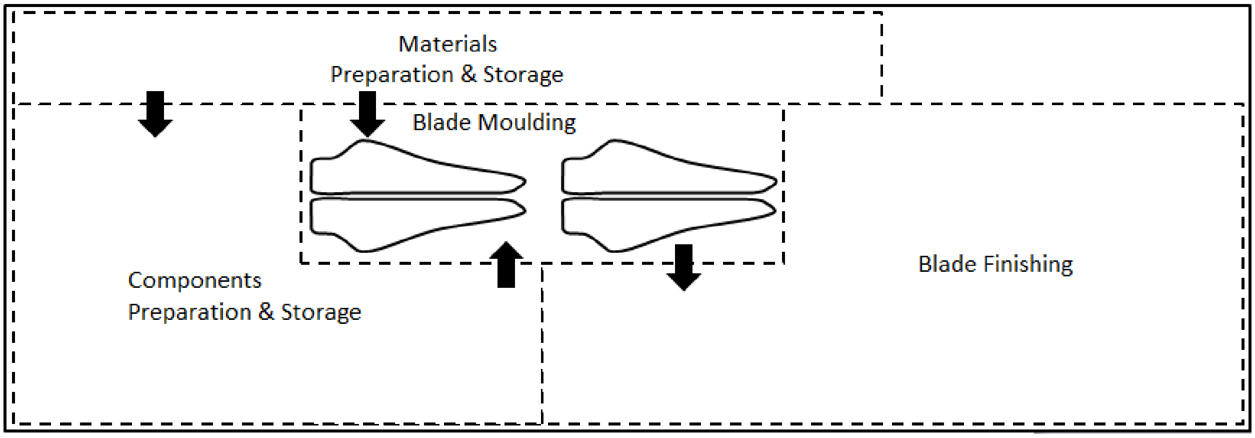

Figure 10: General plant layout

2.3.1 Material Preparation (MP)

The MP phase is responsible for preparing and cutting layers of raw material in different shapes, which will be laid on the blade moulds and component moulds to create the core bodies' structure. The prepared raw materials are organised in kits, where one kit is enough material to service the blade moulding and the creation of all the components that will be placed into the blade. Thus, the output of the MP department is expressed in kits, and it is based on the slowest process of the department. Because of the use of kits, a blade will only start production when a complete materials' kit is ready next to the moulding station, the same logic applies to the components.

2.3.2 Components Preparation (CP)

The CP phase is responsible for creating all of the blade components and storing them in their corresponding storage areas. The creation of each component is a smaller scale version of the blade production process, again we have a first moulding step and a second step where the items are polished and checked for conformity to standards.

The CP moulding and polishing are organised with a pull logic, which means that the production of the items continues as long as there is storage space available. The storage area for components works with a supermarket logic and is the decoupling point between the pull production logic in the CP area and the push logic used in the BM and BF phases. This is necessary to avoid stock outs at the BM phase, which is the pacemaker of the manufacturing line. Furthermore, each artefact type has its own moulding station and a polishing area assigned to it, this allows for parallel production of all component types.

With the current set-up of the CP, the total Work In Progress (WIP, stocks plus components being made at the previous stages) of each component is higher than the allocated storage area, and it reaches a value which is two units higher than the storage dimension. This is due to the capacity of the moulding area and the polishing area, both equal to one for each component.

2.3.3 Blade Moulding (BM)

The BM phase is responsible for the moulding of the blade, where the raw materials used to create the core body are glued together through resin and the external components are attached. All the tasks to be performed in this phase are done on the blade moulding stations, which means that process-wise the blade is not moving but still undergoing many operations.

The BM is considered to be a critical phase of the process and probably a bottleneck, as it is commonly regarded as the pacemaker of blade production and the main focus for any new research on processes. It is important to mention that the lead times of kits and components lead time are not directly influencing the BLT, however they increase the DMT when causing delays in the moulding phase due to stock-outs.

2.3.4 Blade Finishing (BF)

The BF phase consists of different polishing operations of the blade, repairing tasks, a protective coating process, the formation of a batch (also called “set”) of 3 blades, and a quality check with certification of standards compliancy. These steps are performed on different stations in the plant, following a one-piece flow logic, which means the blade is visiting all the stations in a sequential order and should not require reprocessing at previous stations. Also, when a blade repair is needed it is performed at BF stations that are already assigned to standard tasks, creating delays on the production line. These repair delays are referred to as *RD*.

The most critical process in the BF area is the batch formation, where the blades are grouped in batches of three to be attached on a wind turbine. This task requires the first blade of a batch to wait for the arrival of the next two, then weighing and balancing operations – piercing of the blades, pouring of heavy materials, closing, curing and painting the hole – are performed to bring the three blades to the same characteristics. Since one blade is used as a reference for the other two, only two of the three blades of the batch will require pouring of heavy materials, also called mass addition, unless the reference blade is below a minimum weight threshold. The task is completed after a full blade quality check and necessary repairs and re-painting.

2.3.5 Stations

Let us explain better what a station is in SBT-NL: in general, a station is an area assigned to a task and based on the task there will be a different supporting structure to position the blade as necessary. Then, tasks are mainly performed manually with the help of tools. Therefore, “station” is a general term for an area assigned to a specific task, and when changing the order of the tasks, the location of the stations is also easily changed as a consequence by repositioning the supporting equipment, which is cheap and easily obtainable.

The workstations assigned to the BF phase are of two types: convertible stations and fixed stations. The convertible stations are the ones described before, their supporting structure can be easily moved and the tasks performed at these stations only need some manual tools, thus they are called convertible as they can be switched from being assigned to a certain task to another. Conversely, tasks performed at fixed stations require complex tools whose relocation is more difficult and expensive, e.g., the equipment necessary to the formation of a batch of blades. To increase the capacity of a convertible station, it is sufficient to increase the area allocated to the corresponding task, while to increase the capacity of a fixed station it is necessary both to increase the allocated area and to purchase the required equipment.

The equipment used in the BM phase is expensive and hard to move, therefore it is considered as fixed equipment. The equipment in the MP and CP phases is not considered as exchangeable with the BF and BM phases, because of different sizes and dimensions. Regarding the batch formation task in the BF phase, we have an area that can contain four blades, divided between three convertible supports area and one fixed special equipment for weighing the blades. Effectively, only three blades at a time are contained in the batch formation area, and are moved between the weighing stations and the supports.

2.3.6 Cranes, forklift, and trailer

In the production plant, cranes are used to move the blades between stations, then a trailer is used to get the blade from the dispatch area to the storage bay. To lift a blade (or a long component) requires the use of two cranes at the same time, which engage the blade at predetermined position at its root and at its tip, thus when referring to cranes we henceforth refer to couples of cranes. Cranes move on rails that are positioned on the walls, close to the roof, and they can all move simultaneously but cannot move past one another: a crane that is positioned on the left of another crane will always be on its left, and vice versa for cranes on the right. Therefore, should one crane on the left move to the right, the other cranes on his path would have to move away and free the area. Studying cranes' performance is of interest to the company, especially when ramping up the production, which may lead to conflicts in the usage of this resource.

Aside from cranes, there are forklifts and a trailer. The forklift is dedicated to one specific component type only and moves it through its production processes in the CP area, it is used to lower the usage of the components' crane. The trailer is moving blades from the end of the BF area to the blade storage yard, it partially enters the production plant when a blade is ready for dispatch and loads it with the help of a crane.

2.3.7 Shifts

The production plants organise the employees in work shifts: there are three working shifts of 8 hours per day and breaks are not considered in the current model, both to lower complexity and because they are considered negligible.

More details on the specific production process for the type of blade prepared at the Ratlam plant will be presented in Chapter 4 of the thesis.

2.4 Current situation at SBT-NL

At Suzlon Blade Technology, layout and process improvements are mostly generated by cross-functional teams, which preliminarily analyse the projects with regards to benefits, costs, time and difficulty of implementation. A project plan is generated and sent to a supervisor. If approved, it is sent to the next supervisor and so on, in order to reach the required hierarchical level to obtain resources and support. The cross-functional teams are composed by researchers employed at the office in Hengelo and supported by employees managing the process in India.

Due to the hierarchy and the long distances, knowledge and data is lost to organisational inefficiencies. As of now, in the research phase there are two major issues resulting from that:

1. To get relevant and correct data from the production plants in India, to include uncertainties and to satisfactorily estimate the results of an intervention.
2. To align the design and production phase, and to manage the implementation backlog of developed solutions.

The first point is of statistical and quantitative nature, and is self-explanatory. On the other hand, the second point is more subtle: the research department is an entity of its own and cannot wait for the production plants to completely apply new interventions proposed by the R&D office before starting other projects, thus the development process marches forward highly relying on the design documents previously created. These design documents are based on real data from plant processes, both old and newly gathered, but also contain previous developed interventions that are still not in place at the plants. While the plants are lagging behind in implementing the “old” ideas (e.g., new tools, machinery, layout, different task order), effectively creating an intervention backlog, the research department is already moving forward with new analysis basing its information on the expected performance of the plant. A sketch of the misalignment cycle is shown in Figure 11.

The lack of proper data and the reliance on design documents with expected performances forces the researchers to assume deterministic processing times for each task and transportation required during production. These deterministic processing times are measured in the prototyping phase of the New Product Development (NPD) cycle of blades. However, the prototyping phase represents an optimal production situation for one batch of three blade, where the material and components are ready next to the stations, there is no WIP on the production line, and all workforce is ready.

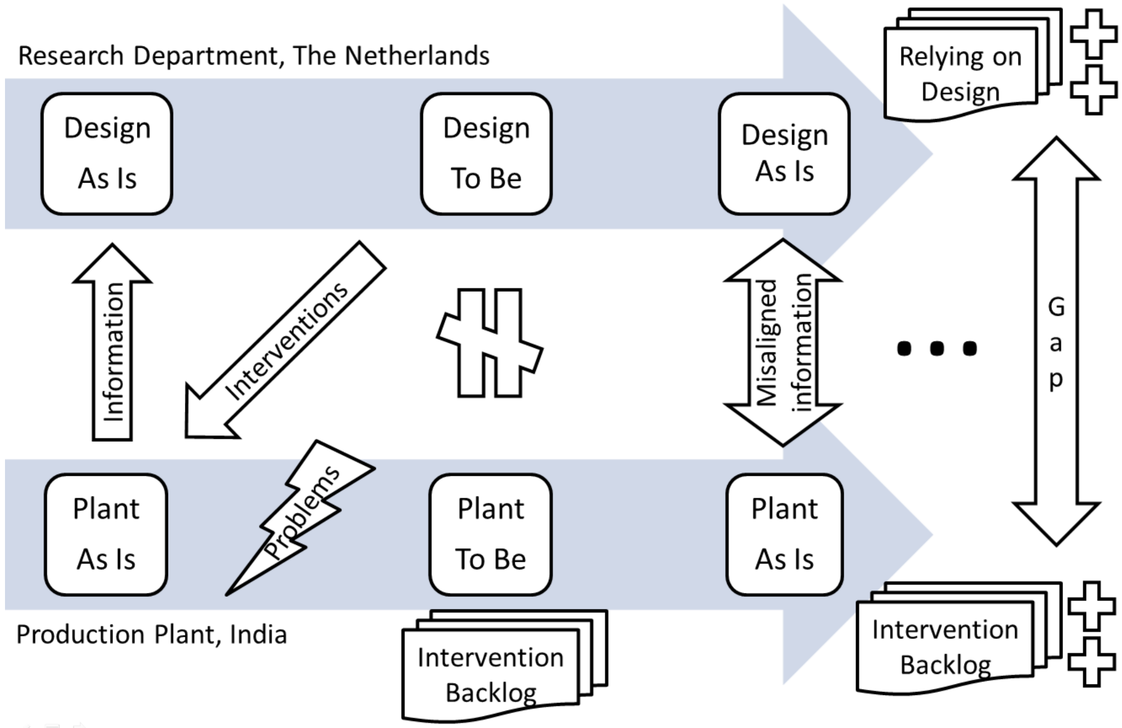

Figure 11: Process misalignment cycle

It is not possible to reproduce a full-scale production environment and obtain a statistically relevant number of observations in the prototyping phase, due to the size and cost of each blade. Therefore, stock outs, overlapping requests of handling equipment and tools, waiting time for the next station to be available, the stochasticity of processing times, and missing interventions at the plant, are not considered in the deterministic time estimated for each task at the research department.

Based on this reasoning, we can define two axis, which identify four scenarios, as shown in Table 2, valid for all plants working with SBT-NL:

- Situation: the status of an entity or system which is subject to change. The As Is column corresponds to the current situation and the To Be column corresponds to the future scenarios after the implementation of one or more interventions.
- Perspective: the approach and mind-set of an entity or a group of entities. The research department applies a simplified design perspective over the general production process, assuming deterministic processing times, no queueing effects, and complete implementation of any completed project's intervention. The production plant instead is forced by reality to work with stochastic processing times and accumulates an intervention backlog due to lack of budget, design issues discovered during roll-out phase, lack of time, etc.

Table 2: Design and plant perspective on the present and future situation

		Situation: As Is	Situation: To Be
Perspective	Design	Simplifications on processing times, all previously developed interventions implemented	Simplifications on processing times, known performance of new interventions implemented
	Plant	Stochastic processing times and delays, intervention backlog from previous projects	Stochastic processing times and delays, unknown performance of new interventions implemented due to intervention backlog

These issues, quantitative analysis complexity and misalignments between design and plant, partially invalidate the preliminary analysis performed to start a project and make it difficult for supervisors in Hengelo – i.e., project managers – to allocate resources to the "right" projects.

We can expand our previous definition of what would make simulation a useful strategic tool, in Section 1.4, as follows: to be deemed a useful strategic tool, simulation should help us to structure the research process at the company, to better gather and generate data, to achieve reliable preliminary analyses, to represent the plant environment in detail, to create various scenarios based on the plant perspective with and without specific interventions in the backlog, and to virtually test the newly proposed interventions which are too costly to test at the real plants.

Knowing the general wind turbine blade manufacturing process, the situation at SBT-NL, and what we expect from simulation to be deemed useful, we search the literature for the most fitting simulation methodology and practical examples of its use.

Chapter 3: Literature Review

In this chapter, the first goal is to answer Q2.

“What simulation methodology best fits SBT-NL improvement process and how can we adapt it?”

To do this, we investigate the literature for simulation methodologies, generate relevant criteria for comparison, choose the methodology that best fits SBT-NL, and adapt it to the company’s improvement procedure.

Then, we search the literature for case studies similar to ours, where DES was applied to the wind energy sector and to industrial manufacturing in general. Insights will be derived from these case studies to answer Q3.

“How has simulation been used in practice?”

Before diving in the literature, an introduction to specific simulation terminology is necessary.

- Methodology: the definition of the Merriam-Webster dictionary is used in this document: “a body of methods, rules, and postulates employed by a discipline: a particular procedure or set of procedures”.
- Validation: the process of ensuring that our idea and simplifying assumptions of the model are consistent with the real system – “building the right thing”.
- Verification: the process of ensuring that what we are programming is consistent with the model concept – “building the thing right”.
- Certification: the process of independently awarding a ‘certificate’, formally attesting that a simulation model fulfils specific quality criteria for a certain scope (Balci 2012); e.g., a third-party certification.
- Credibility: the level of confidence that the project stakeholders have in the simulation model. It is obtained through documenting and reporting, and highly affects the implementation phase.
- Intended uses (or purposes): the set of objectives that a simulation model should achieve within given constraints.
- Reusability: the degree to which the simulation model or its components are capable of being used again or repeatedly. Depending on the intended uses of the new project, it is achievable for subroutines, submodules, the entire model, conceptual constructs, etc.. (Balci 2011).
- Architecting: the process of ensuring that our simulation model “fits” in a network of models and applications or is the founding stone for such networks, obtained by

producing a related architecture specification (Balci 2012); e.g., the High Level Architecture (HLA) standard of the Department of Defense (DoD).

- Composability: “the degree to which an artefact is capable of being constituted by combining things, parts, or elements” (Balci 2011).

3.1 Theoretical framework on simulation methodologies

When reading the literature regarding simulation methodologies, it was noticeable that most of it derives from conference papers, especially the Winter Simulation Conference, and only few from journal articles. This is because simulation is a relatively new subject, which acquired scientific respect in recent years and resorts more on conference proceedings than journals, due to a general bias regarding the mathematical techniques applied – considered a brute force approach – and a lack of knowledge on simulation aspects by editors and referees. Nevertheless, many simulation conferences uphold a wide scientific respect and their proceedings are of high quality (Sargent 2018).

Simulation methodologies usually share a few core steps: Problem Formulation, Conceptual Modelling, Model Coding, Experimentation, and Implementation. They usually differ on the concept the author wanted to highlight when creating the model and their visual representation. In total nine methodologies are analysed stemming from six authors; a summary of the main feature per methodology is shown in Table 3. All the diagrams and flowcharts representing the following methodologies are shown in Appendix A.

The first author is R. E. Shannon (1998), he does not provide a visual representation of his methodology but describes twelve steps to be followed, together with some guidelines. A visual representation was drawn by us to allow for ease of comparison.

The second group of authors is Banks et al. (2010), whom depicted an iterative procedure that separates model conceptualisation and data collection, due to the criticality of gathering valid data. Also, they stress the importance of correctly documenting, reporting and implementing the simulation project.

Following, the popular methodology from A. Law (2007, 2015) was analysed in both his papers, the latter including features and guidelines from Banks’ procedure. Law’s framework is simple, flexible and is complemented with many powerful statistical and data gathering techniques.

Next is S. Robinson (2004), whom based his methodology on Landry et al. (1983) and extensively addresses the validation and verification topic through the whole simulation study. This is the first methodology to display a cyclic concept but it is done in an iteration perspective to better refine the simulation study, not regarding future and different intended uses. He created two diagrams, one regarding the simulation study as a whole and the other to further detail the conceptual modelling phase. The two diagrams were merged by us to obtain a complete representation of Robinson’s simulation methodology, which is shown in Figure 35.

The fifth author is R. Sargent (1984, 2015). He wrote a series of papers regarding his validation and verification (V&V) methodology, where he presented both a simplified and a complex diagram of his methodology but Banks, Gerstein, and Searles (1988) deemed the first to better convey the methodology. He also presented a process flowchart of his simplified cyclic diagram (Sargent 2015), therefore the flowchart was used for evaluation and comparison. Sargent's procedure is simple and iterative, with a strong focus on validation, but does not include the implementation phase.

The last author is Balci (1987, 2012), whom presented a methodology explicitly integrating the life-cycle concept, which is the idea that simulation models are an asset, especially for large and complex models, and should be certified, stored, and maintained for future re-use in a similar context of intended uses. His methodology implements software engineering techniques, like requirements specification and elicitation, to ease both conceptual and coding modelling, and to better validate every step in the simulation study. This approach makes the methodology more complex and detailed, but it is well suited for large simulation projects distributed over different teams, with a high level of detail and which will be part of an existing architecture of models. Only the latest version of the methodology is considered in the comparison, in his linearized versions.

Table 3: Methodologies' key points

First author	Year	Key points
Shannon	1998	Simple, no explicit iteration
Banks	2010	Iterative, separate data collection, supports credibility
Law	2007	Very simple, research focus, supports credibility
Law	2015	Very simple and adaptable, research focus, iterative, supports credibility, used a lot in practice
Robinson	2004	Conceptual modeling focus, extensive validation, highly iterative
Sargent	2015	Extensive validation, highly iterative, no experimentation and implementation
Balci	2012	Extensive V&V and Certification, software engineering perspective, reusability and maintainability focus, life-cycle concept, highly supports credibility

3.1.1 <u>Definition of comparison criteria and selection of methodology</u>

To select the best fitting methodology for SBT-NL, it was necessary to define and select several comparison criteria. The process is conducted in three steps.

In the first step, a large number of criteria was generated based on three approaches: an analysis of what was explicitly written in the papers and books consulted while selecting the methodologies, a visual comparison of the methodologies' diagrams, and a brainstorming session focusing on the blade manufacturing context.

Many criteria obtained from this first step were redundant, therefore a second step of aggregation and rewriting was performed, which resulted in a long list of criteria shown in Figure 12.

Long list:

- 5 fundamental steps present (Problem Formulation, Conceptual Modelling, Model Coding, Experimentation and Implementation)
- Simplicity
- Flexibility
- Life-cycle concept
- Research focus
- Data validation
- Supporting credibility
- Focus on Problem Formulation
- Focus on Conceptual Modelling
- Focus on Model Coding
- Focus on Experimentation
- Focus on Implementation
- Validation during Problem Formulation and Conceptual Modeling
- Validation during Implementation
- Verification of coded model
- Detailed modularization and division of project in areas.
- Integration in the architecture and business system
- Support in identifying new improvements

Figure 12: Long list of generated criteria

In the last step, a short and meaningful list of criteria for SBT-NL was generated, together with a knock-out criterion, and is shown in Figure 13. When looking at the long list, some considerations were made regarding the research department and the future uses of the simulation methodology:

- It is the company's first attempt to apply simulation, in a specific case (wind turbine blades manufacturing) that is relatively new for simulation studies. This implies that some steps will have to be performed over and over until satisfactory results are obtained (simplicity, iteration).
- The company will expand from this methodology and apply it to different plants, which are similar, but not the same (life-cycle concept).
- Data gathering is still in its prime regarding manufacturing processes and must be thoroughly checked. Furthermore, simulation output is useless without reliable inputs (data validation).
- There is a large geographical distance between the simulation analysts and the experts at the plant, thus there is need for continuous and clear reporting to managers to ensure support and resources (credibility).

- The goal of the simulation is to increase the knowledge on the manufacturing processes and compare different proposal for plant improvement (research focus, which requires reliable statistical techniques).
- There is no need to focus on other specific parts of the simulation study as it is not known yet what will be harder to perform in this business context, and because by selecting a simple methodology, it can be easily expanded to cope with future issues.
- Also, detailed modularization is not necessary, because each simulation study is going to be of small size, with small teams and on a helicopter-view level of detail of the manufacturing plants.
- Moreover, there is no existing architecture or simulation management system in the company and it is currently not necessary, therefore architecting (and integration) is not selected.
- Lastly, while generating new interventions is important to the company, it is of primary concern to assess their effectiveness on the processes, their effects on the production plant as a whole, and to prioritise them.

The knock-out criterion was deemed necessary to assure there will be guidelines explicitly supporting the inexpert analysts through the whole simulation study.

Knock-out criterion:

- 5 fundamental steps present (Problem Formulation, Conceptual modelling, Model Coding, Experimentation and Implementation)

Short list:

- Simplicity (easy to grasp procedure, adaptable to company needs)
- Flexibility (iteration and backtracking)
- Life-cycle concept (reusability, maintainability)
- Research focus (statistics and comparison)
- Data validation (checking data, gathering it accurately)
- Supporting credibility (stakeholders involvement and communication)

Figure 13: Short list of generated criteria with knock-out criterion

With the current set of criteria, a comparison is performed between the methodologies mentioned in Section 3.1 and summarised in Table 4.

When assigning a tick to the methodologies for a certain criteria, we do not mean to state that the methodology is perfectly addressing the issue or, vice versa, completely missing it, but we mean to represent an explicit and satisfactory focus regarding that feature, possibly comprehensive of specific guidelines, tips and techniques. Moreover, Sargent's methodology was knocked-out of the comparison, because it does not address sufficiently model coding, experimentation and implementation, even though it describes in detail the problem formulation and conceptual modelling phases.

Based on the comparison, a final choice between Law's 2015 model and Balci's model was made by the company stakeholders. Balci's methodology is considered to be more on the software engineering perspective, for large and advanced simulation studies, which will be part of an already existing federation of simulation models (or the start of one), thus it was discarded, even though it is the only one clearly addressing the life-cycle concept.

Law's model from 2015 is the chosen methodology for SBT-NL due to its simplicity, flexibility and extensive statistical support.

Table 4: Comparison of the six authors, based on the chosen criteria

Final criteria	Shannon	Banks	Law 2007	Law 2015	Robinson (integrated)	Sargent (simplified)	Balci
5 Core steps	Yes	Yes	Yes	Yes	Yes	No	Yes
Simplicity	V		V	V		V	
Flexibility		V		V	V	V	V
Data validation		V	V	V	V	V	V
Research focus	V	V	V	V			V
Supporting credibility	V	V	V	V	V		V
Life-cycle concept							V
Total	3	4	4	5	3	Knocked-out	5

3.1.2 Adaptation of the chosen methodology

Being simple and flexible, Law's methodology was easily integrated in the pre-existing decision-making procedure, see Figure 14. Five steps were added to the original flowchart from Law (2015): the cross-functional team idea generation, the choice of using simulation, the alternative approaches to simulation, the updating and storing of the generated model, and the comparison with other interventions. Two steps were slightly modified: the first to explicitly include the possibility to (partially) reuse a previous model, namely "Collect data, define and/or reuse a model", the second to focus the experimental design step on different plant scenarios.

The idea generation is a prior responsibility of the research teams and does not require additional explanations.

Conversely, understanding when to perform a simulation study can be considered part of the simulation methodology and crucial part at that, to avoid embarking on an expensive project when results could have been achieved with analytical models, as it is already done in the company. Law (2015) describes the reasoning that leads to a proper approach when studying a system, this is the procedure that we applied at the end of Section 1.4.

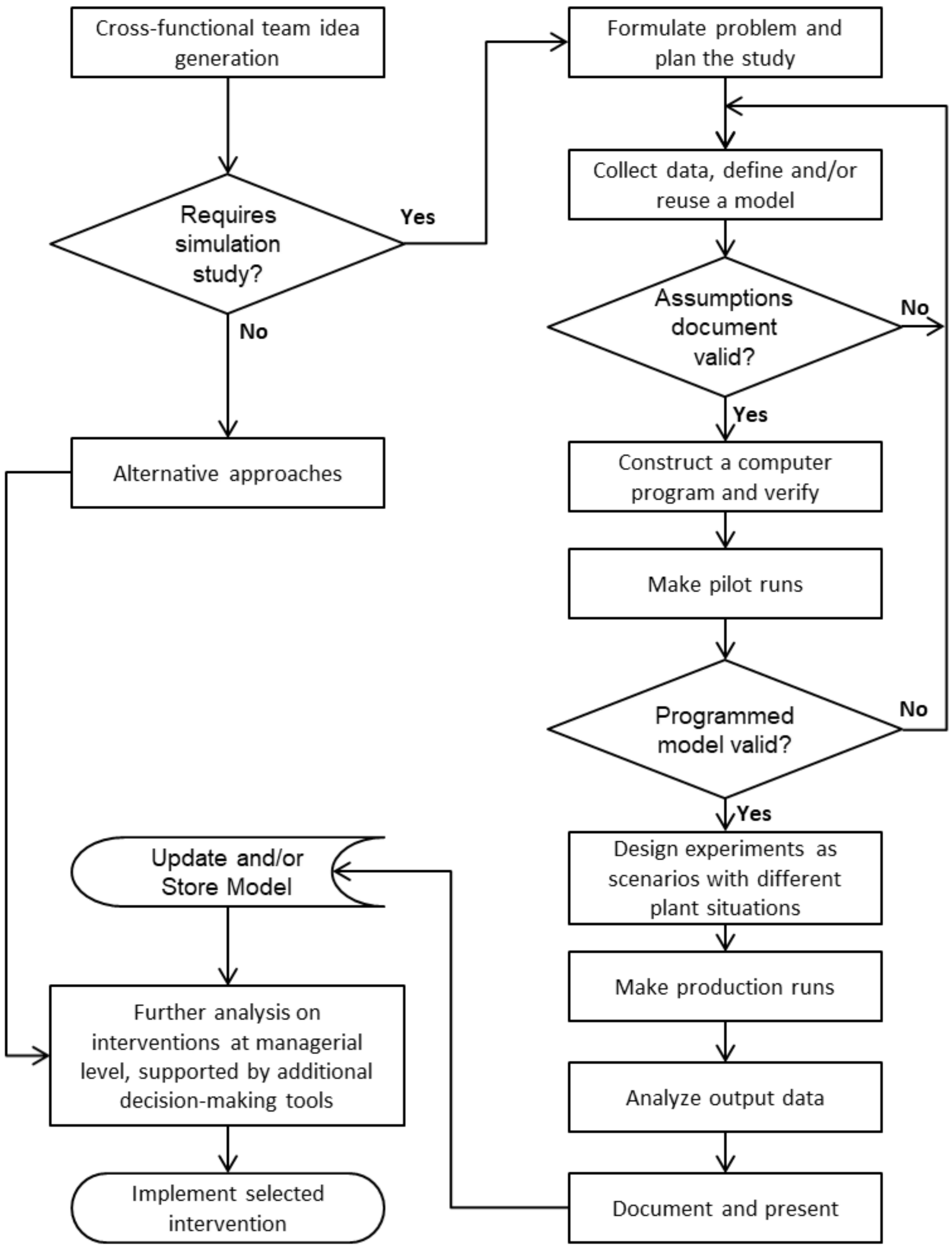

Figure 14: Methodology for the new improvement procedure of SBT-NL, adapted from Law (2015).

The experimental design step will be crucial to reduce the uncertainty effects of the information gap between design and plant situation. We can test the new (and old) interventions using plant data against design data, or different combinations of the two, which will correspond to different level of alignment of plant production to the design situation. Therefore, we will obtain alternative performance results for each intervention varying on the range of plant alignment to design, allowing for a more accurate and flexible prioritisation of new projects and projects still in the plant backlog.

As suggested by Balci (2012), the storage of simulation models should also comprehend sub-models, documentation and data; it should be done in a repository, which can be accessed by the whole organisation and with metadata to facilitate access. Regarding reusability, he suggest that a previously developed model should always be checked for its credibility regarding its intended uses and their match with the new project intended uses. Any change to an earlier developed model or its sub-models will require new verification and validation efforts of the entire model. Furthermore, the hardware and software (programming language, operating system, simulation program) differences should be taken into account when reusing a model.

To allow for effective Reuse & Composability (R&C), Balci et al. (2011) suggest to focus on Conceptual Models (CMs) with a high level of abstraction and conceptual constructs for the specific problem domains. This approach bypasses hardware and software differences as well as specific modelling design, and points to the highest R&C achievability, as shown in Figure 15. The focus on conceptual constructs helps analysts in designing many different models in the same problem domain, and enables better communication between stakeholders involved in model development. We refer again to the paper of Balci et al. for the full list of benefits achieved when focusing on CMs.

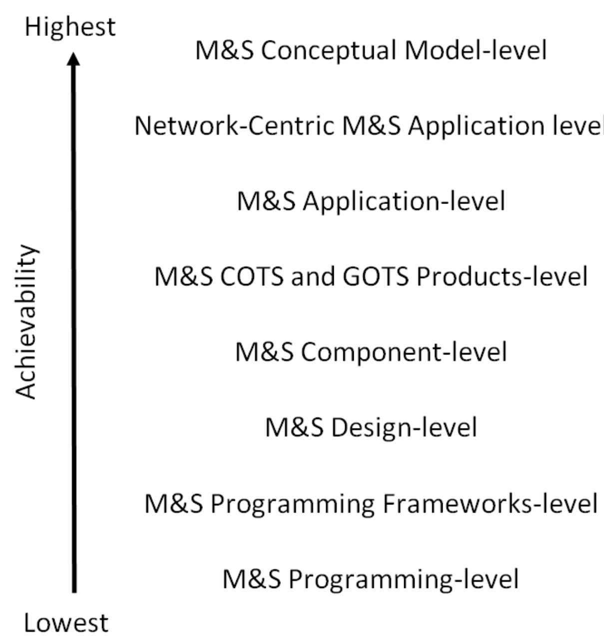

Figure 15: Achievability of Reusability & Composability at different Modelling & Simulation (M&S) levels, adapted from Balci et al. (2011).

Comparing interventions of different teams is the responsibility of the middle management, which should now be eased in the process by the scenario analysis performed. However, since the simulation results will be based on stochastic and deterministic analyses, it is advised to have statistical grounding in the generation of other alternatives, to better compare them. Also, the comparison could be performed following different methods, for example the Analytic Hierarchy Process (AHP) from Saaty (1990). The addition of a decision-making tool like the AHP would complement the simulation outcome by including criteria that are left out from the simulation study, be it due to simplifying assumptions or lack of data, e.g., the cost of an intervention. Also, it can include qualitative considerations in a quantitative fashion, e.g., the difficulty of implementation of an intervention.

3.2 Simulation in practice

After selecting a simulation methodology, we want to further prepare ourselves by widening our knowledge on the application of simulation in the wind turbines field and for general manufacturing. This knowledge will serve to support our use of DES in giving advices on interventions for wind rotor blade production. Furthermore, we hope to gather insights that may prove useful in our simulation study.

A quick literature search is enough to notice the most common applications of simulation in wind turbines' field:

- Structural testing of whole wind turbines or blades in different wind speed scenarios, e.g., Jensen et al. (2006).
- Performance evaluation of wind turbine blades design and wind turbine wakes in different wind inflows, e.g., Troldborg et al. (2007).
- Designing or optimisation of individual forging, moulding, and thermal processes in general for blades and their components, e.g., Bariani et al. (2004).

Regarding general observations, we refer to Sturrock (2019). He performs an analysis on the possibilities of DES for the growing concept of Industry 4.0, by discussing various case studies in fields where simulation was applied extensively and successfully, e.g., healthcare, logistics, manufacturing, defence contractors. He summarises the perks of simulation in practice as the strategic capability to predict the performance of alternative interventions and identifying areas of risk before implementation, and the organisational capability to establish a knowledgebase, aid communication and create a shared standard for data, systems and processes.

We could not find specific papers on improving the productivity of a blade manufacturing plant or a set of processes, where queueing effects, delays, stock outs, or handling equipment were considered. However, we came across three specific simulation studies that can be closely related to ours.

The first simulation study is an application of DES combined with cost analysis for the optimisation of an automotive component produced through liquid composite moulding, a process similar to that of blade moulding. The authors (Kendall 1998) recognise how the typical paradigm in process improvement tends to focus on individual processes or on individual stages, and suggest an improvement approach that focuses on the integration of each stage. This is the same situation we are faced with in blade production: the focus is on improving single mechanical or thermal processes and not on considering the overall balancing of the line or the production flow.

In the paper, Technical Cost Modelling (TCM) is used together with simulation modelling to compensate for the difficulty of including costs in DES, not just for equipment but also for material, process variables, and changing economic scenarios. On the other hand, the traditional TCM approach is substantiated to often underestimate manufacturing costs because it estimates the cost of each process as a standalone entity, without considering the interactions between processes during production. The authors suggest using TCM and Simulation together can solve both problems and that DES is useful in evaluating various future production scenarios. The article of Kendal et al. represents a practical instance where an approach similar to ours has been used in the composite moulding production. It also provides us with a suggestion for further research on the addition of costs in the simulation model through TCM.

The second practical application of DES we use to justify our research approach is a case study conducted by Brown & Sturrock (2009) for a Heating, Ventilation, and Air Conditioning (HVAC) manufacturer by Deloitte with the DES software SIMIO, where simulation is used to evaluate different scenarios with process interventions to reduce WIP and increase productivity. The manufacturing system described by the authors has many similarities with our blade production:

- A manufacturing lead time of the final products of 7 day, which is shorter but similar as in order of magnitude (days) to the lead time of a blade.
- The presence of a kitting logic in one of the departments producing components to be assembled into the final product.
- The assembly line moves at the pace of the slowest process on the line, because all processes are connected by a conveyor belt. In our case, the manufacturing flow is not connected by a conveyor belt but by cranes that move blades from one station to the other. Similarly, the blade production pace depends on the slowest process because new blades will have to wait for the stations to be available before transportation can be performed and the sequence of tasks is fixed for all blades.
- Both production systems have resources shared between different stations, in the paper it was due to the sharing of workforce while for us it is the crane resource.
- Downtime and breakdowns are not considered in the study because of negligible effects, which is an assumption we also make.
- The simulation study was performed in an operational environment new to the analysts and within a company with limited modelling experience.

The analysts first created a baseline version of the model and proceeded to add processes, the interactions of components, and details in a modular additive fashion, which is what our simulation methodology also suggests. Through the testing of multiple interventions, the study achieved reliability and agreement on significant results attainable regarding WIP, throughput and reallocation of workforce. Moreover, the authors stress the importance of achieving credibility with clients and stakeholders participating in the study, by means of: white-boarding the model and guiding the client through the simulation approach. This helps to foster discussion on assumptions and data. Another way to foster credibility is to include the company's programming experts in the process of reviewing the model, and the reuse of client's models which have already gained acceptance. Aside from performance improvements, the simulation study raised questions about given concepts of the production system, e.g., the use of a conveyor belt instead of other movement systems. They conclude that simulation can provide a different perspective and help discussing production line assumptions, leading to radical system changes.

Due to the strong parallelism between the two production systems, on a high-level process perspective and on the level of experience with simulation within the companies, we have confidence in the potential of performance improvement through DES in our blade production plant and plan to focus on bolstering the credibility and acceptance of our simulation model.

The last practice case we present to the reader is a DES project led by Hughes (2019) that employs the same software we will be using in our simulation study, Tecnomatix Plant Simulation, in the aerospace field. The software is used to create a 3D representation of a plant still undergoing construction, producing high-tech components for Boeing's 737, 737 MAX, and 767 aircrafts. Using the model, the analysts wanted to validate the current production concepts and test alternatives to increase productivity in a risk-free environment, with the final goal of the model being the first step in establishing a digital twin factory following the Industry 4.0 paradigm.

The simulation study described in the paper of Hughes follows the general approach that we describe in Section 3.1. What we are interested in is the approach related to 3D simulation in practice and the lack of data due to the plant not being operational: the team led by the author collected 3D drawings for layout and machinery, gathered conceptual data on the production from cross-functional teams assigned to the plant project, built a first 2D model version, validated it and then translated it into a 3D graphical version. When adding 3D features, care had to be put into correct representation and orientation of machinery and processes, as the level of process detail that is graphically shown influences the ability of decision-makers to examine the default scenario and evaluate scenarios with different interventions. When using 3D simulation, Hughes suggest to setup a highly detailed digital model, also in the perspective of the transition to a future digital twin factory.

We conclude that problems deriving from lack of data can be effectively minimised by including many stakeholder in the study from different company functions, even when modelling high-complexity production and products. This allows for the unification of distributed fragments of knowledge into a proper data set that can be used for an acceptably accurate model of the system. Furthermore, we set on creating a detailed 3D model, to increase the ease of use of simulation as a strategic tool for decision makers in SBT-NL.

Figure 16 and Figure 17, screenshots of the 2D and 3D model of the Boeing facility respectively, give us a practical idea of what can be achieved with the DES software regarding representation of the system and conveying of the simulation model to stakeholders of the study.

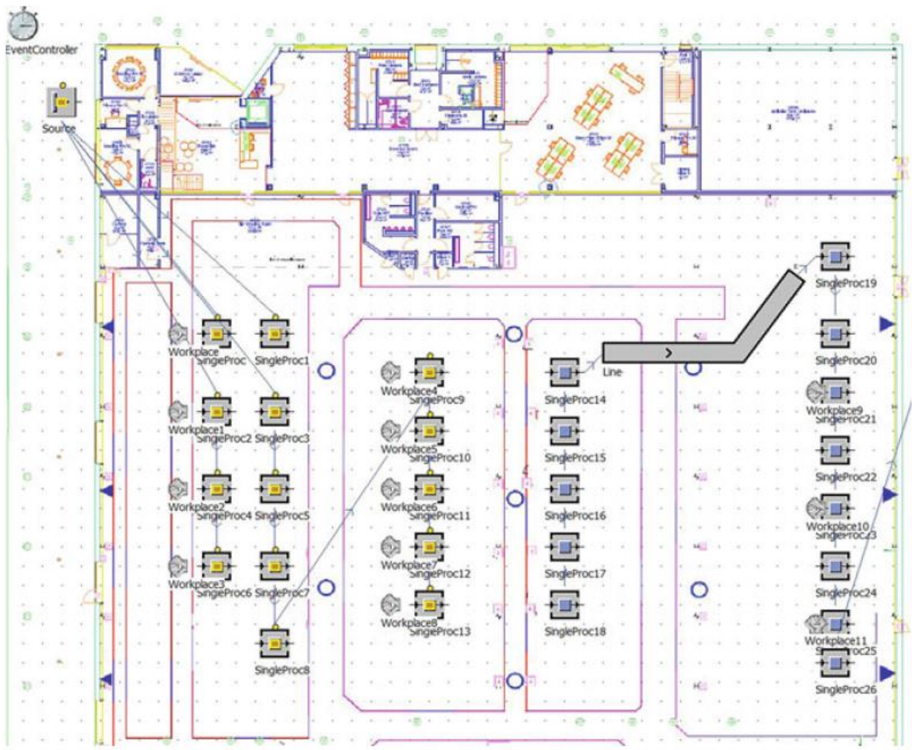

Figure 16: 2D representation of Boeing’s facility (Hughes 2019)

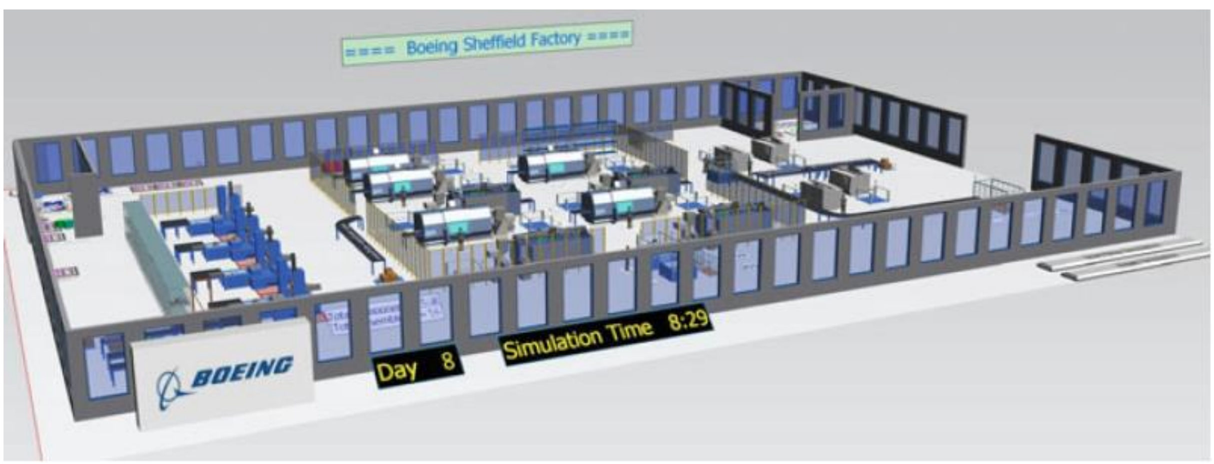

Figure 17: 3D representation of Boeing’s facility (Hughes 2019)

We widened our knowledge on simulation methodologies, compared and chosen one, and lastly adapted it. Moreover, we looked for practical insights from other simulation projects, performed in fields similar to that of wind turbine blade manufacturing. The next logical step is to perform our own simulation study using the adapted methodology, in order to assess its applicability to Suzlon’s blade manufacturing, its usefulness, and provide a future guideline for the company.

Chapter 4: Building the simulation model

In the past, the research effort of SBT-NL focused mostly on blade design, blade materials, and mechanical properties. In this study, the focus will shift to process design, to create a balanced production system and align to the growing demand for wind turbines. To improve the production system, it is first necessary to represent it in a suitable media, which allows for quantitative as well as qualitative analysis. Such a tool is usually called the model of a system and the information necessary to its creation will be provided by answering Q4.

"What information do we need to create a detailed digital model of the manufacturing plants?"

The chapter will describe the modelling steps presented in Law's simulation methodology as they were applied to the blade production plant, to provide a foundation for future models in SBT-NL and increase the credibility of its results. The answers to Q3 sub-questions will be found throughout the chapter.

Following the methodology, we should perform these steps when creating a valid and verified simulation model:

1. Formulate problem and plan the study.
2. Collect data, define and/or reuse a model.
3. Check validity of Assumptions document.
4. Construct a computer program and verify.
5. Make pilot runs.
6. Check validity of programmed model.

4.1 Formulate problem and plan the study

Chapter 1 stated the goal of the project and the core problem to tackle. In Section 2.4 the definition of simulation as a useful strategic tool was expanded. However, the objective of the simulation study itself is only a part of the main goal and it is focused on the core problem: *to gain quantitative knowledge about the overall plant performance, about the effects of the misalignment gap described in Section 2.4, and the best implementation schedule for the interventions considering the previous two points*.

To do so, we first create a detailed digital model of the current plant comprising the four main production phases and the handling equipment, and evaluate it using as input the processing times based on the design (deterministic) perspective and the plant (stochastic) perspective. Then, we want to include the process interventions and the backlog as different scenarios and again evaluate them under both perspectives. All the models will have a 2D and 3D version to represent the handling equipment in the design perspective and in the plant perspective respectively.

However, more has been set when planning the simulation study, thus we will now give more information regarding the simulation software, the Key Performance Indicators (KPIs) that will be used to evaluate proposed system configurations, and the selected experts.

The chosen DES software, Tecnomatix Plant Simulation, is from Siemens. It is object-oriented software with inheritance structure, which promotes reusability and composability, makes model changes easier, and allows for better user understanding of the system (Law 2015; Derrick, Balci, & Nance 1989).

The KPIs chosen by the management of SBT-NL are:

- Average Blade Production Pace (PP): period of time between the completion of two time-subsequent blades at the production plant.
- Average Blade Finishing Lead Time (FLT): the average time between the start of finishing area operations and completion of a blade.
- Monthly average number of Components Stock-Outs (CSO).
- Monthly average number of Materials Stock-Outs (MSO).

These KPIs were selected based on the type of interventions that are simulated, which directly impact the Blade Finishing area and the Blade Production Pace, as well as indirectly increase the requirements for components and materials.

During our simulation study, we received support by many company stakeholders both in Hengelo and in India. The experts selected from Hengelo are senior engineers that have been at the production plants in India and know details regarding the whole plant as well as crane movements. With their help, the production process was streamlined and simplifying assumptions were made to exclude unnecessary details from the model, which do not substantially increase representativeness. The expert selected from India is a direct subordinate of the plant manager whom was already assigned to our research department to provide information regarding the plant, also called Single Point Of Contact (SPOC). He provided us with data on real processing times, rated characteristics of handling equipment and machinery, and updates on the production stage compared to design.

4.2 Collect Data, define and/or reuse a model

The management selected a type of blade to study, from the 2 MW blades platform, and a production plant for the study, the Ratlam plant, which produces only one type of blade. The first sources of data analysed were the Design Cycle Time documents of the blade, which presented the deterministic processing times of each task in the four blade creation phases together with the task order, and the Ratlam plant layout, which was used to determine the number of stations per task and the location of stations and storage areas. Now, we present the specific blade production process for blade created at the Ratlam plant, as per design documents in Figure 18.

The Ratlam plant follows the same general procedure described in Section 2.3. It is operational for six days a week and non-stop for the day, for an average of 24 days in a month, which is obtained by excluding Sundays and holidays throughout the year. Moreover, remind that the plant is daily organised in three work shifts of 8 hours, but in our model we do not consider the breaks in between shifts, as they're negligible based on experts experience. The Blade Lead Time (BLT) at Ratlam is defined as before, with the added detail of the FLT being divided in seven different task lead times (tasks *BF1* to *BF7*), which are present in its BF phase.

$$Blade\ Lead\ Time_{(DMT,BF1,BF2,BF3,BF4.BF5,BF6,BF7,CM,CD,RD)}$$

All processing times in the MP and CP phases will be defined as a percentage of the Design Moulding Time (*DMT*) to better visualise the materials and components consumption rate by the BM phase. However, the *DMT* values will not be disclosed due to industrial secrecy. The remaining process times are also kept from the reader, aside for task BF7 which is subject to the main intervention and for the *FLT* as a whole, to allow for evaluation of the simulation results.

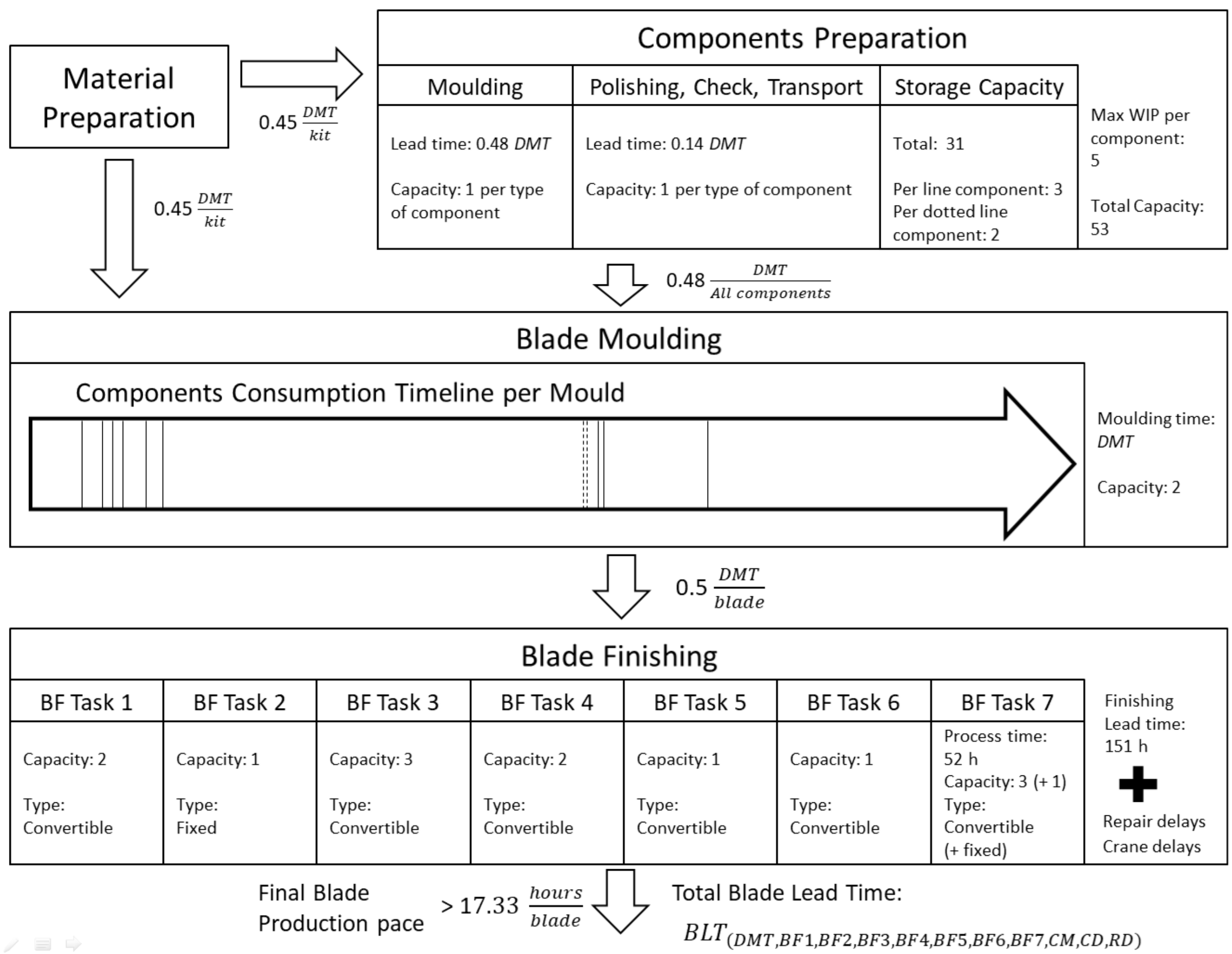

Figure 18: Blade production phases at Ratlam plant, station details, and plant performance on average as in design documents

The MP department sends the cut materials to the CP and BM areas every 45% of the *DMT* on average, because that is the longest time required for the materials in the kits. These materials are used in the production of the components required for 2 MW blade at the CP phase, and the two blade moulding stations present in the BM area of the Ratlam plant.

In the CP phase we have eleven unique components, with their respective component moulds, and a polishing area large enough to contain all of them at once. In general, the lead time to produce one artefact is slightly longer than the time for producing kits, with the longest component taking 48% of the *DMT* on average.

Of the eleven components necessary for a blade, nine components have a storage area containing three pieces, while two unique components have a storage area containing two pieces. The maximum WIP for each type of component is then five and four respectively, with a total maximum WIP of 53 for the CP phase.

As briefly mentioned before, our case study plant can mould two blades at a time, thus allowing for one blade to exit the BM phase on average at half the *DMT*. Production is scheduled based on customer demand but the demand (plus the backlog of orders) is very high, thus requiring blades to be produced constantly. As soon as a the moulding stations complete a blade and there is an available station at the next task, the blade is transported to the next operation and a new blade starts the moulding process. Therefore, the blocking effect of unavailable stations in the BF area slows down production when the manufacturing line is not balanced. Moreover, to balance resource requirements during the BM phase and the successive phase, the two blades have a time gap between the start of each which is also half the *DMT*, this keeps the blade production shifted and reduces blocking effects. The production logic and the start gap can be modified in the model, but we will not do so during this assignment.

The consumption of components by the BM area is shown as (dotted) lines on the moulding timeline in Figure 18. The eleven unique components from the CP phase are inserted in the blade during its moulding at different times, but we can state that on an aggregate level the BM requires eleven unique components every 0.5 *DMT*, which is its production pace.

In the BF phase, a total of seven tasks is performed:

- Task 1 has a capacity two convertible stations
- Task 2 has a capacity of one fixed station.
- Task 3 has a capacity of three convertible stations.
- Task 4 has a capacity of two convertible stations.
- Task 5 has a capacity of one convertible station.
- Task 6 has a capacity of one convertible station.
- Task 7, the batch formation, has a capacity of three convertible stations (mass addition and related operations) and one fixed station (weighing).

A blade has lead time of 151 hours by design perspective to undergo all processes in the BF area, and on average a blade is released every 17.33 hours by the production plant. Noticeably, the bottleneck of the system is not the Blade Moulding phase but task 7 in the BF phase, already by design perspective.

Lastly, we provide details on the cranes and use Figure 19 to better convey the handling logic. There are currently two main crane couples (in yellow) being used for blade transportation from the BM area to the BF and its sub-stations, and one smaller crane couple (in green) to move the larger components along their production stations and to the BM area. When moving a blade from station to station, a time of 30 minutes is required, based on experts experience. The time required for crane movements is referred to as *CM*, the crane delays due to crane requests overlapping are referred to as *CD*.

We divided the plant in five areas: two are shared areas between cranes and three are default areas assigned to a single crane couple, to move back to when freeing shared areas and avoiding collisions. We assigned the areas to cranes as follows.

- Area 1 is the default area of the smaller crane, where it moves components from their moulding stations to their polishing area.
- Area 2 is a shared area, where the smaller crane moves components to their storage and then to the first moulding station, while the middle main crane moves component from their storage to the second moulding station in Area 3 and moulded blades from the first moulding station to the start of the BF phase in the lower half of Area 3.
- Area 3 is the default area of the middle main crane. Here, moulded blades from the second moulding station are retrieved and moved to the start of the BF phase.
- Area 4 is a shared area between the middle main crane and the right main crane. The stations in area 4 will first request the right main crane for transportation. If that crane is busy, they call the middle main crane when the blade has to be moved to another station in area 4, otherwise wait for the right main crane. If a blade is to be transported to area 5, the stations always wait for the right crane.
- Area 5 is the default area of the right main crane. The right crane moves blades through their final operations and lastly loads them on the trailer when it is available. We modelled the loading task on the trailer to have priority over any other requests for the right crane, to prevent the plant from stopping due to a an excessive WIP of blades in the BF area.

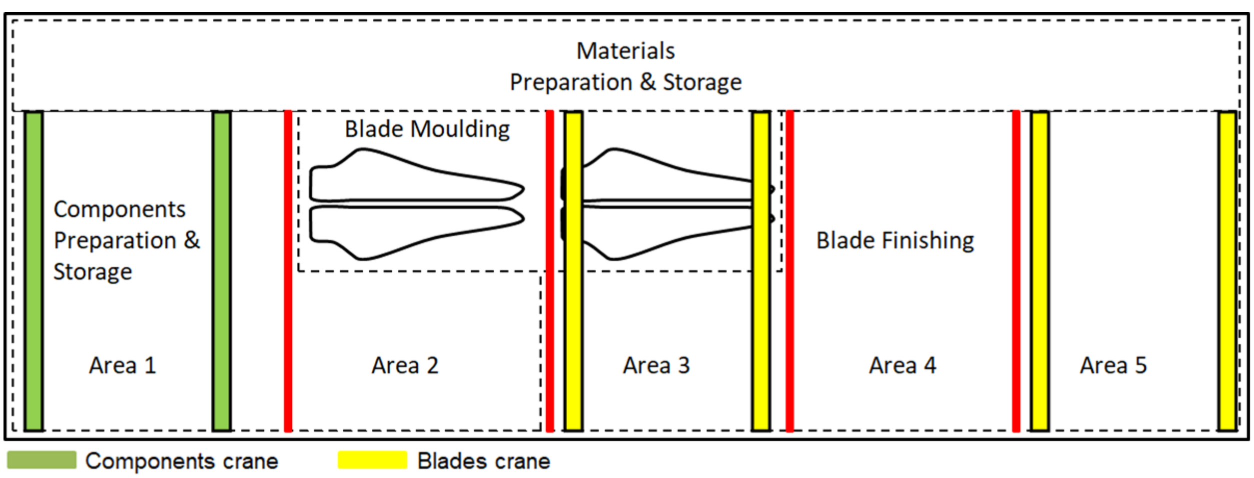

Figure 19: Cranes and allocated areas in the plant

Moving on to the plant perspective version of the model, data on the actual processing times has been gathered by our SPOC at the Ratlam plant in India, and used to fit a probability distribution for each task: due to the production being on halt during the simulation study, and a consequent lack of observations on the processes, triangular distributions were used to represent all tasks' processing times. Also, the number of distributions to fit is over fifty, which would require extensive time when performed for distributions more complex – but potentially more accurate – than the triangular.

To use a triangular distribution, we were provided with the minimum, maximum, and mode processing time for each task, as in the experience of experts working at the plant (i.e., team leaders at the shop floor). Furthermore, a random seed is assigned automatically to every unique process by the software. By using the same random numbers while experimenting with different system configurations, we reduce variance and exploit a positive correlation. This technique is called Common Random Numbers and is also sustained by Law's methodology.

Due to the two perspectives, design and plant, and to the project backlog defined in Section 2.4, the deterministic processing times, also called DCTs, and stochastic processing times, also called ACTs, were systematically divergent for most tasks. For example, a task had an ACT that was at minimum several hours longer than the corresponding DCT. Therefore, two versions of the model were created: one using DCTs as input and representing the situation using the simplified design perspective, i.e., deterministic processing times and no project backlog; the other using ACTs as input and representing the situation by plant perspective, i.e., stochastic processing times and the effects of the project backlog on processing times.

Note that team leaders did not provide us ACTs for cranes, the forklift, and the trailer, instead they gave us values for transportation that are more conservative than their corresponding DCTs (e.g., 60 minutes instead of 30), as that is the way they try to account for system queues in the single processes using the design format. Therefore, for the plant perspective version of the model we use nameplate data, e.g., speed per type of movement, size, etc., for cranes, the forklift, and the trailer. This, together with the 3D visualisation of the model, allows us to represent cranes, the forklift and the trailer as realistically as possible, and overcome the lack of observations and knowledge on the handling processes. We kept the plant division in areas and crane allocation, as shown in Figure 19, also for the version of the model using the plant perspective. Furthermore, the addition of 3D features allows us to easily represent the distances and sizes of equipment taken from layout drawings, but also allows for a better graphical validation of the model for senior engineers in Hengelo that have real experience at the production plant.

Finally, we obtained the two model versions based on different input data, and another two variants for each model version depending on the use of 2D or 3D modelling for cranes, the forklift and the trailer:

- A design perspective version of the model in 2D, using DCTs, no project backlog, and simplifying assumptions on cranes movements.
- A design perspective version of the model in 3D, using DCTs, no project backlog, and more realistic crane, forklift and trailer movements.
- A plant perspective version of the model in 2D, using ACTs, the effects of the project backlog, and simplifying assumptions on crane movements.

- A plant perspective version of the model in 3D, using ACTs, the effects of the project backlog, and more realistic crane, forklift and trailer movements.

Since this is the first simulation study on process design at SBT-NL, a new conceptual model was created in the form of an assumptions document. This document contains all the gathered data as well as the information stated in this modelling procedure and diagrams to represent the model structure.

The conceptual model is composed of different levels, or layers, which gradually move deeper into the process details and sub-task. The highest level is presented in Figure 20, with the inputs required and KPIs gathered at that level of detail, and attributes of the blades initialised at the start of the simulation. Elements of the conceptual model with red borders have sub-levels that comprise the tasks performed at each plant area, other inputs (e.g., processing time of tasks, number of stations), and intermediate KPIs (e.g., stations utilisation, crane utilisation). The other model layers are presented in the assumptions document in Appendix E.

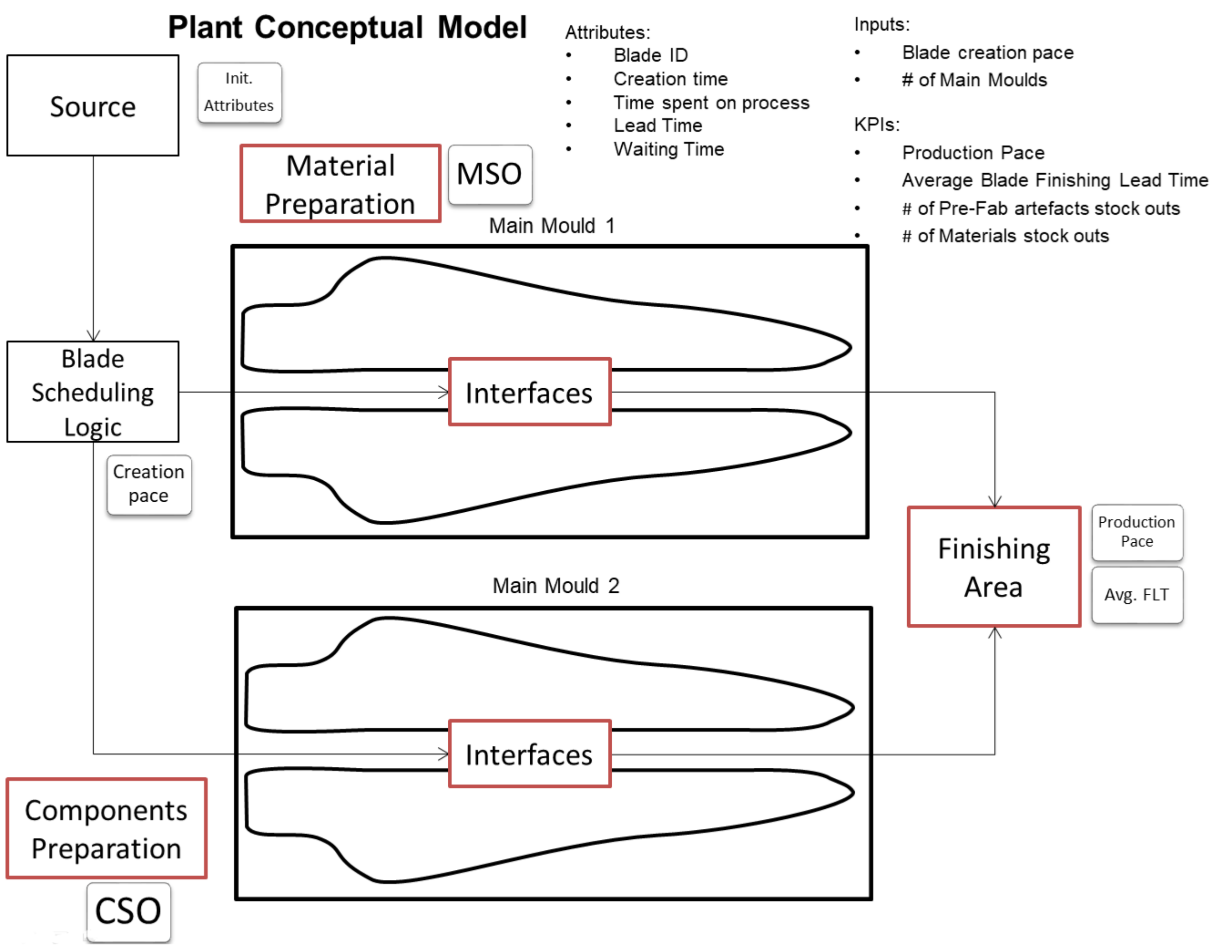

Figure 20: Highest level of the Conceptual model

When defining the model, it is necessary to make assumptions to avoid unnecessary complexity. For example, we decide not to include workforce in the current version of the model, due to the high number of workers in the plant and the lack of data on their allocation to tasks, which is left completely to the plant managers and changes continuously. Also, we assume not to consider the availability of tools and machinery, again due to a lack of data. These extra details would surely influence the performance of the plant model, but it would require a long time to obtain reliable data to implement them and it would increase the complexity of the model greatly. Considering that SBT-NL is new to this type of process simulation, the trade-off choice tipped towards excluding such features.

Furthermore, in our simulation models we want to represent the queueing effects and delays between stations in the plant. These queueing effects are not considered in the current design DCTs and design perspective, as the general idea is to optimise each process individually and have cascade effects on the overall system. The creation of a simulation model, which evaluates the performance of the integrated processes composing blade production, will allow us to test the accuracy of this design assumption.

Lastly, it is necessary to understand the effects of initial conditions and output analysis on the model to better represent the real system. A system's behaviour over time can either be defined as transient or steady state:

- Transient: the system's performance is influenced by initial conditions and by the run length of the simulation.
- Steady state: the system's performance does not depend on initial conditions after a certain minimum run length, which is called warm-up period, and will vary in a range around a certain stable value.

Moreover, a simulation model can either be defined as terminating or non-terminating:

- Terminating: a natural event specifies the end of a simulation run, which increases the influence of initial conditions and leads to transient behaviour.
- Non-terminating: no natural event to specify the end of a simulation run, which usually leads to steady state behaviour.

Ideally, the plant in India should never stop and empty the production line due to events that are part of the normal schedule, thus the model is considered to be a non-terminating simulation. Furthermore, after a ramp-up phase, the production stabilises and variations in the flow are due to process variability. Therefore the model is considered to have a non-terminating and steady state output. This influences our choice on the KPIs to be measured: non-terminating and steady state outputs are usually measured in averages over the simulation runs, which is coherent with our KPIs selection in the previous section.

Now, we summarize the inputs, assumptions, and collected outputs used to create the conceptual model.

The inputs:

- In the design perspective version of the model, processing times and transportation times are deterministic. We have taken them from design documents regarding the MP, CP, BM, and BF phases.

- In the plant perspective version of the model, processing times are represented with a triangular distribution. The data was collected by our SPOC from team leaders at the plant, managing the MP, CP, BM, and BF phases.
- The blade production is continuous and a new blade is started as soon as the blade moulding station is ready. Furthermore, there is a gap of 12 hours between the two different blade moulding stations, to reduce the level of WIP and the queuing effects on the line.
- We obtained the number of stations per process and their layout in the design documents regarding the sequence of tasks for the 2 MW blade and the layout drawing for the plant in Ratlam.
- The crane logic that we use in the model to pair up the cranes and to assign different cranes to different tasks is based on experts' experience at the plant.
- In the 3D versions of the model, we use nameplate values to model the behaviour of cranes, the forklift, and the trailer, e.g., speed per type of movement, sizes.
- Lastly, we create the 3D version of the model by importing and converting 3D drawings obtained by colleagues in the research department.

The assumptions:

- We assume workforce not to be a cause of delays.
- We assume Tools and handling equipment availability to be 100%.
- We assume Aiding materials (commodity items) to have negligible effects on the system.
- We assume transportation time of raw material kits to be negligible.
- We assume the management of the storage yard to have negligible effects on production and enough area to park all necessary blades.
- For the crane logic, we assume the addition of the plant division in areas and the allocation of cranes to default areas, as shown in Figure 19, to have negligible altering effect on the performance of cranes.
- We assume production to have a continuous flow and breaks between work shifts to be negligible.
- We assume for all blades to require the mass addition operation in the last task of the BF area.

The collected outputs:

- The two KPIs for the BF area lead time and the production pace are collected as averages over the simulation run, FLT and PP respectively.
- The two KPIs for components and materials stock outs are collected as monthly averages, CSO and MSO respectively.

4.3 Check validity of assumptions document

Before programming the computer model, the assumptions document was validated by means of two structured walkthroughs, where three senior engineers were invited and identified assumptions to be improved, added or removed. At the end of the validation step, an agreement was reached on our assumptions on processing times, both DCTs and ACTs, on the operations schedule and logic, on machinery, cranes and tools. Validating the assumptions document before entering the coding phase supports model's credibility and prevents significant reprogramming afterwards.

4.4 Construct computer program and verify

The process as modelled in the computer program is shown in Figure 21 and an overview of the control panel (or root frame) is shown in Figure 22. The simulation starts with the initialisation of stocks levels for materials and components, the first step for both corresponding rows in Figure 21, then the normal moulding process follows for the blades, the components and the materials. The production of blades, components and materials is performed in parallel and continuously, as mentioned in Section 2.3 and 4.2: when the blade or component moulding starts, materials are required and stocks are decreased, if available.

If there is no material, stock out data is stored and the process requesting it is set on hold until new stocks becomes available, then stocks are consumed and moulding continues. This is shown in the Material Preparation row of Figure 21. The same happens for the blade moulding phase when requesting components, either stocks are decreased or stock out data is stored and the task is put on hold until the stocks of the required component are replenished. The movement of components to the blade moulding stations activates a crane request for the smaller couple. This is represented in the Components Preparation row of Figure 21.

The blade moulding process is modelled with greater detail and represented with subsequent operations. When these operations are performed in parallel, we aggregated them in the software as single tasks creating new ranges for the triangular distributions with conservatives assumptions on processing times, e.g., taking the earliest start between aggregated tasks and the longest minimum, mode, and maximum between their triangular distributions data. Moreover, we decided to preserve the tasks where placement of a component on the blade moulding station is performed. During the BM phase, processing times for each operation and delays due to stock-outs or shift breaks are gathered. Then, the gathered data is stored in a table after the last moulding operation. After completing the moulding, a crane is requested to move the moulded blade to the first station of the finish area. This is described in the Blade Moulding row of Figure 21.

The cranes manage requests coming from the two moulding stations and from the BF stations: they answer calls in chronological order, move to the station containing the prioritized blade, move it to their destination, and cancel the call from the list of requests. This is shown in the Crane Movements row of Figure 21, where the intended operations are for the smaller couple of cranes when requested by a component, or for the main crane couples when requested by a blade in the BM or in the BF phase. In the software, cranes are modelled with an availability of 100%, because they have dedicated maintenance days on Sundays, when production is halted, and with different speeds based on the type of movement they are performing: vertical (hook), transversal (trolley), and longitudinal (portal), quarter blade turn or half blade turn.

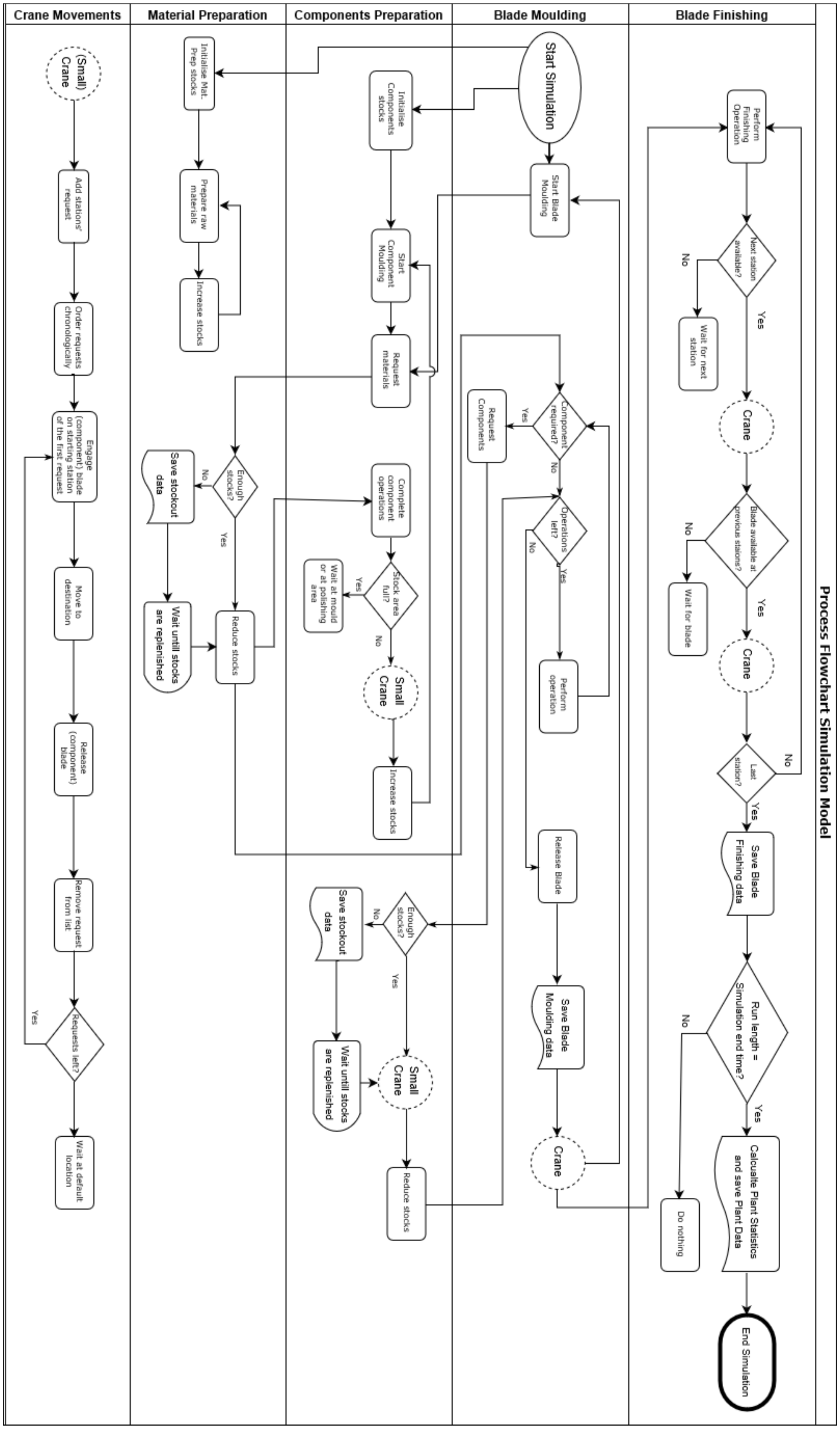

Figure 21: Computer model flowchart

In the BF area, represented in Figure 21 with the Blade Finishing row, some stations may finish their operations before the next station has free capacity to accept a blade or, conversely, some stations may have free capacity and wait for the previous station to complete operations. In all cases, the predecessor station is assigned to the successor station and the crane request is performed through the predecessor station.

Then, in the first case, as soon as the successor station is available it re-activates the crane request from the predecessor. In the second case, the successor station simply waits for the previous station to release the blade and requests the crane. After the last operation in the BF area, data on the BF processing times is stored in a table and the blade is forwarded to the storage yard through the trailer. The storage yard is represented with a drain in the simulation model, which is a special station used to delete entities from the model and release computer memory.

The simulation run stops when its run length reaches the pre-set simulation end time, this event triggers the calculation of the overall plant statistics. This can be seen at the end of the Blade Finishing raw in Figure 21.

The control panel in the final version of the computer models is presented in Figure 22, the upper left corner of it contains the programmed modules which correspond to the conceptual model shown in Figure 20. Each module has its own settings area with the methods controlling its production, handling and stock out logic, aside for the BF area that has its settings inside the dedicated model frame due to programming reasons. The crane and trailer also have their own complex logic and dedicated settings, in the lower right corner. The upper right half of the control panel is dedicated to general plant settings and performances: we collect data on each production phase, on the blades, and on the cranes, through charts, computed KPIs and tables.

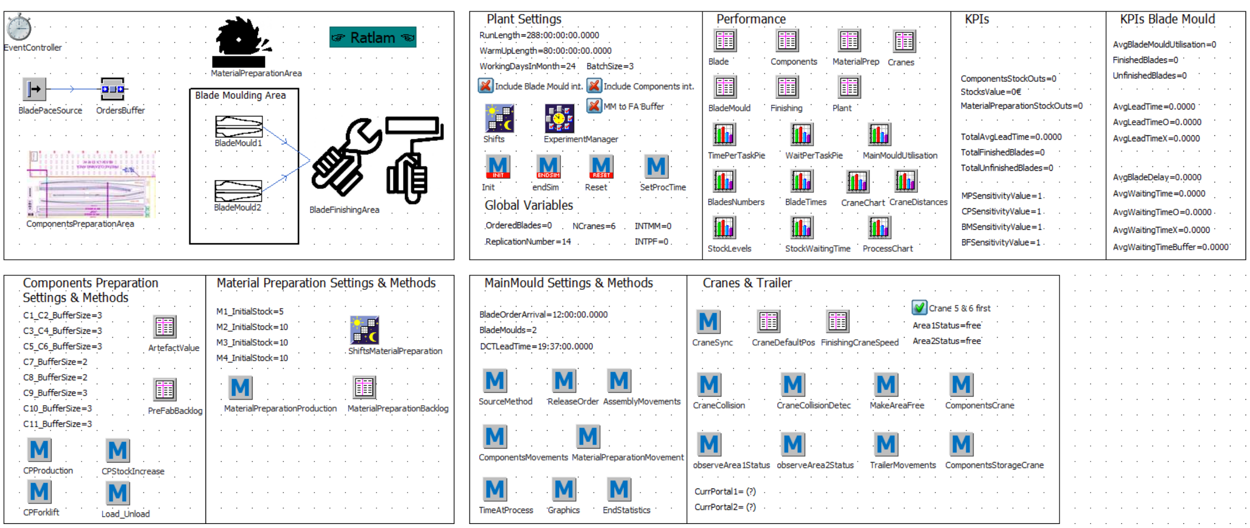

Figure 22: Control panel with production areas, general and area-specific settings and KPIs.

Similarly to Validation, Verification should not take place at the end of the coding phase. It should be performed while programming, to prevent a complex treasure hunt for logical mistakes or typos, and extensive rewriting.

Therefore, the computer program was divided into modules, roughly the four production areas plus handling equipment (cranes, forklift, trailer), and sub-modules, then programmed additively. Every new module was verified by means of the interactive built-in debugger in Tecnomatix Plant Simulation, to check behaviour in critical parts of the code, e.g., the crane movement algorithm. This type of verification technique is called trace, because it traces the state of the simulated system (e.g., variables, counters) after the occurrence of each event.

Also, expected values of the performance indicators were calculated analytically for default and extreme configurations under the design perspective, thus with deterministic processing times, and the computer model results matched the analytical ones.

Regarding the 3D representation of the model, which is partially shown in Figures 23, 24 and 25, we imported and converted drawings from CATIA, a 3D design engineering software, in the simulation model for the type of blade, for all components, stations, storage areas and machinery. The equipment for which we could not obtain official CATIA drawings from SBT-NL, were represented using standard objects from the Tecnomatix Plant Simulation 3D library. The cranes library was recently added in the software and it allowed for the synchronisation of cranes in the computer model. This eased the representation of cranes working as couples and the stations' call logic, as it requires only the main crane of the couple to receive a request for transportation. Then, we added sensors (i.e., virtual lines that perceive the movement of cranes) perpendicularly to the plant's longer side to translate our division in area from Figure 19 into the virtual environment. The modelling of the 3D features for all processes and entities in the model, for cranes, the forklift and the trailer and their logic, required a significant portion of the project duration. However, we obtained a higher level of detail for our results and extra validation and verification of the model. Moreover, compelling animation is substantiated to increase credibility in the model (Law 2015) and our experience in Suzlon supports that.

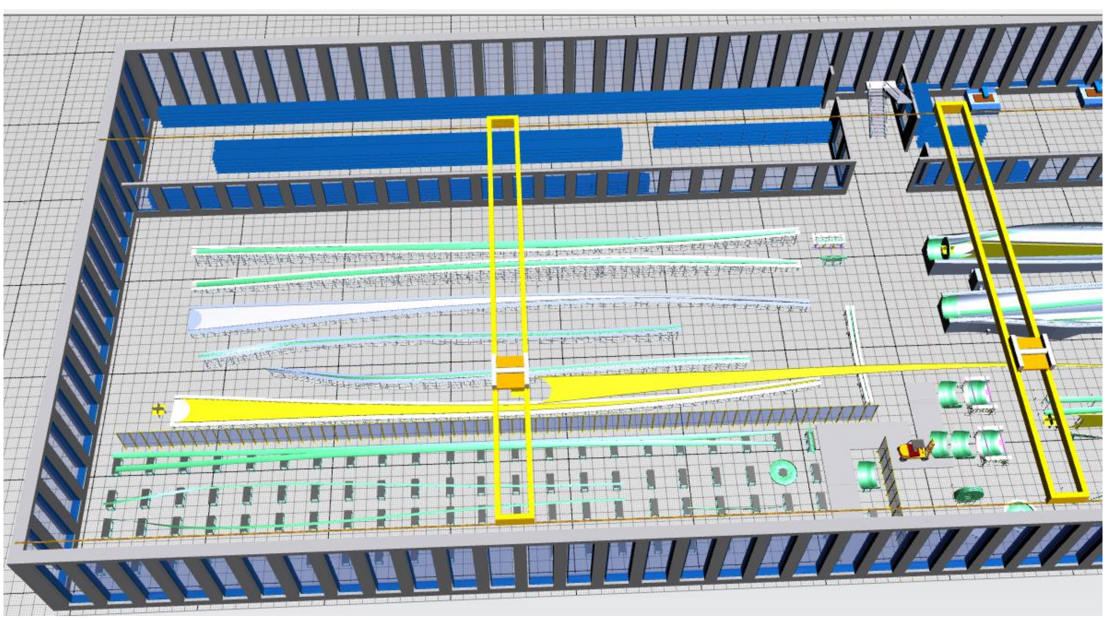

Figure 23: Area 1 as in 3D model, components being moulded and polished, forklift operating between polishing and storage area.

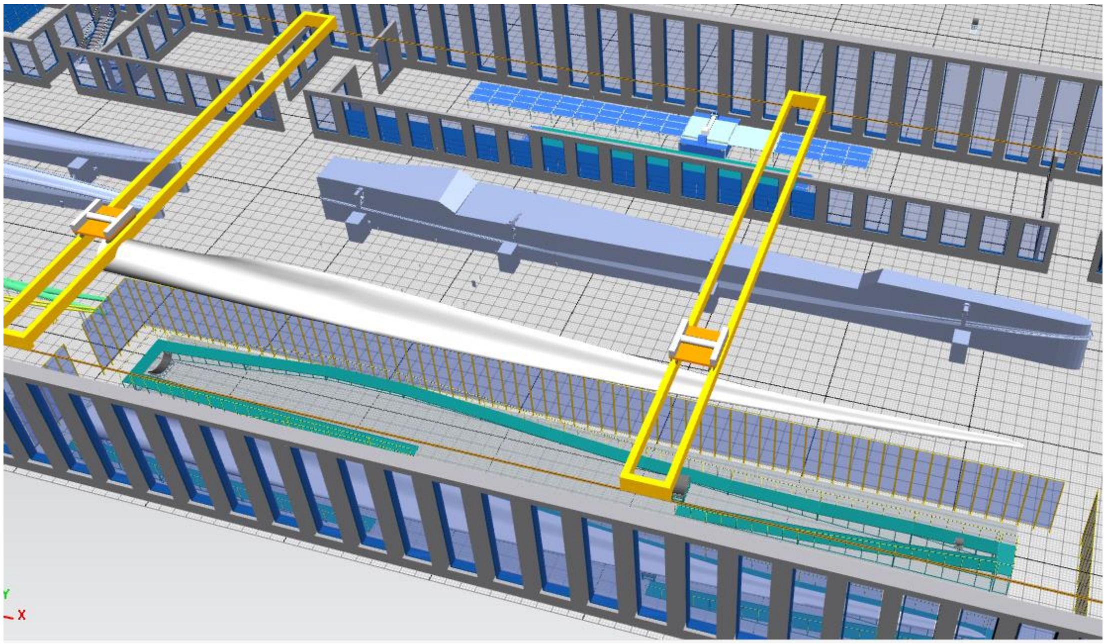

Figure 24: Area 3 as in 3D model, second moulding station performing thermal operations and blade from first moulding station moving to the first operation of the blade finishing area.

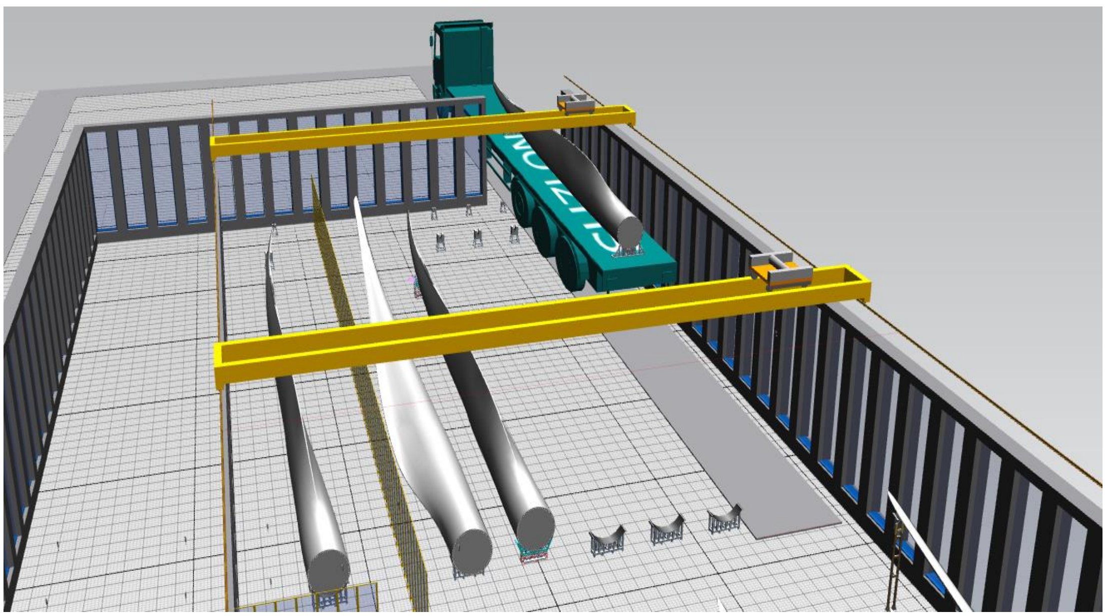

Figure 25: Area 5 as in 3D model, blade loaded on trailer and exiting the plant.

Lastly, after graphical features were added to the simulation model and debugged, a visual verification was performed to check the logic and consistency of blades, components, and materials behaviour. The visual verification was performed both with 2D and 3D graphics.

4.5 Make pilot runs and check validity of programmed model

After various modelling iterations, to model, program and verify each module, the model was deemed sufficiently detailed to perform the first experimentation. Before stepping to the next simulation study step, pilot runs were performed to validate the model as a whole. The results of these pilot runs were shown to a senior engineer in the Hengelo facility and deemed plausible when compared to his experience and knowledge of the production plant.

The Verification & Validation techniques described in this chapter did not only help in producing a functional and representative model, they also boosted its credibility and the stakeholders' feeling of ownership towards it, which in turn will facilitate the implementation of future interventions supported by simulation.

For more details on the plant, blade type, production areas and tasks, consult Appendix E, which also contains the assumptions document. For the flowcharts of the most interesting algorithms used in the model, see Appendix B.

Following the adapted methodology from Law (2015), we structured the simulation study. We defined the study problem, collected data, created a conceptual mode and a computer model, validated and verified them. We strived to obtain representative and credible models of the blade manufacturing processes at the plant in Ratlam, using various validation and verification techniques, also involving stakeholders from other departments in SBT-NL. After achieving representative and credible simulation models, we proceed to test the interventions proposed by our colleagues in the company, by evaluating their performances in different virtual scenarios.

Chapter 5: Design of experiments

While developing a detailed 2D and 3D digital model of the current situation based on Plant and Design perspectives, cross-functional teams came up with new interventions to increase wind rotor blade production. In this chapter, we will first describe these proposed interventions and implement them in the model. Then, we will be ready to tackle Q5:

“How should we experiment with the interventions?”

To do so, we’ll define our Design of Experiments (DOE) to assess the interventions with regards to the performances mentioned in Section 4.2.1 and to the effect of the Plant and Design misalignment gap. Afterwards, the analytical procedures to estimate the experimental settings will be reported.

5.1 New Interventions

Two types of interventions were developed by our colleagues at research office in Hengelo together with employees at the plant in India:

- Operation optimisation on processing times.
- Layout re-dimensioning through task rescheduling and stations balancing.

The first focuses on reducing processing times for each operation performed at each station by redesigning the work procedure and remove inefficiencies, where possible. The second takes into account the overall processing time for each station and aims to lower it below a reference production pace for the plant, also called Takt time. To achieve the alignment to the estimated Takt time for each stations, our colleagues at SBT-NL suggested to change the layout – shifting of equipment and different space allocation – and redistribute tasks between stations.

When describing the effects of the new interventions, we still refer to the *DMT* of the As Is situation, to allow for comparison. The expected effects of the two types of interventions on the plant are shown in Figure 26.

5.1.1 Operation Optimisation

The first intervention is performed in the CP and BM areas. The operations team discovered inefficiencies in the moulding phase of the components and in the blade moulding. By optimising those operations, they expect to save up to 1,5 hours for some components, reduce the blade moulding time by 8%, and lower material costs for all involved processes. The component with the longest moulding phase is now requiring 45% of the *DMT* and the optimised blade moulding process now requires 92% of the starting *DMT*. To refer to the two sub-interventions on the components moulding and on the blade moulding, we will use the names Components Optimisation and Blade Optimisation respectively.

To perform the newly designed operations in the plant, it is necessary to spend time and money on training the employees and to hire a few extra ones, but expenses for equipment are not necessary and there will be savings on required materials. Therefore, the intervention is considered to be low cost.

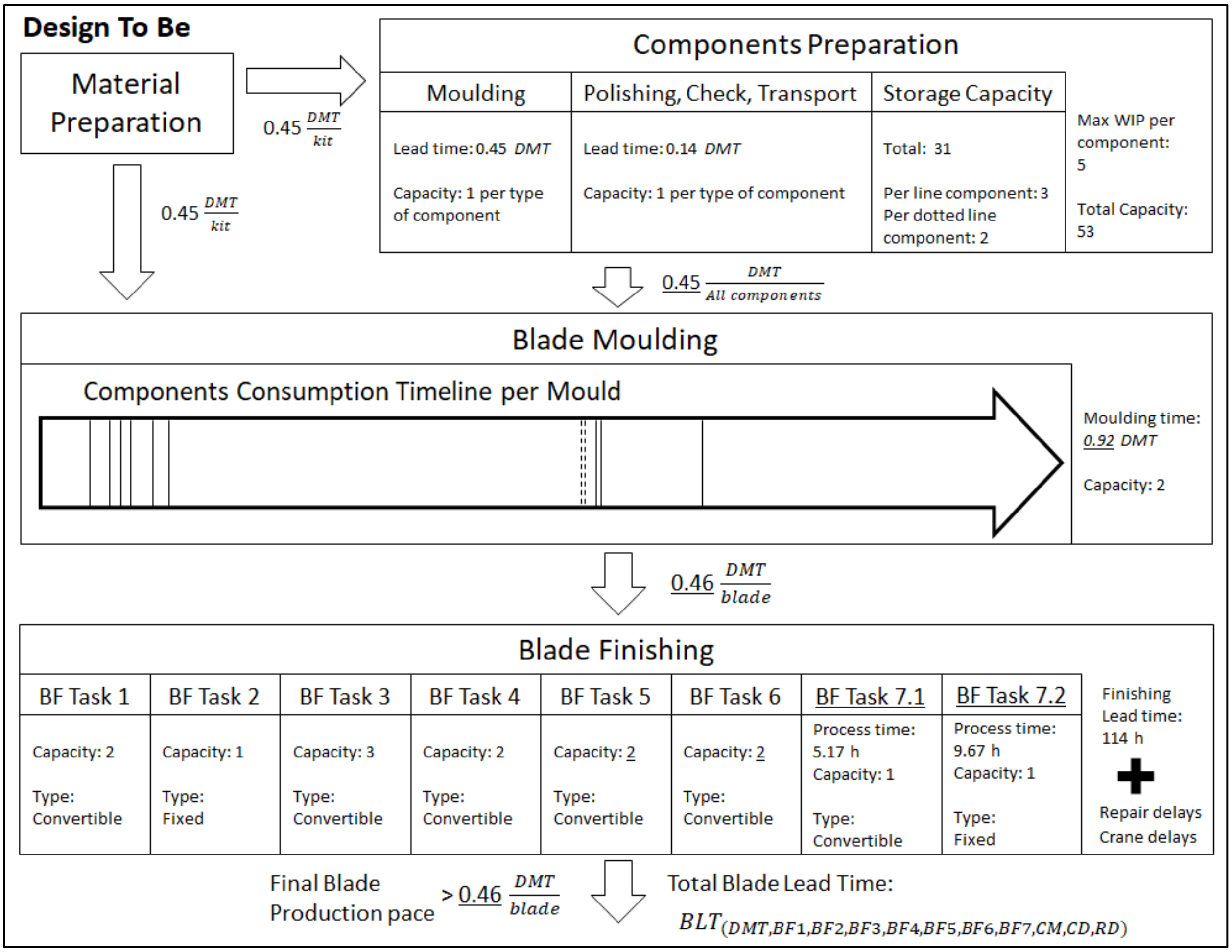

Figure 26: Blade production phases at the Ratlam plant, station details, and new plant performance on average as for design documents, with underlined changes due to interventions

5.1.2 Layout re-dimensioning through task rescheduling and stations balancing

To devise the second intervention, we helped our colleagues from SBT-NL to set-up lean manufacturing tools and procedure. In Figure 27, we show our Obeya (Japanese for "great room"), a dedicated space for lean visual tools, which is actually a wall in our case. On our Obeya wall, we positioned:

- A Spaghetti chart, representing the blade movements in the plant.
- A detailed sequence of tasks and processing times for each station.
- A Yamazumi chart, using the Takt time estimated from blade demand as threshold and plotting it against the workload for each station. This helps to identify over(under)-utilised stations.
- An Improvement Kata, a project management tool that helps to set target and actual conditions, experimental steps to improve the actual condition, obstacles, deadlines, and

lessons learnt. Moreover, the Improvement Kata is organised in Plan-Do-Check-Act (PDCA) cycles that support in structuring the research process.

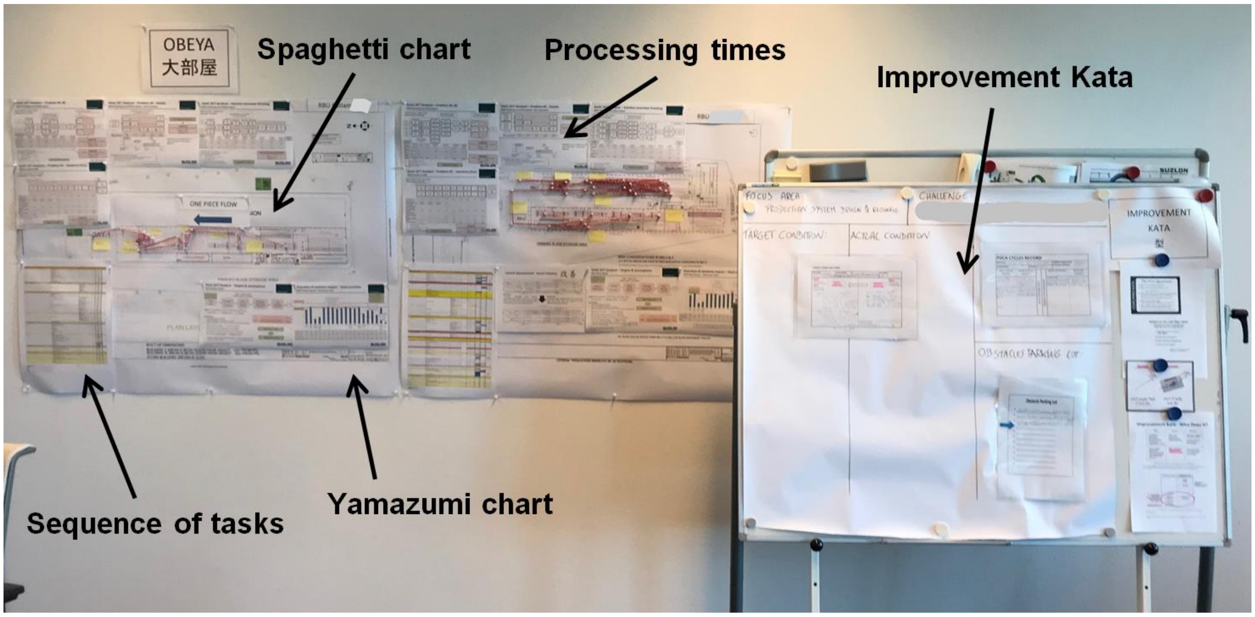

Figure 27: Obeya wall with lean manufacturing tools

The second intervention is performed on the BF area. As stated in Section 2.3.4, the production bottleneck is station BF 7, where the blade batch is formed. The station has a capacity of 4 but effectively uses only 3 of the stations, keeping one always free to move blades between the weighing equipment and the three supports, which is very inefficient. To implement a complete one-piece flow production for the BF area, the tasks at station BF 7 are redistributed in two separate stations, BF 7.1 and BF 7.2, each having a capacity of one blade, and the batch formation is no longer performed, which saves hours spent waiting for the second and third blade of the group. The new processing times for BF 7.1 and BF 7.2 are expected by prototyping measurements to be respectively 5.17 hours and 9.67 hours. These values are used both in the design perspective and in the plant perspective as deterministic times, because no one at the plant has any real life experience with the new process.

Instead of the batch formation, we now increase the weight of each blade up to three different standard values, also called “classes”: each blade has a certain weight when reaching the balancing station, and the goal of the balancing station is to add mass to the blade so that it reaches the next closest class of weight. The blades are then deposited in the corresponding storage area for the weight class in the yard, thus the batch formation is bypassed by selecting three blades from the same storage area, which we assume to be large enough for all the blades. Station BF 7.1 is assigned convertible equipment while BF 7.2 utilises the same dedicated weighing equipment that was considered fixed for BF 7 as a whole, thus no further capital investment is necessary.

By removing the batch formation and using two stations with a capacity of one blade for all the tasks previously performed at BF 7, which occupied an area of four blades, a capacity of two blades has been freed in the form of free space and convertible equipment. This capacity is redistributed equally to station BF 5 and BF 6, which are the next most over-utilised stations – the next bottleneck – in the blade finishing area.

To implement this intervention in the plant, it is necessary to move the supports from BF 7 to BF 5 and 6, which are close to each other, and to order more material to be poured into the blade during balancing operations. The reason for the extra material will now be explained. In the former station, BF 7, the batch logic used the first blade arriving at the station as a reference for the other two, which means the first blade only required mass addition when its weight was below the minimum blade weight threshold. Furthermore, the second and third blade could also weigh the same as the batch reference blade. Conversely, the new balancing based on predefined weight classes always requires for mass to be added to the blade, except for those rare cases when a blade weights exactly as one of the three values for the classes. However, the pouring material is cheap, thus the intervention is considered to be low-cost.

Since both interventions, namely Operation Optimisation and layout re-dimensioning, are considered to be low cost and we miss the necessary data for a cost analysis, we assume the two interventions to have an equal expenditure in resources and initially only compare them on the four selected KPIs in Section 4.1.

5.1.3 Including the interventions in the model

Adding the intervention to the model required little re-coding effort thanks to the model itself being composed of different modules. For the rescheduling and stations balancing, we slightly modified the model layout in the BF area based on new drawings obtained by the colleagues in the R&D department, and we removed the batch formation logic. We assume that all blades must undergo mass addition and are raised up to one class of weight, because we lack data on the blade weight distributions and because we do not focus on the management of the storage yard. For the Operation Optimisation, we added buttons to the control panel that allow to include one, both, or none of the time reductions on components and blade moulding. The virtual model was verified against expected performance of the interventions computed analytically. Lastly, the interventions were included in the Assumptions document together with the relative data.

DES characteristics and our modelling approach, which is modular and additive, helped in minimizing the necessary re-programming.

5.2 Experimental approach for the interventions

First, we evaluate the neglected effect of queues on the system, by comparing the analytical design model in Figure 18 against the default system configuration under design and plant perspective in our simulation model. Then, we experiment with the implementation of one type of intervention at a time and the combination of the two. This allows us to calculate the expected effects for each intervention and to give priority to one implementation over the other. The interventions are also tested for each of the two perspectives defined in Table 2 and with the 2D/3D model versions defined in Section 4.2. The analysis over the two perspectives is used to compare the expected differences in performance, at the plant and based on design documents, to quantify the reduction of the intervention backlog, described in Section 2.4. Henceforth, when referring to comparisons between configurations using design and plant perspectives, we mean to assess the reduction of the intervention backlog. The analysis with 2D and 3D models helped us to perform a realistic assessment of the Crane, Forklift and Trailer resources, which we compared to the current way of considering the handling times and delays by design.

Table 5 summarises all the experimented configurations and the juxtapositions matrix that we use to draw conclusions. We now describe in more detail the purpose of each juxtaposition.

5.2.1 Description of juxtapositions

When comparing experimental results, we use the term "juxtaposition", as we are not performing pairwise comparisons of all experiments but only performing specific pairings to draw conclusions on the topics described above. With this analysis through juxtapositions, we show how reliable data achieved with simulation can be used to better understand the current production system, to quantify negative effects that are only perceived qualitatively by the research department, and to increase the accuracy of estimations on the interventions' effects. Moreover, the juxtapositions will be used in the next chapter to propose a suggested implementation schedule for the interventions at the plant. The topics investigated by each juxtaposition are aligned to the project goal and are derived from the situation defined in Section 2.4.

- Juxtaposition 1: we have two goals. First, we plan to estimate the quantitative effect on plant performances of the gap between design and plant perspectives, by comparing the two As Is configurations using simplified processing times from design and the triangular distributions for the plant (Configurations 1 and 2). Second, we plan to assess the effectiveness of the current design assumptions against 3D simulation in accounting for handling resources when little data is available, by comparing the two As Is configurations with design perspective against their As Is plant perspective counterpart, and then the difference between the two pairs (Configurations 1 and 3, 2 and 4).

- Juxtaposition 2: our goal is to compare the performance of the full Operation Optimisation intervention with the design perspective and the plant perspective, to estimate the performance loss due to the gap. This will be done for 2D and 3D models (Configurations 9 and 10, 23 and 24).

- Juxtaposition 3: our goal is to compare the performance of the Rescheduling & Balancing intervention with both perspectives, to estimate the performance loss due to the gap. This will be done for 2D and 3D models (Configurations 11 and 12, 25 and 26).

- Juxtaposition 4: our goal is to compare the performance of the combined interventions – full Operation Optimisation and Rescheduling & Balancing – with both perspectives, to estimate the performance loss due to the gap. This will be done for 2D and 3D models (Configurations 17 and 18, 31 and 32).

Table 5: Experimental configurations and juxtaposition matrix

Situation	Model design	Layout	Intervention	Data	Configuration	Juxtaposition 1	Juxtaposition 2	Juxtaposition 3	Juxtaposition 4	Juxtaposition 5	Juxtaposition 6	Juxtaposition 7	Juxtaposition 8	Juxtaposition 9	Juxtaposition 10
As Is	2D	E	None	D	Config 1	x				x	x				
				P	Config 2	x							x	x	
	3D	E	None	D	Config 3	x				x	x				
				P	Config 4	x							x	x	
To Be	2D	E	Components Optimisation	D	Config 5					x					
				P	Config 6								x		
		E	Blade Mould Optimisation	D	Config 7					x					
				P	Config 8								x		
		E	Full Optimisation	D	Config 9		x			x	x				
				P	Config 10		x						x	x	
		N	Rescheduling & Balancing	D	Config 11			x			x	x			
				P	Config 12			x						x	x
		N	Components Optimisation, Rescheduling & Balancing	D	Config 13							x			
				P	Config 14										x
		N	Blade Mould Optimisation, Rescheduling & Balancing	D	Config 15							x			
				P	Config 16										x
		N	Full Optimisation, Rescheduling & Balancing	D	Config 17				x		x	x			
				P	Config 18				x					x	x
	3D	E	Components Optimisation	D	Config 19					x					
				P	Config 20								x		
		E	Blade Mould Optimisation	D	Config 21					x					
				P	Config 22								x		
		E	Full Optimisation	D	Config 23		x			x	x				
				P	Config 24		x						x	x	
		N	Rescheduling & Balancing	D	Config 25			x			x	x			x
				P	Config 26			x						x	
		N	Components Optimisation, Rescheduling & Balancing	D	Config 27							x			
				P	Config 28										x
		N	Blade Mould Optimisation, Rescheduling & Balancing	D	Config 29							x			
				P	Config 30										x
		N	Full Optimisation, Rescheduling & Balancing	D	Config 31				x		x	x			
				P	Config 32				x					x	x

E = existent, N = new, D = design, P = plant

- Juxtaposition 5: we plan to evaluate the effects of the different Operation Optimisation interventions – only for components, only for blades, or for both – on the As Is system under design perspective. We perform the same comparison for their 3D counterparts, and then a comparison between 2D and 3D configurations (configurations 1, 5, 7, and 9, against configurations 3, 19, 21, 23).

- Juxtaposition 6: we plan to prioritize the two types of interventions and their combined use to better schedule the implementation process, by comparing the As Is system under design perspective to the full Operation Optimisation, the Rescheduling & Balancing, and the combination of the two under design perspective, for the 2D and 3D configuration separately and then against each other (configurations 1, 9, 11, and 17, against 3, 23, 25, and 31).

- Juxtaposition 7: with this juxtaposition we want to reach a more detailed implementation schedule and understand what process should be optimised first under design perspective, assuming the Rescheduling & Balancing to be already prioritized (as we expect it will be). This will be done by comparing the Rescheduling & Balancing with Components Optimisation, Blade optimisation, or both, first in 2D, then in 3D, and lastly the 2D results against the 3D results (configuration 11, 13, 15, and 17, against 25, 27, 29, and 31).

The remaining juxtapositions, namely juxtaposition 8, 9 and 10, will be used to draw conclusions on the same topics of juxtaposition 5, 6, and 7 respectively but under plant perspective, to understand if the misalignment gap also influences the implementation schedule.

5.2.2 Warm-up period, replications, and run length

When determining the experimental settings, we must consider the KPIs that will be analysed. In Section 4.2.1, four KPIs were selected for this study: average blade Production Pace (PP), average blade Finishing Lead Time (FLT), monthly average number of Components Stock-Outs (CSO), and monthly average number of Materials Stock-Outs (MSO). After the pilot runs mentioned in Section 4.2.5 and few experimental trials, it was noticed how the CSO and MSO were almost always zero and how the PP had very little variability in between replications of the same configurations. Moreover, the PP and FLT were similarly influenced by the initial state of the system; we expected this as they are somehow directly related to each other, e.g., a short FLT would lead to a better PP. Therefore, FLT was chosen to estimate the minimum warm-up and number of replications. The warm-up calculation was done with the individual finishing lead time of all the blades produced in one simulation run, while the replication number used the average FLTs over each simulation run.

Furthermore, the experimental settings will be estimated for configurations 2, 4, 18, and 32. The choice is due the use of stochastic data (not available in the design perspective), to the way cranes are accounted for, and to assess the As Is situation and the most developed To Be situation, as any change is bound to influence the inherent variability of the KPIs. The minimum warm-up period and minimum number of replications required by the four configurations will be calculated. Then, the respectively longest and highest values will be used for all the experiments.

The estimation of a warm-up period is necessary to avoid steady-state performance parameters being subject to bias due to the system initial conditions. As we have no clear event corresponding to the end of the warm-up phase, the simulation model must be run for a time set by us before gathering data on the performance parameters.

To determine the warm-up period, a graphical procedure from Welch (1983) was used. This procedure is suggested by the chosen simulation methodology and substantiated to be simple and general (Law, 2015). It consists in performing *n* independent replications of the same simulation configuration, each with the same length *m* chosen to be way larger than the expected warm-up. Then, an average of the same data point (i.e., average of blade 1 for all replications, average of blade 2, etc.) is performed over the *n* replications. The resulting replication-averaged data points are then used to compute moving averages over the simulation run with different windows *w*, with the goal of smoothing the plot and ease graphical visibility of the warm-up phase. Either this *w* is increased until the plot is sufficiently smoothed or the *n* replications are increased, following a trade-off logic of data information lost to aggregation against computation time for extra replications. All the parameters are shown in Table 6.

Table 6: Warm-up estimations and parameters

Common settings	*w*	Configuration	Warm-up
n = 5 *m* = 288 days	5, 10, 25	2	48 days
	5, 10, 25	4	42 days
	5, 10, 25, 50	18	72 days
	5, 10, 25, 50	32	80 days

We used five replications and 288 days of simulation length, which correspond to one production year in Suzlon, and the window size *w* had to be further increased for the To Be configurations due to a higher variability. To compute the number of production days necessary for warm-up, we plotted the different smoothed moving averages and selected the blade data point *k* roughly corresponding to the start of the steady-state phase of the KPI. Then, we ran each configuration until the completion of blade number *k* for multiple replications, and rounded up the longest required simulation time to the next integer number of days. Figure 28 shows Welch's procedure for Configuration 32, where we chose $k = 130$. Finally, we chose the 80 days required by Configuration 32 as the warm-up period for all configurations. For details on Welch's graphical method we refer to Appendix C.

Moving forward to the replications' number, its choice will give statistical confidence to our results, in the form of a confidence interval $100(1 - \alpha)$ for our point estimate of the mean KPIs and a chosen relative error.

The simulation methodology suggests – among others – the Replication/Deletion approach for means, because it provides good statistical performance, is easy to understand and apply, can be used for all types of KPIs, can be used to estimate different parameters for the same simulation model and lastly, it can be used to compare different system configurations (Law, 2015). This approach can be used as a simple formula to estimate the level of confidence with a given set of replications and relative error, or as a sequential procedure to reach a desired confidence interval with a given relative error.

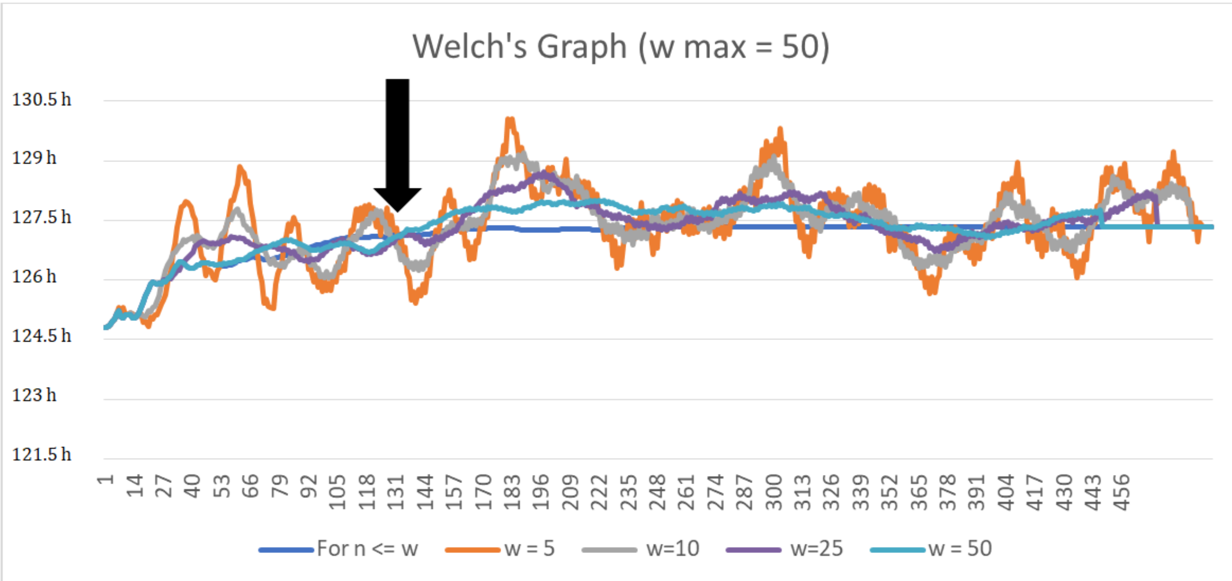

Figure 28: Welch's procedure for Configuration 32

Generally, a 95% confidence interval with a relative error of less than 5% compared to the mean is considered to be acceptable. Given the low variance in simulation output, we only require a limited number of replications. Law (2015) suggests to always performing at least three to five replications to ensure proper assessing of the parameters variability in a stochastic simulations, thus a calculation of the achievable confidence intervals against a relative error of 1% or 2% has been performed. Results are shown in Table 7.

We decided to attain a confidence interval of 99% with a relative error of at most 1%, which means all configurations are then replicated fourteen times.

In this chapter, we described the two types of interventions that we test through simulation and their expected performances, based on the current design approach. Moreover, we defined how to test them using a DOE and a set of juxtapositions related to our scope. Lastly, we set-up the experimental settings – warm-up length, number of replications, simulation run length – for all configurations, or scenarios, to be tested. Performing all the experiments and organising the resulting data required roughly 5 hours. The results are analysed in the next chapter.

Table 7: Number of replications required to achieve certain confidence intervals with a given relative error

		Confidence Interval			
		99.9% (α = 0.001)	99% (α = 0.01)	98% (α = 0.02)	95% (α = 0.05)
Relative error	0.01	Config 2: 4 Config 4: 4 Config 18: 21 Config 32: 21	Config 2: 3 Config 4: 4 Config 18: 10 Config 32: 14	Config 2: 3 Config 4: 3 Config 18: 7 Config 32: 13	Config 2: 3 Config 4: 3 Config 18: 5 Config 32: 1
	0.02	Config 2: 4 Config 4: 3 Config 18: 7 Config 32: 11	Config 2: 3 Config 4: 3 Config 18: 5 Config 32: 7	Config 2: 3 Config 4: 3 Config 18: 4 Config 32: 7	Config 2: 2 Config 4: 2 Config 18: 3 Config 32: 6

Chapter 6: Experimental results and analysis

In this chapter, we assess the effects of queues on the system as explained at the start of Section 5.2, and then we compare interventions using the predefined juxtapositions, as per our DOE in Section 5.2.1. By analysing the experimental results, we assess the effectiveness of the design perspective against the plant perspective and define a suggested implementation schedule for the tested interventions considering the plant perspective, as the plant in Ratlam is the final utiliser of the interventions. The resulting implementation schedule will be more reliable and it will be our answer to Q6:

“Which interventions can be implemented at Suzlon’s manufacturing plant?”

The full range of experimental results is shown in Table 8.

At first glance, we can notice how the 2D As Is system with design inputs and simplifying assumptions on cranes (Configuration 1) has a FLT of 228 hours that is 77 hours longer than the expected FLT of 151 hours, based on the analytical design model represented in Figure 18, in Section 4.2. This difference is already a gap of 51% and it is due to the simplifying assumptions on queues and waiting times in the system, which are not considered by the design documents but are included in all our simulation models. If we compare the difference between the analytical design model in Figure 18 and the corresponding plant perspective model (Configuration 2), we see the gap is of 131 hours, or 87%, which is a quite worrisome offset when trying to estimate the effects of new interventions.

Although the FLT gap is quite significant, we see that the PP gap is 0.19 $\frac{hour}{blade}$, or 1%, for the 2D As Is design perspective model, while for the plant perspective model it is 4.11 $\frac{hour}{blade}$, or 23.7%.

PP is not directly influenced by the queuing and waiting time effects, as it is just equal to the process with the least throughput, also called bottleneck. Therefore, the PP difference between the analytical design model and the plant perspective simulation is due to the difference in input data. This does not mean that configurations with different FLTs and equal PPs are performing equally good, as the configurations with lower FLTs have on average a lower amount of blades and components in the system, which means a lower WIP and a leaner production.

Regarding Component Stock Outs (CSO) and Material Stock Outs (MSO), the As Is production pace is too slow to cause stock outs of components and materials, this is aligned to the analytical design model and it is even less of a problem when considering the longer processing times under plant perspective.

We conclude that the representation of the Ratlam plant production line currently used by the design department, shown in Figure 18, does not perform properly compared to the simulation model, when considering queueing effects and delays. The assumption on queues and delays is too inaccurate and we quantified it as gap of 51% on the FLT. When adding to the backlog of interventions at the plant, the gap between the current design approach at SBT-NL and the plant processes as modelled by us grows to 87% on lead times and from zero to 23.7% on PP.

Table 8: Experimental results

Situation	Model design	Layout	Intervention	Data	Configuration	FLT(h)	PP (h/blade)	CSO	MSO
As Is	2D	E	None	D	Config 1	227.75	17.52	0.00	0.00
As Is	2D	E	None	P	Config 2	282.60	21.44	0.00	0.00
As Is	3D	E	None	D	Config 3	223.82	16.21	0.00	0.00
As Is	3D	E	None	P	Config 4	275.28	19.76	0.00	0.00
To Be	2D	E	Components Optimisation	D	Config 5	227.75	17.52	0.00	0.00
To Be	2D	E	Components Optimisation	P	Config 6	282.60	21.44	0.00	0.00
To Be	2D	E	Blade Mould Optimisation	D	Config 7	227.75	17.52	0.00	0.00
To Be	2D	E	Blade Mould Optimisation	P	Config 8	282.61	21.42	0.00	0.00
To Be	2D	E	Full Optimisation	D	Config 9	227.75	17.52	0.00	0.00
To Be	2D	E	Full Optimisation	P	Config 10	282.61	21.42	0.00	0.00
To Be	2D	N	Rescheduling & Balancing	D	Config 11	119.50	11.37	0.00	0.00
To Be	2D	N	Rescheduling & Balancing	P	Config 12	118.79	14.85	0.00	0.00
To Be	2D	N	Components Optimisation, Rescheduling & Balancing	D	Config 13	119.50	11.37	0.00	0.00
To Be	2D	N	Components Optimisation, Rescheduling & Balancing	P	Config 14	118.79	14.85	0.00	0.00
To Be	2D	N	Blade Mould Optimisation, Rescheduling & Balancing	D	Config 15	116.36	10.74	107.31	0.00
To Be	2D	N	Blade Mould Optimisation, Rescheduling & Balancing	P	Config 16	119.01	14.00	0.00	0.00
To Be	2D	N	Full Optimisation, Rescheduling & Balancing	D	Config 17	119.56	10.49	0.00	0.00
To Be	2D	N	Full Optimisation, Rescheduling & Balancing	P	Config 18	119.01	14.00	0.00	0.00
To Be	3D	E	Components Optimisation	D	Config 19	223.82	16.21	0.00	0.00
To Be	3D	E	Components Optimisation	P	Config 20	275.26	19.76	0.00	0.00
To Be	3D	E	Blade Mould Optimisation	D	Config 21	223.82	16.21	0.00	0.00
To Be	3D	E	Blade Mould Optimisation	P	Config 22	275.28	19.74	0.00	0.00
To Be	3D	E	Full Optimisation	D	Config 23	223.82	16.21	0.00	0.00
To Be	3D	E	Full Optimisation	P	Config 24	275.28	19.74	0.00	0.00
To Be	3D	N	Rescheduling & Balancing	D	Config 25	116.24	11.14	0.00	0.00
To Be	3D	N	Rescheduling & Balancing	P	Config 26	126.92	14.51	0.00	0.00
To Be	3D	N	Components Optimisation, Rescheduling & Balancing	D	Config 27	116.24	11.14	0.00	0.00
To Be	3D	N	Components Optimisation, Rescheduling & Balancing	P	Config 28	126.94	14.51	0.00	0.00
To Be	3D	N	Blade Mould Optimisation, Rescheduling & Balancing	D	Config 29	113.96	10.47	55.04	0.00
To Be	3D	N	Blade Mould Optimisation, Rescheduling & Balancing	P	Config 30	128.11	13.64	0.00	0.00
To Be	3D	N	Full Optimisation, Rescheduling & Balancing	D	Config 31	117.82	10.25	0.00	0.00
To Be	3D	N	Full Optimisation, Rescheduling & Balancing	P	Config 32	128.11	13.63	0.00	0.00

E = existent, N = new, D = design, P = plant

We now proceed to evaluate the interventions in deeper detail using the juxtaposition of our experimental results.

6.1 Discussion on juxtapositions

Starting with Juxtaposition 1, whose results are shown in Table 9, we evaluate the input gap between design and plant perspective and the current procedure to account for crane movements. We can see that the input gap is quite consistent both for the 2D versions and the

3D version. Regarding the FLT, it is approximately 55 hours for the first and 51 hours for the second, that corresponds to a 23-24% increase to the estimated values by design. Regarding the PP, the gap is of 4 $\frac{hour}{blade}$ for the 2D version and 3.5 $\frac{hour}{blade}$ for the 3D version, which corresponds to a 22% increase to the design estimations.

Therefore, the input gap due to the backlog of interventions is in the range of 23-24% for the FLT and 22% for the PP. The size of this gap was unknown to the company, its quantification demonstrates the usefulness of simulation in understanding blade production. Also, it provides clear values to justify spending resources on its reduction.

Coming from the previous analysis between the analytical design model and the As Is systems, the reader would expect the FLT gap to be equal to 36% – the general plant perspective gap of 87% minus the 51% queueing design gap – and that is correct. The different number is due to the juxtaposition being between Configuration 1 and 2, and 3 against 4, which changes the determinant of the fractions. This gap of 23-24% corresponds to a gap of 37% if compared to the analytical design model in Figure 18. Henceforth, we consider this matter clarified and will not rescale the following percentages between the juxtaposition and the analytical design model.

Regarding the cranes, forklift, and trailer accounting gap measured as the difference between the 2D and 3D versions of the model, we see there is a change of -4 hours and -1.3 $\frac{hour}{blade}$ between the design configurations, namely Configurations 1 and 3 , and a somewhat greater change of -7 hours and -1.7 $\frac{hour}{blade}$ between the plant configurations, namely Configurations 2 and 4. The 3 hours difference between the two pairs is due to the conservative values we were given by the plant experts when accounting for transportation using the design format, as explained in Section 4.2 when discussing ACTs.

The input gap due to the assumptions for the cranes, the forklift, and the trailer is in the range of -2.6% to -1.7% of the FLT. Thus, we settle on cranes' effect being overestimated by several hours per blade in the As Is system, where processes are longer and cranes are requested at slower pace, even though there is a higher WIP. Therefore, we judge the design assumptions on cranes to be sufficiently accurate for standard sized plants, like the Ratlam one, but they should be tested on larger sized plants to clear remaining doubts.

Table 9: Quantifying the gap and assessing crane accounting

	FLT (h)	PP (h/blade)	CSO	MSO	Gap (FLT)	2D vs 3D (FLT)	Gap (PP)
Config 1	227.75	17.52	0.00	0.00	-	-	-
Config 2	282.60	21.44	0.00	0.00	24.1%	-	22.4%
Config 3	223.82	16.21	0.00	0.00	-	-1.7%	-
Config 4	275.28	19.76	0.00	0.00	23.0%	-2.6%	21.9%

Moving forward to Juxtaposition 2, whose data is shown in Table 10, we want to measure the performance gap of the full Operation Optimisation when implemented on its own. We can see that the differences between the design perspective and the plant perspective are the same, both for the 2D and 3D versions, to what is presented in Table 9. We conclude that we cannot quantify the performance loss for the Operation Optimisation on its own, since the intervention effects are zero regarding FLT and PP.

Table 10: Performance gap of full Operation Optimisation

	FLT (h)	PP (h/blade)	CSO	MSO	Gap (FLT)	2D vs 3D (FLT)	Gap (PP)
Config 9	227.75	17.52	0.00	0.00	-	-	-
Config 10	282.61	21.42	0.00	0.00	24.1%	-	22.3%
Config 23	223.82	16.21	0.00	0.00	-	-1.7%	-
Config 24	275.28	19.74	0.00	0.00	23.0%	-2.6%	21.8%

With Juxtaposition 3, we assess the performance gap of Rescheduling & Balancing when implemented on its own, based on its data in Table 11. The layout re-dimensioning impacted dramatically the FLT and the PP, as much as to almost halve the lead time for the finishing area. In the 2D version, the new system configuration has roughly the same FLT performance for the design and the plant perspective, but not for the PP, which means the queueing effect is greatly reduced and the bottleneck is no longer in the BF phase, so it must be the BM phase. In the 3D version, we notice a similar situation regarding the performance improvement, moreover the configuration with design perspective (Configuration 25) has a shorter FLT, aligning itself with the previous considerations for Juxtaposition 1.

However, the 3D configuration using the plant input (Configuration 26) has a longer FLT than its design counterpart and a similar PP to its 2D counterpart (Configuration 12). This difference cannot be due to crane movements or to the input gap alone, otherwise we would see a longer FLT in Configuration 25 or a higher PP in Configuration 12 respectively. The difference must be due to a soft spot in the combination of the two, and we hope to understand more about this soft spot in the following juxtapositions.

For now, we conclude the gap for task rescheduling and layout interventions to be not significant regarding the FLT but significant regarding the PP, with a 30% loss.

Table 11: Performance gap of Rescheduling & Balancing

	FLT (h)	PP (h/blade)	CSO	MSO	Gap (FLT)	2D vs 3D (FLT)	Gap (PP)
Config 11	119.50	11.37	0.00	0.00	-	-	-
Config 12	118.79	14.85	0.00	0.00	-0.6%	-	30.5%
Config 25	116.24	11.14	0.00	0.00	-	-2.7%	-
Config 26	126.92	14.51	0.00	0.00	9.2%	6.8%	30.3%

In Juxtaposition 4, we perform the same analysis as for Juxtapositions 2 and 3, but on the combination of the two interventions. The results shown in Table 12 highlight an even better performance regarding the FLT and PP, and the presence of the aforementioned soft spot, which is probably an inherent consequence of the Rescheduling & Balancing intervention.

The performance gap behaves similarly to the previous juxtaposition, thus we record the gap for the combination of the full Operation Optimisation and Rescheduling & Balancing to be not significant regarding the FLT but significant regarding the PP, with a higher 33% loss.

The evaluation of the performance gaps performed above shows that we can estimate with more accuracy the effects of interventions to be implemented at the plant, when using simulation instead of the current design procedure. SBT-NL will be able to better prioritize future projects and allocate resources, which is a critical task for R&D offices.

Table 12: Performance gap of full Operation Optimisation plus Rescheduling & Balancing

	FLT (h)	PP (h/blade)	CSO	MSO	Gap (FLT)	2D vs 3D (FLT)	Gap (PP)
Config 17	119.56	10.49	0.00	0.00	-	-	-
Config 18	119.01	14.00	0.00	0.00	-0.5%	-	33.3%
Config 31	117.82	10.25	0.00	0.00	-	-1.5%	-
Config 32	128.11	13.63	0.00	0.00	8.7%	7.6%	32.9%

We continue with Juxtaposition 5, whose data is shown in Table 13, to prioritise in more detail the implementation schedule, by analysing the effect of the Components optimisation and Blade Optimisation separately and then combined, under design perspective. The intervention effect is estimated by comparing the 2D As Is model under design perspective with all the 2D implementation variants under design perspective, namely configurations 1, 5, 7, 9. The same is done for the 3D configurations under design perspective, namely configurations 3, 19, 21, 23.

We notice there is no positive effect on lead times and the production pace for any variant of the Operation Optimisation – components, blade, or both – when implemented on its own, and this aligns to our findings in Juxtaposition 2. This is due to the CP phase not being a critical process in the As Is production and not impacting on the blade moulding lead time.

Table 13: Prioritisation of Components Optimisation, Blade Optimisation, or full Operation Optimisation, under design perspective

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	2D vs 3D (FLT)	Effect (PP)
Config 1	227.75	17.52	0.00	0.00	-	-	-
Config 3	223.82	16.21	0.00	0.00	-	-1.7%	-
Config 5	227.75	17.52	0.00	0.00	0.0%	-	0.0%
Config 7	227.75	17.52	0.00	0.00	0.0%	-	0.0%
Config 9	227.75	17.52	0.00	0.00	0.0%	-	0.0%
Config 19	223.82	16.21	0.00	0.00	0.0%	-1.7%	0.0%
Config 21	223.82	16.21	0.00	0.00	0.0%	-1.7%	0.0%
Config 23	223.82	16.21	0.00	0.00	0.0%	-1.7%	0.0%

Through Juxtaposition 6 we want to prioritise the two types of interventions individually or their combination under design perspective. We can already foresee from Juxtaposition 4 and 5 that Juxtaposition 6 will prioritise the Rescheduling & Balancing, under design perspective, and implement the Operation Optimisation in a second period. From the results in Table 14, we notice how the Rescheduling & Balancing improves the situation in the BF phase up to a 47.5% reduction on the FLT and a 35% reduction of the PP, then the addition of the Operation Optimisation would not reduce the FLT any further but would reduce the PP, because it reduces the blade moulding time by 1 hour and 45 minutes and this phase is the new bottleneck after the implementation of the layout intervention.

The difference between the performance of the Rescheduling & Balancing and the combined implementation of the two types of intervention is not significant enough to convince us about implementing both intervention at the same time and as fast as possible, considering eventual problems at the plant which are not included in this juxtaposition. Therefore, we support the choice of implementing the Rescheduling & Balancing intervention first and the Operation Optimisation at a later stage, considering the design perspective.

Moreover, we notice how the reduction in PP through the optimisation intervention would increase slightly the FLT in the 3D model. The increase is due to the higher pace at which blades would be forwarded to the BF, that influences the more accurately represented crane performance and slightly slows down the finishing area. This is another insight on the system behaviour obtained through simulation.

Table 14: Prioritisation of full Operation Optimisation, Rescheduling & Balancing, or their combination, under design perspective

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	2D vs 3D (FLT)	Effect (PP)
Config 1	227.75	17.52	0.00	0.00	-	-	-
Config 3	223.82	16.21	0.00	0.00	-	-1.7%	-
Config 9	227.75	17.52	0.00	0.00	0.0%	-	0.0%
Config 11	119.50	11.37	0.00	0.00	-47.5%	-	-35.1%
Config 17	119.56	10.49	0.00	0.00	-47.5%	-	-40.1%
Config 23	223.82	16.21	0.00	0.00	0.0%	-1.7%	0.0%
Config 25	116.24	11.14	0.00	0.00	-48.1%	-2.7%	-31.3%
Config 31	117.82	10.25	0.00	0.00	-47.4%	-1.5%	-36.8%

We step into deeper detail with Juxtaposition 7, presented in Table 15, where we want to prioritise the secondary implementation of the Operation Optimisation variants after we already prioritised the Rescheduling & Balancing, still under design perspective.

As in the previous juxtaposition, we see how reducing the PP through the blade moulding optimisation will increase the FLT slightly. Also, the Components Optimisation is only useful after the blade moulding optimisation has been implemented, because only then will the system actually need the shorter moulding time for components. The effect of stock outs on the lead time is relatively small, but the stock outs do happen very frequently – remember that the stock out KPIs are calculated as monthly averages – after the blade moulding is optimised, which is considered unacceptable by the plant managers and would be a hindrance when planning new future interventions.

Therefore, we conclude the two Operation Optimisation interventions should be implemented together, after the Rescheduling & Balancing. Even more so, if we consider they are both improving moulding processes and will require similar equipment and training, whose cost and time expenditure can be pooled.

We can see how simulation allowed us to test combined interventions in specific scenarios, to attain a greater detail of analysis and a better project prioritisation. Also, it allowed us to prepare these various scenarios in a very short time, once the main model was created.

Table 15: Secondary prioritisation of Components Optimisation, Blade Optimisation, or full Operation Optimisation, having already prioritised Rescheduling & Balancing, under design perspective

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	2D vs 3D (FLT)	Effect (PP)
Config 11	119.50	11.37	0.00	0.00	-	-	-
Config 25	116.24	11.14	0.00	0.00	-	-2.7%	-
Config 13	119.50	11.37	0.00	0.00	0.0%	-	0.0%
Config 15	116.36	10.74	107.31	0.00	-2.6%	-	-5.6%
Config 17	119.56	10.49	0.00	0.00	0.1%	-	-7.8%
Config 27	116.24	11.14	0.00	0.00	0.0%	-2.7%	0.0%
Config 29	113.96	10.47	55.04	0.00	-2.0%	-4.6%	-6.1%
Config 31	117.82	10.25	0.00	0.00	1.4%	-1.5%	-8.0%

Regarding Juxtaposition 8, 9 and 10, we will discuss the major points already extrapolated from their design counterparts, namely Juxtaposition 5, 6 and 7 respectively, but for the plant perspective and add specific insight only valid for it. The juxtaposition logic is the same as for their design counterparts.

For Juxtaposition 8 and its data in Table 16, we see the same results for plant perspective as for the design. The Operation Optimisation intervention on its own does not lead to a time or PP reduction.

For Juxtaposition 9 and its data in Table 17, the insight from Juxtaposition 6 holds. Therefore, also under design perspective we support the prioritisation of the Rescheduling & Balancing intervention over the Operation Optimisation, and decline their concurrent implementation. Moreover, we notice how the Rescheduling & Balancing intervention has a bigger effect on the plant perspective model compared to the design perspective, due to the bottlenecks in the BF phase resolved by the intervention being even more critical under plant perspective.

For Juxtaposition 10 and its data in Table 18, we see that the Components Optimisation is completely ineffective time-wise and that Blade Optimisation is less effective and does not lead to stock outs of components. This is due to the intervention backlog at the plant, which is affecting mostly the BM phase, the new bottleneck after the Rescheduling & Balancing implementation.

Under the plant perspective, we do not support the idea of implementing the Operation Optimisation intervention, instead the plant should focus on the intervention backlog and reduce it before investing resources into further optimisation of the moulding processes. This will increase productivity and reduce lead times in a more efficient way, reduce the WIP at the plant, increase the utilisation of stations, and push the plant operations towards the standards expected by design.

Furthermore, we can easily recognize the soft spot in the FLT and PP results that we first noticed in Juxtaposition 3. We can now safely assume this soft spot is due to the bottleneck shifting from the BF phase to the BM phase; this is more visible under plant perspective, due to some processes taking longer time, especially the BM phase. Moreover, the negative effect is worsened by the higher pace at which blades would be forwarded to the BF after the implementation of the blade moulding optimisation. As stated for the design perspective in

Juxtaposition 6, the detailed modelling of the crane performance allows us to notice the extra waiting time in the BF area due to a more crowded production line.

Table 16: Prioritisation of Components Optimisation, Blade Optimisation, or full Operation Optimisation, under plant perspective

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	2D vs 3D (FLT)	Effect (PP)
Config 2	282.60	21.44	0.00	0.00	-	-	-
Config 4	275.28	19.76	0.00	0.00	-	-2.6%	-
Config 6	282.60	21.44	0.00	0.00	0.0%	-	0.0%
Config 8	282.61	21.42	0.00	0.00	0.0%	-	-0.1%
Config 10	282.61	21.42	0.00	0.00	0.0%	-	-0.1%
Config 20	275.26	19.76	0.00	0.00	0.0%	-2.6%	0.0%
Config 22	275.28	19.74	0.00	0.00	0.0%	-2.6%	-0.1%
Config 24	275.28	19.74	0.00	0.00	0.0%	-2.6%	-0.1%

Table 17: Prioritisation of full Operation Optimisation, Rescheduling & Balancing, or their combination, under plant perspective

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	2D vs 3D (FLT)	Effect (PP)
Config 2	282.60	21.44	0.00	0.00	-	-	-
Config 4	275.28	19.76	0.00	0.00	-	-2.6%	-
Config 10	282.61	21.42	0.00	0.00	0.0%	-	-0.1%
Config 12	118.79	14.85	0.00	0.00	-58.0%	-	-30.7%
Config 18	119.01	14.00	0.00	0.00	-57.9%	-	-34.7%
Config 24	275.28	19.74	0.00	0.00	0.0%	-2.6%	-0.1%
Config 26	126.92	14.51	0.00	0.00	-53.9%	6.8%	-26.6%
Config 32	128.11	13.63	0.00	0.00	-53.5%	7.6%	-31.0%

Table 18: Secondary prioritisation of Components Optimisation, Blade Optimisation, or full Operation Optimisation, having already prioritised Rescheduling & Balancing, under plant perspective

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	2D vs 3D (FLT)	Effect (PP)
Config 12	118.79	14.85	0.00	0.00	-	-	-
Config 26	126.92	14.51	0.00	0.00	-	6.8%	-
Config 14	118.79	14.85	0.00	0.00	0.0%	-	0.0%
Config 16	119.01	14.00	0.00	0.00	0.2%	-	-5.7%
Config 18	119.01	14.00	0.00	0.00	0.2%	-	-5.7%
Config 28	126.94	14.51	0.00	0.00	0.0%	6.9%	0.0%
Config 30	128.11	13.64	0.00	0.00	0.9%	7.6%	-6.0%
Config 32	128.11	13.63	0.00	0.00	0.9%	7.6%	-6.0%

6.2 Suggested implementation schedule

We can now present our suggested schedule for the prioritisation of the new interventions and of the intervention backlog, to improve the plant situation based on the FLT, PP and on the stock outs. The backlog is considered as a whole and not as a set of projects, because of the lack of data and time to perform a proper analysis of it at this point. All considerations on the interventions are now based on the plant perspective, as we want to suggest the best schedule for real operations at the plant.

We estimated that the backlog of interventions currently accounts for a performance loss of 23-24% on the FLT and of 22% on the PP, compared to what could be achieved if already developed interventions were to be correctly and completely implemented at the Plant. Moreover, its reduction would also lead to an easier estimation process for the research department, easier implementation of new projects, and increase the usability and reliability of plant data in the design environment. This is one of the main goals for our research in SBT-NL.

However, we tested the Rescheduling & Balancing intervention and discovered it has a performance loss on the PP due to the input gap, but not a significant loss regarding FLT. Also, the Rescheduling & Balancing intervention has a reduction effect on the FLT and the PP of 58% and 30% respectively, under plant perspective.

Furthermore, we found the Operation Optimisation intervention to be ineffective on its own and unnecessary to avoid systematic stock outs of components once the layout intervention is implemented in the plant perspective. On the other hand, we understand it has a reducing effects on the PP that is relatively higher than the consequent increase in FLT time, plus cost reductions which we are not able to quantify but are supported as a positive investment by colleagues at SBT-NL.

We suggest the Rescheduling & Balancing intervention to be the first implemented intervention, because it has a very high positive effect on the FLT and the PP and because the input gap does not influence its FLT performance significantly. Then, we support the reduction of the intervention backlog as it will improve the reliability of the improvements procedure and the alignment of the design and plant perspectives, which is one of the desired goals of SBT-NL. It would also have a higher effect on the selected KPIs, especially on the PP, than the Operation Optimisation intervention as a whole. Lastly, we advocate for implementing the Operation Optimisation intervention, but we propose to implement the Components Optimisation and the Blade Optimisation concurrently to pool the training costs for employees at the plant and to avoid a mismatch in lead times between components and blade moulding. Finally, the implementation schedule is as follows:

1. Rescheduling & Balancing.
2. Reduction of the intervention backlog.
3. Full Operation Optimisation.

Following the implementation schedule should transform the system as shown in Table 19. The starting point is Configuration 4, the 3D As Is system under plant perspective, that is our most detailed representation of what currently happens at the plant in Ratlam. By implementing the Rescheduling & Balancing, the system should reach the performances of Configuration 26, the 3D To Be system with layout intervention and using plant perspective. The intervention backlog reduction would then shift the system to the situation of Configuration 25, which is the same as the previous implementation step but under design perspective. As a last step, the implementation of the full Operation Optimisation should allow the plant to reach the results of Configuration 31, the 3D To Be system with all intervention implemented and aligned to the design perspective.

Table 19: Plant performance based on implementation schedule's steps

	FLT (h)	PP (h/blade)	CSO	MSO	Effect (FLT)	Effect (PP)
Config 4	275.28	19.76	0.00	0.00	-	-
Config 26	126.92	14.51	0.00	0.00	-53.9%	-26.6%
Config 25	116.24	11.14	0.00	0.00	-57.8%	-43.6%
Config 31	117.82	10.25	0.00	0.00	-57.2%	-48.1%

The suggested implementation schedule can be further assessed considering quantitative factors missing in the current simulation models, e.g., detailed cost of interventions, or other qualitative factors, e.g., the difficulty of implementation. This is represented by the last step of the adapted methodology in Figure 14.

We did not have time to perform an extensive analysis with additional decision-making tools and other factors. Furthermore, it is a step of the procedure not directly linked to the goal of this research, which is to demonstrate the usefulness of simulation as an asset in SBT-NL. Therefore, in Appendix D, we provide an example on how to use the AHP to assess the complexity of implementing proposed interventions. By using the AHP, managers can prioritise interventions based on contingently weighted factors and on the availability of resources at a given time. The performance analysis through simulation and the complexity analysis through AHP can be complementarily used by decision-makers to obtain a comprehensive perspective.

Aside from the implementation schedule, we have two other recommendations based on our experiments, which will be useful for the research department of SBT-NL to improve the intervention procedure:

I. We advise the research department to improve its procedure to account for queueing times and delays, as the identified current gap is significant, namely a 77 hours increase, or an FLT increase of 51%, compared to the analytical design model in Figure 18. Simulation has proved itself to be an effective tool to account for queueing effect and should be chosen for this goal.
II. We advise the research department to use 3D simulation to account for the cranes, forklift, and trailer movements only when assessing production plants with a larger size than the one in Ratlam and more handling requests. While 3D simulation would still be useful for its compelling animation and better visualisation, it is not necessary to represent the detailed crane movements for standards sized plant like the one in Ratlam,

since we noticed how the handling equipment's movements are now just slightly overestimated. For larger plants, the current transportation's assumption will probably underestimate the required time and delays, thus requiring better modelling.

We analysed the experimental results following our juxtapositions, obtaining many insights. We managed to assess the inaccuracy of the current design approach for interventions compared to simulation. We quantified the misalignment gap between plant and design standards for operations. We evaluated the performance of the tested interventions and suggested an implementation schedule that should improve plant productivity and reduce lead times in the most effective way. Lastly, we provided insights on how to use 3D modeling.

Performing a simulation study with a proper approach proved to be fruitful and helped the research facility to better foresee effects of newly designed interventions, also helping with their prioritisation. In the next chapter, we will draw conclusion on our research project at SBT-NL and discuss further research topics.

Chapter 7: Conclusions, recommendations, and further research

Section 7.1 provides conclusions on our evaluation of DES as a strategic decision tool, based on the definition of such a tool for SBT-NL given in Section 2.4, and recommendations on how to improve production at the Ratlam plant. Section 7.2 follows with topics for further research that were raised in the literature chapter of during the simulation study.

7.1 Conclusions & recommendations

Our assignment had the goal of assessing simulation as a strategic decision tool in the wind turbine sector, with regards to improving manufacturing operations. To reach our goal, we defined how a strategic decision tool would help SBT-NL in the optimisation of blades production and performed a simulation study on one of the standard sized blade production plant of Suzlon, the Ratlam plant. We found different simulation methodologies in the literature and evaluated them through criteria generated by company stakeholders, emphasizing simplicity and statistical guidelines. We selected Law's methodology and adapted it to the company improvement process for operations. Then, we followed the methodology's procedure in collecting data, modelling the Ratlam plant, testing alternative scenarios, and achieving reliable results through statistical procedure. Lastly, we performed a comparison of the resulting scenarios, extrapolated insights, and suggested an implementation schedule to increase the plant performances regarding lead times and productivity.

It is beneficial to present again the definition of simulation as a useful strategic tool for SBT-NL, as we have described it in Section 2.4:

"To be deemed a useful strategic tool, simulation should help us to structure the research process at the company, to better gather and generate data, to achieve reliable preliminary analyses, to represent the plant environment in detail, to create various scenarios based on the plant perspective with and without specific interventions in the backlog, and to virtually test the newly proposed interventions which are too costly to test at the real plants."

We substantiate simulation has answered to all of the point in the previous definition and this is visible through the achievements reached during the simulation study:

- We adapted a powerful and flexible simulation methodology to the improvement procedure at SBT-NL, which is shown in Figure 14.
- In Section 4.2, we collected data on the studied system following the adapted methodology, structured and represented it in different medias – e.g., assumptions document, graphical conceptual models, input documents –, allowing for better knowledge sharing in the company and understanding of the modelling procedure.
- We represented the Ratlam plant through highly detailed computer models, both in 2D and 3D visualisations, thus increasing the results credibility and the comprehension of the interactions in the system.

- We tested different intervention scenarios as model configurations and used the generated data to achieve statistically reliable preliminary analysis, before implementing them at the plant.

Moreover, the simulation study identified an implementation schedule for the proposed interventions, as in Section 6.2, based on quantitative performances which could be achievable by the plant in the near future. These validated interventions will allow the Ratlam plant to potentially reduce the lead time of the blade finishing area by 57%, a reduction of more than 150 hours, and increase its productivity by 48%. The implementation schedule is as follows:

1. *Rescheduling & Balancing*, an intervention which modified the process logic substituting the formation of a batch of blades with the standardisation of blades to three weight classes, and redistributing the extra capacity in a new layout disposition.
2. *Reduction of the intervention backlog*, the dedication of plant resources to implement or correct interventions already released by the research department but never finalised at the plant.
3. *Full Operation Optimisation*, the reduction of components and blade moulding time together with a reduction on usage of materials.

We also quantified the data misalignment gap between the plant data and the design assumptions made at the research department in SBT-NL, defined in Section 2.4 and represented in Figure 11. The gap is composed of three parts: design assumptions queuing effects, design assumptions on handling equipment, and an implementation backlog at the plant of past projects.

- The inaccuracy of design assumptions regarding queueing effects is of 77 hours for the FLT and negligible for the plant productivity, as the system is simply subject to a high WIP that is not considered in design assumptions. This is not influencing the plant throughput but should be addressed by the research department using simulation and other analytical tools, to drastically increase the accuracy on lead times.
- The inaccuracy of design assumptions regarding the cranes, forklift and trailer is in the order of several hours of overestimation, thus it is not significant when considering standard sized plants like the one in Ratlam. Therefore, we suggest to only model handling equipment in high detail when evaluating interventions at larger sized plant where it is subject to a higher utilisation, as modelling its logic and movements requires substantial effort.
- The effect of the intervention backlog – i.e., a set of completed interventions by design that were never finalised at the plant, mostly processing time reductions – was quantified to be more than 50 hours for the FLT and a loss of 22% in productivity, for the Ratlam plant. Its reduction would allow for an important performance improvement and, most importantly, it would re-align the plant situation to the design data at SBT-NL, increasing plant data reliability and easing the development of future interventions. That is why the reduction of the intervention backlog is the second suggested step in our implementation schedule.

Because of the positive results and useful insights gathered through simulation, we recommend SBT-NL to create a dedicated storage for simulation models, assumptions documents and all relevant data. Furthermore, when starting future simulation studies we recommend the creation of high level conceptual models, as the one in Figure 20, to increase reusability and composability between models. This is suggested by Balci (2011, 2012) in his simulation methodology. We discussed the topic of storage and reuse of simulation models in Section 2.4.

To conclude, we consider the simulation study to be successful and suggest SBT-NL to implement the intervention schedule and maintain DES as a strategic decision tool in its portfolio.

7.2 Further research

We encountered difficulties in gathering data and could not include costs in our simulation study. However, we understand that cost is an important factor when evaluating and comparing various interventions, thus we propose SBT-NL to perform a study on material, workforce and production costs and combine the current DES model with Technical Cost Modelling (TCM) as described in Section 3.2. This will prove useful both to validate the proposed schedule under cost perspective and for a more comprehensive analysis for future simulation studies.

Linked to the addition of cost factors, we also suggest to expand the analysis with the AHP reported in Appendix D. It could be better integrated in the comparison of interventions to obtain a unique implementation schedule upfront, with a holistic approach on well-defined criteria that are important for the company. Moreover, the feasibility of other managerial tools could be investigated.

Another topic for further research would be to confute our modelling assumption on processing times being representable with triangular distributions. After the blade production in Ratlam will resume, it would be beneficial to obtain a sufficient number of observations for all production operations included in the model and fit more complex and representative distributions for each operation, or category of operations, e.g., using the gamma distribution that is a commonly used to represent the duration of manufacturing processes.

Before extending the interventions applicable to the Ratlam plant and the gathered insights to other locations, it would be wise to conduct a simulation study on another standard size plant which produces the exact same 2 MW blade type and on a standard size plant which produces a different blade, either from the same platform or from a higher MW blade platform. These studies would not require extensive time, as model reusability is be quite high for the first case and moderate for the second, and would allow for an empirical confirmation of our findings in the original study.

Regarding future improvement to the production plant, a sensitivity analysis could be performed per plant area – MP, CP, BM, and BF – or per operation. Such a sensitivity analysis could be based on the increase and reduction of processing times or of the number of stations. The effects on the performance indicators would highlight areas or processes where incremental improvements would perform best and be more effective.

A last further research subject could be the addition of the full blade storage yard in the model, which would be more interesting considering the new class weight logic implemented with the Rescheduling & Balancing intervention. Demand of blades for wind turbines could be analysed and a distribution could be fit, considering that demand is satisfied in batches of three blades for each wind turbine. The new yard would have to be modelled as divided in three areas, one for each standard weight class, and satisfaction of demand could be evaluated.

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Appendices

Appendix A: Methodologies diagrams and flowcharts

<u>M. Landry</u>

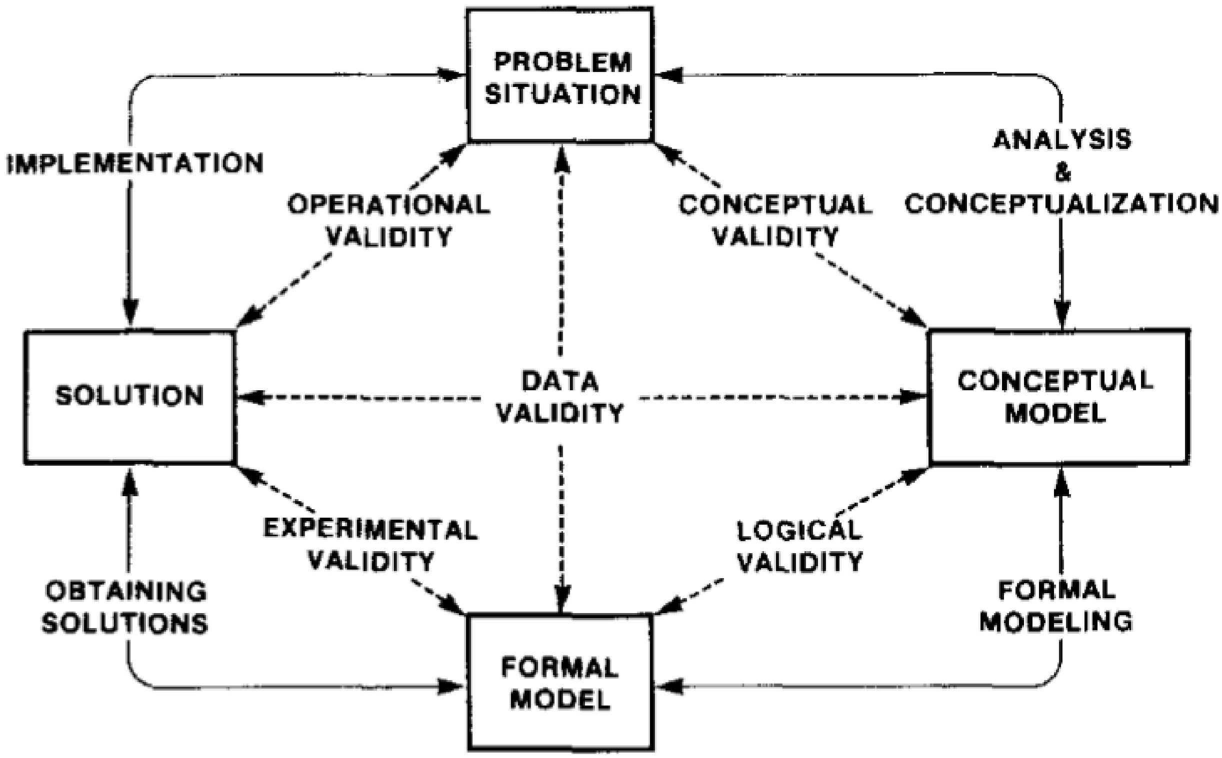

Figure 29: M. Landry, 1983, *Model validation in operations research.*

R. Shannon

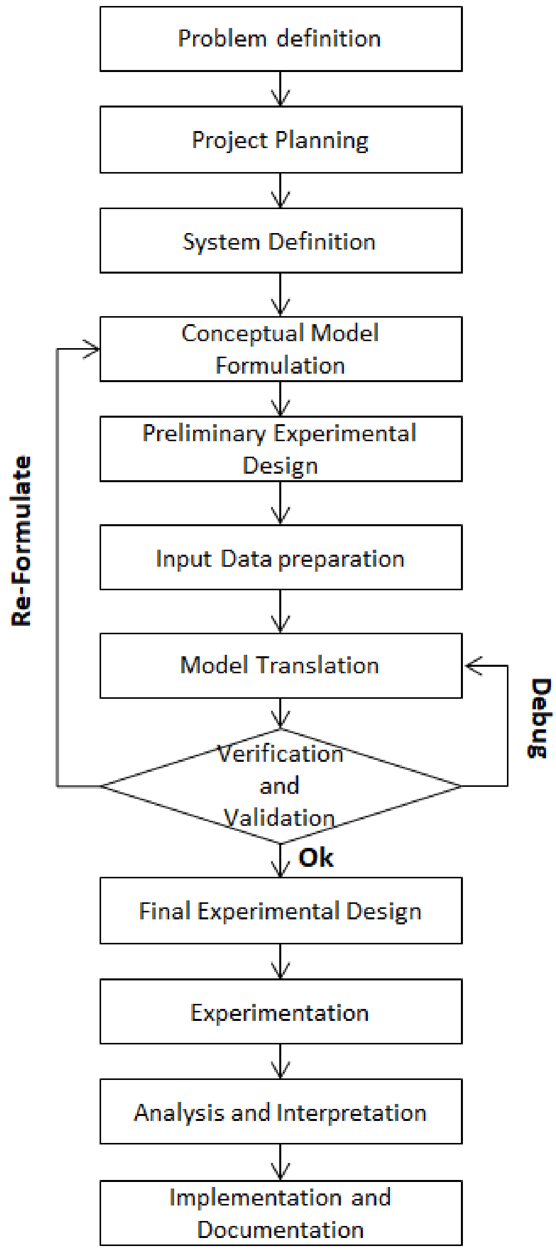

Figure 30: Own representation based on R. Shannon, 1998, *Introduction to the Art and Science of Simulation.*

J. Banks

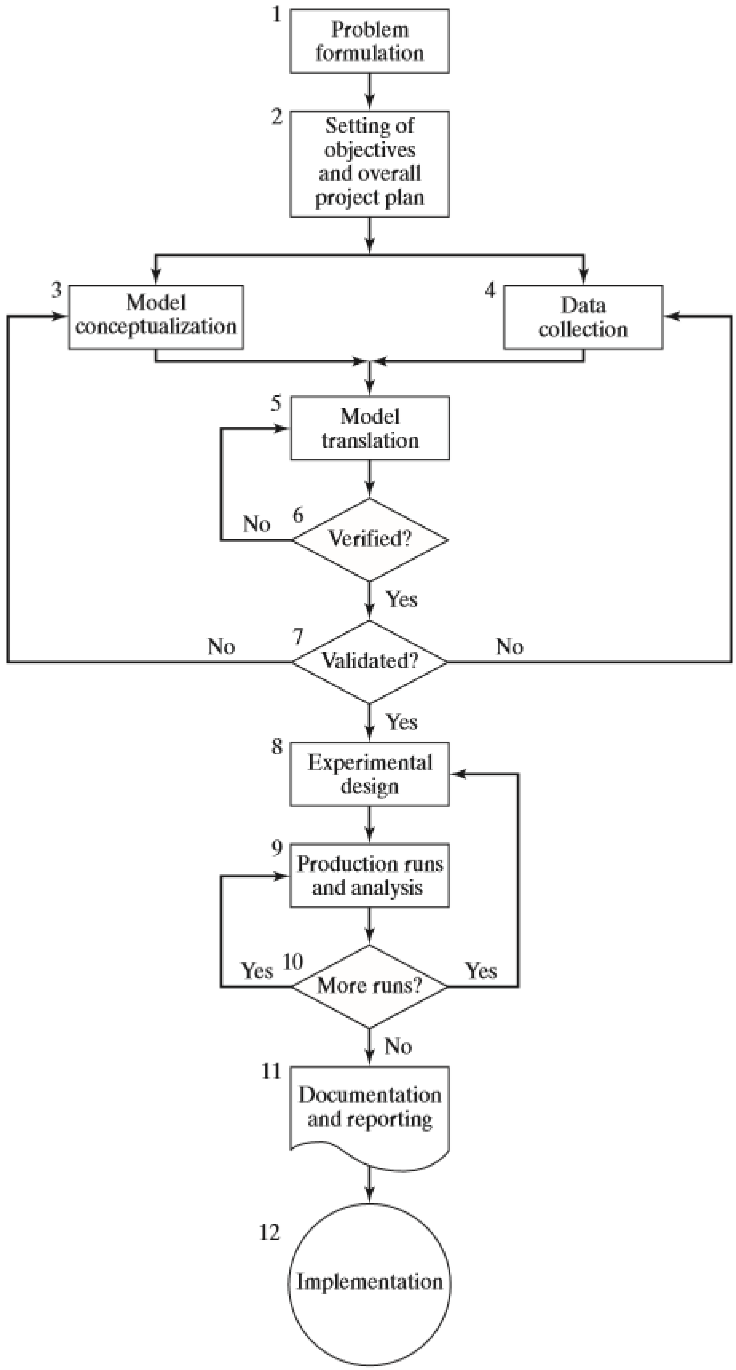

Figure 31: Banks et al. 2010, Introduction to Discrete-Event Simulation, chapter 1 of the book Discrete-Event System Simulation.

A. Law

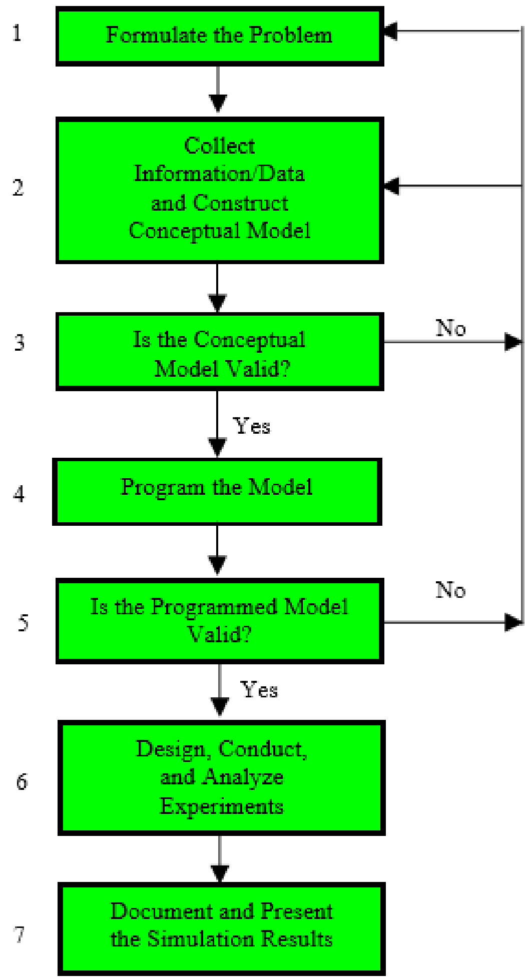

Figure 32: A. Law. 2003, *How to conduct a successful simulation study*.

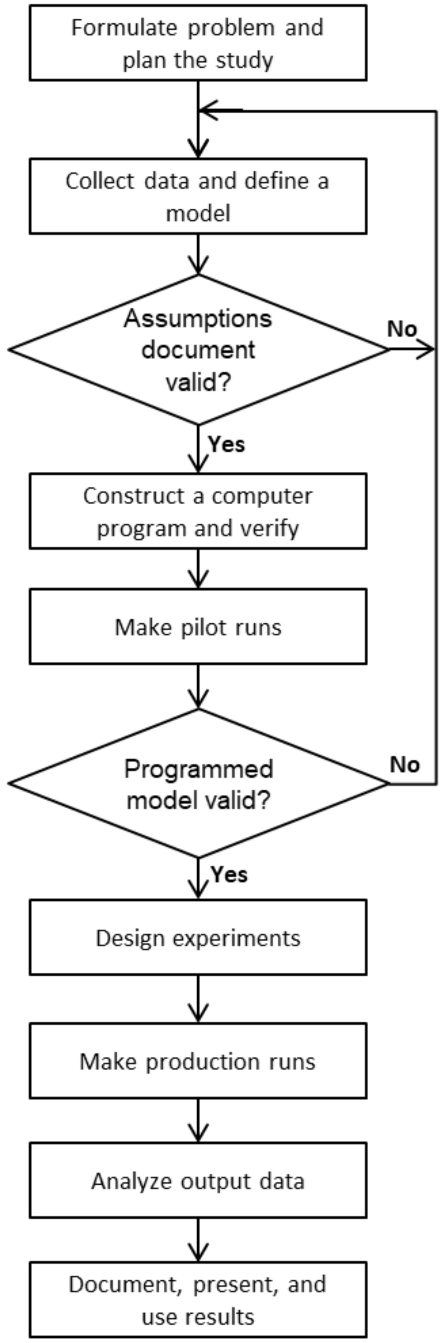

Figure 33: A. Law 2015, *Steps in a sound simulation study*, Simulation Modeling and Analysis, 5th edition.

S. Robinson

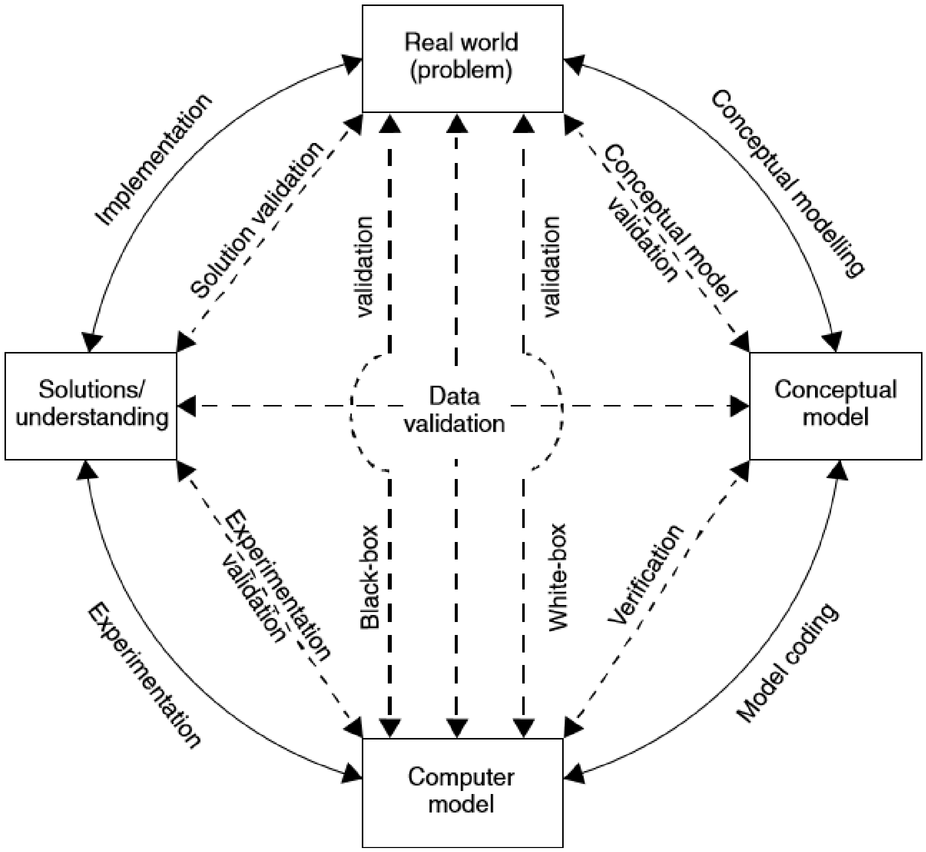

Figure 34: S. Robinson, 2004, *Simulation: The Practice of Model Development and Use,* 1st ed., Chapter 12 *Verification, Validation and Confidence.*

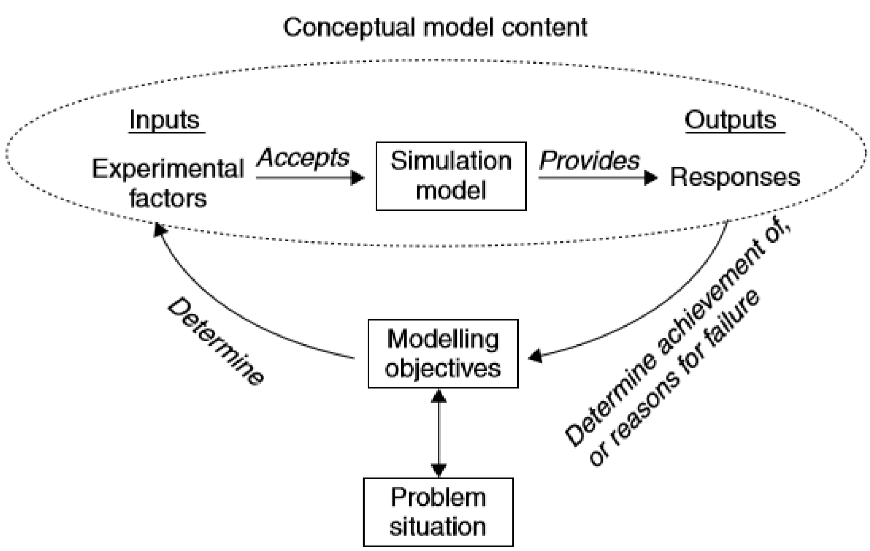

Figure 35: S. Robinson, 2004, *Simulation: The Practice of Model Development and Use,* 1st ed., *Chapter 6 Developing the Conceptual Model.*

Flowchart of Robinson's models integrated

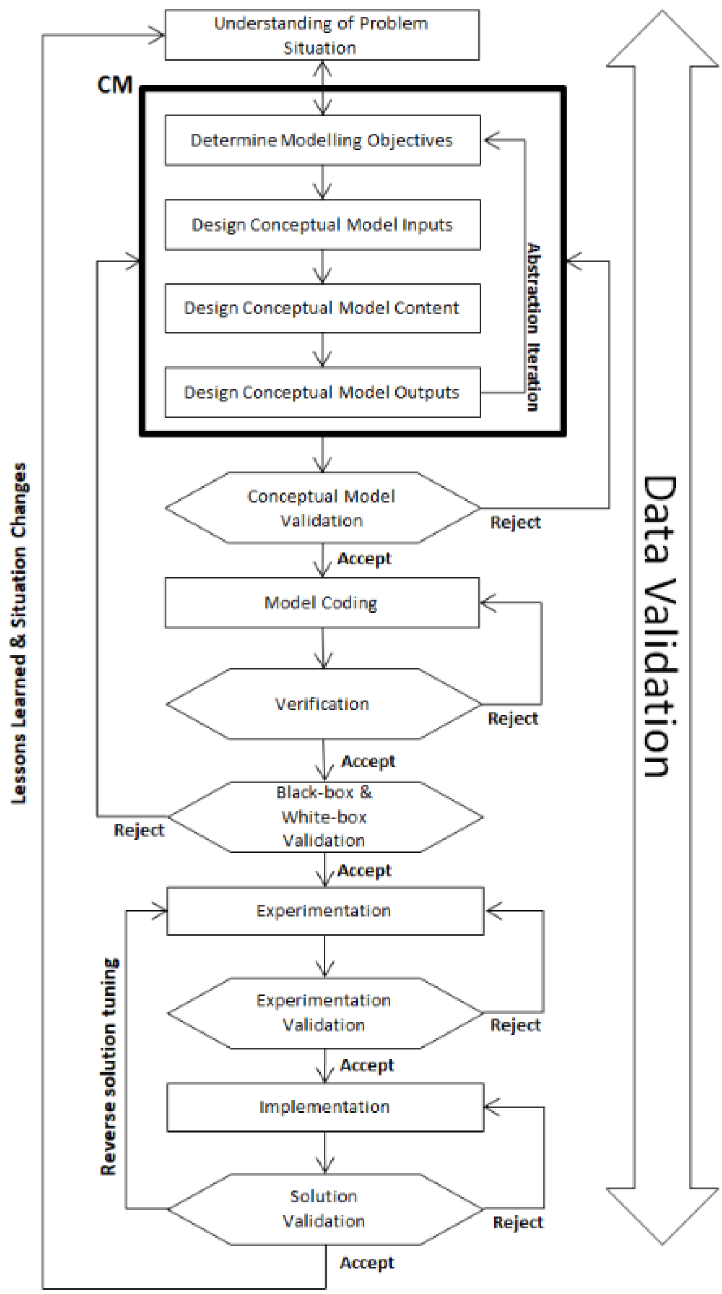

Figure 36: Own made integration of S. Robinson's diagrams.

R. Sargent

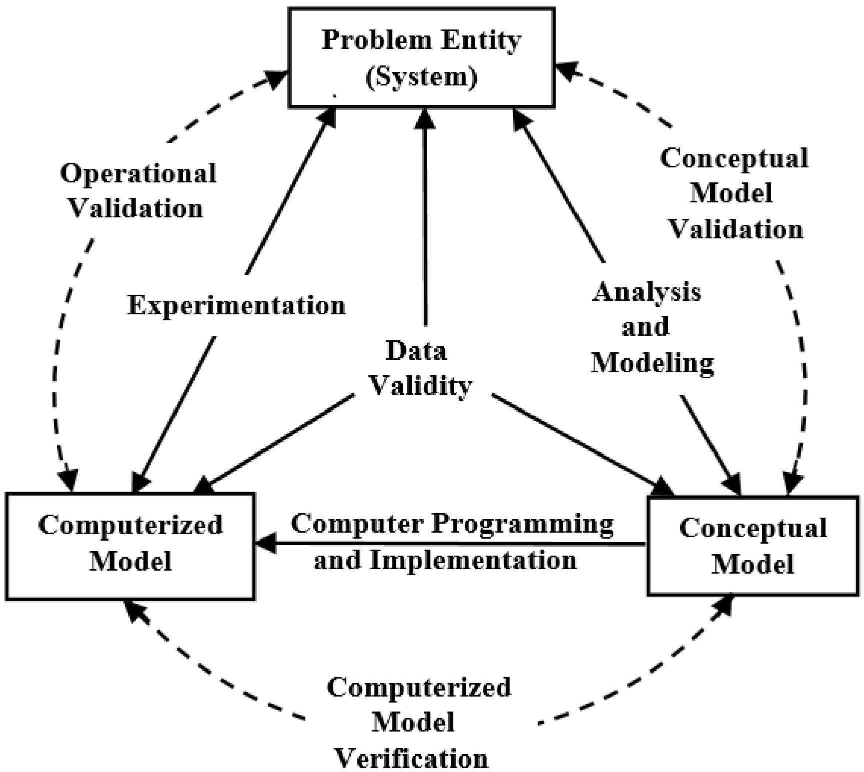

Figure 37: R. Sargent 2007, 2011 and previous, *Verification and validation of simulation models.*

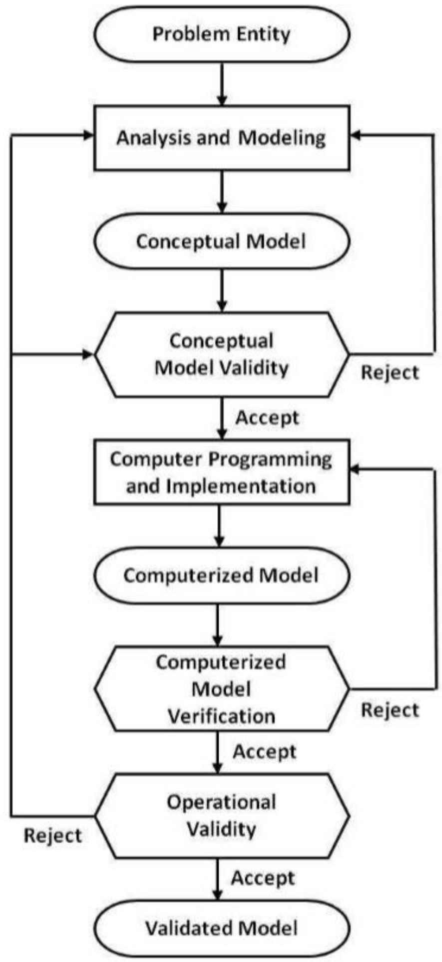

Figure 38: R. Sargent 2015, *An introduction tutorial to verification and validation of simulation models.*

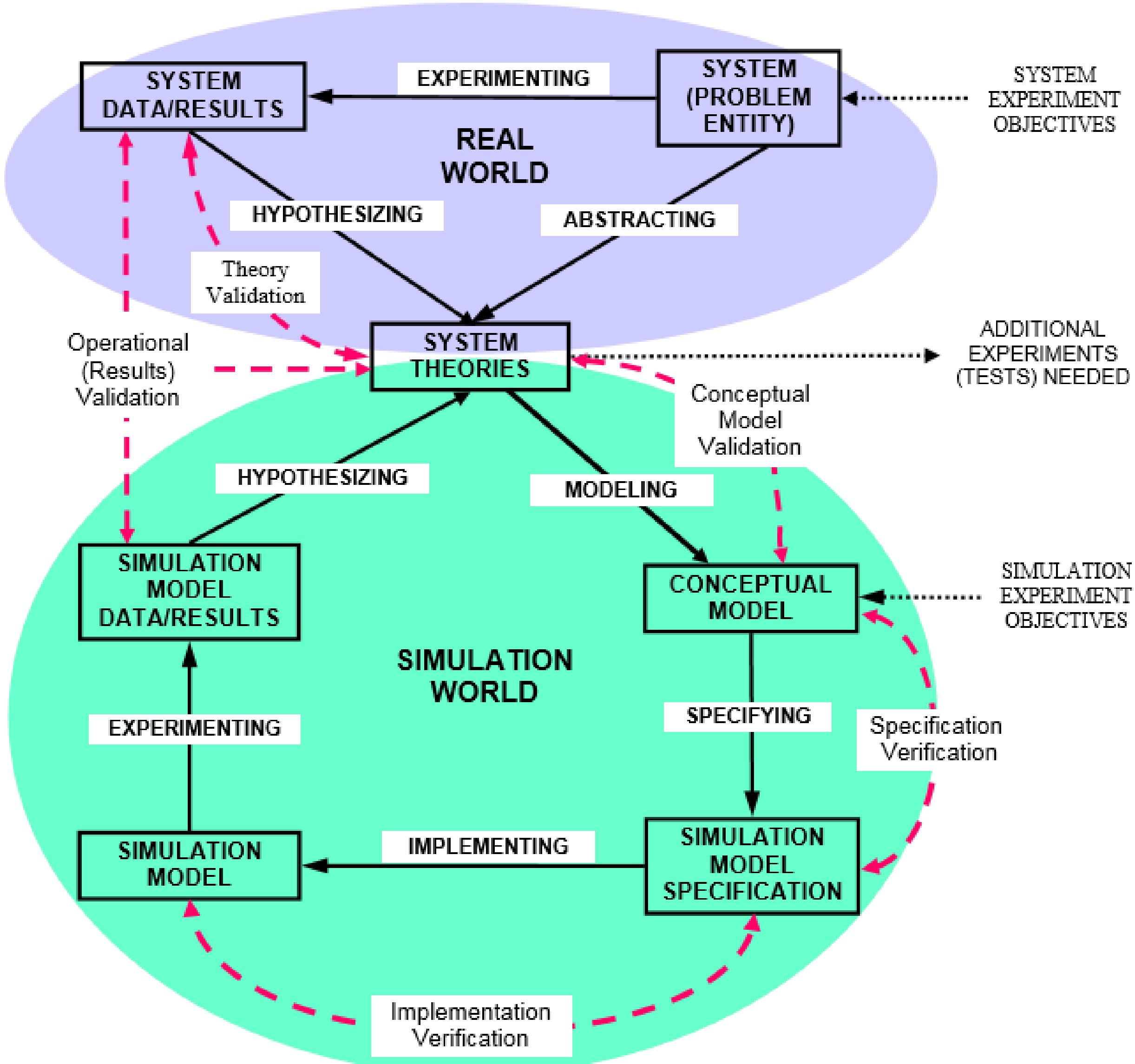

Figure 39: R. Sargent, 2007 and previous, *Verification and validation of simulation models.*

O. Balci

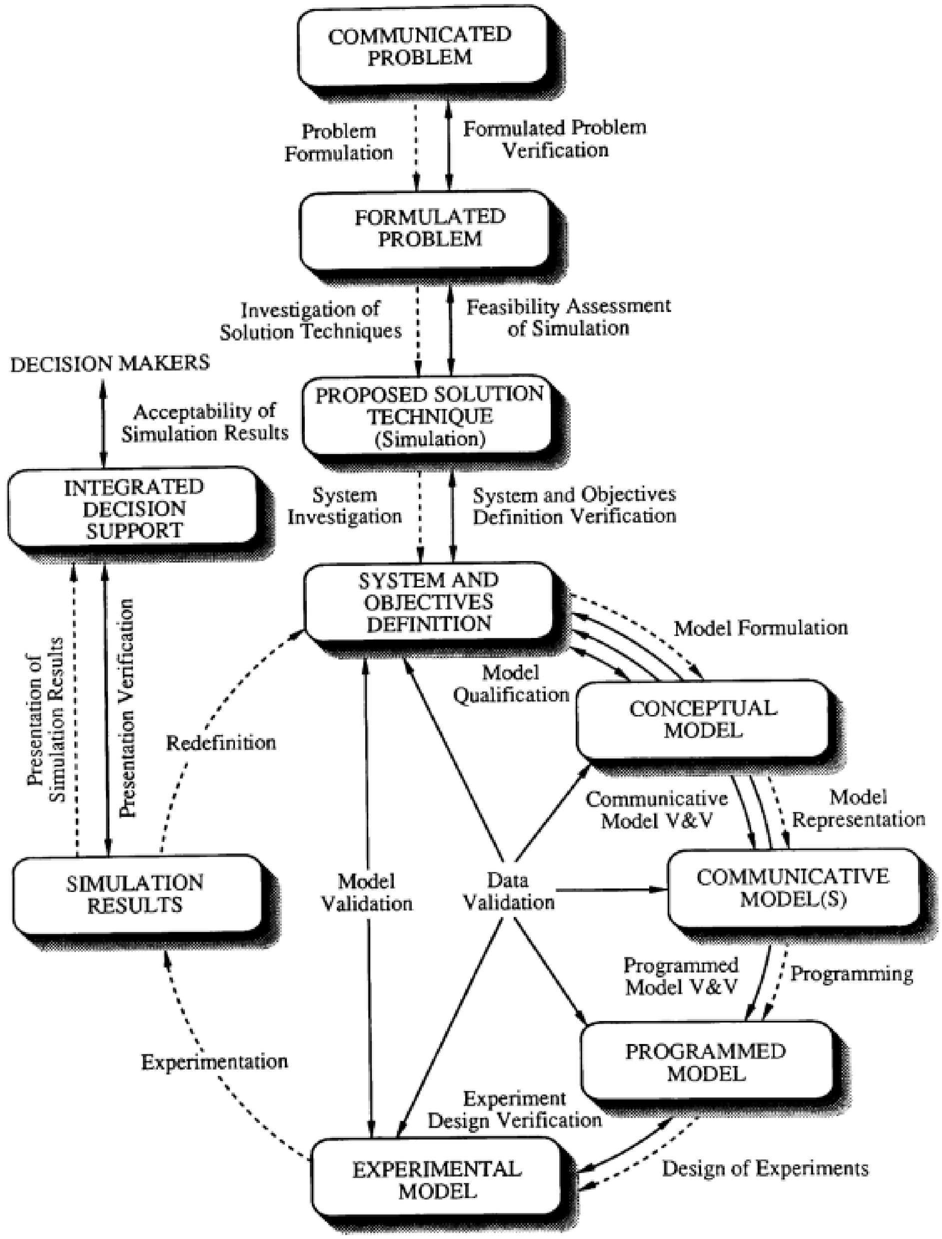

Figure 40: O. Balci 1990,*Guidelines for successful simulation studies.*

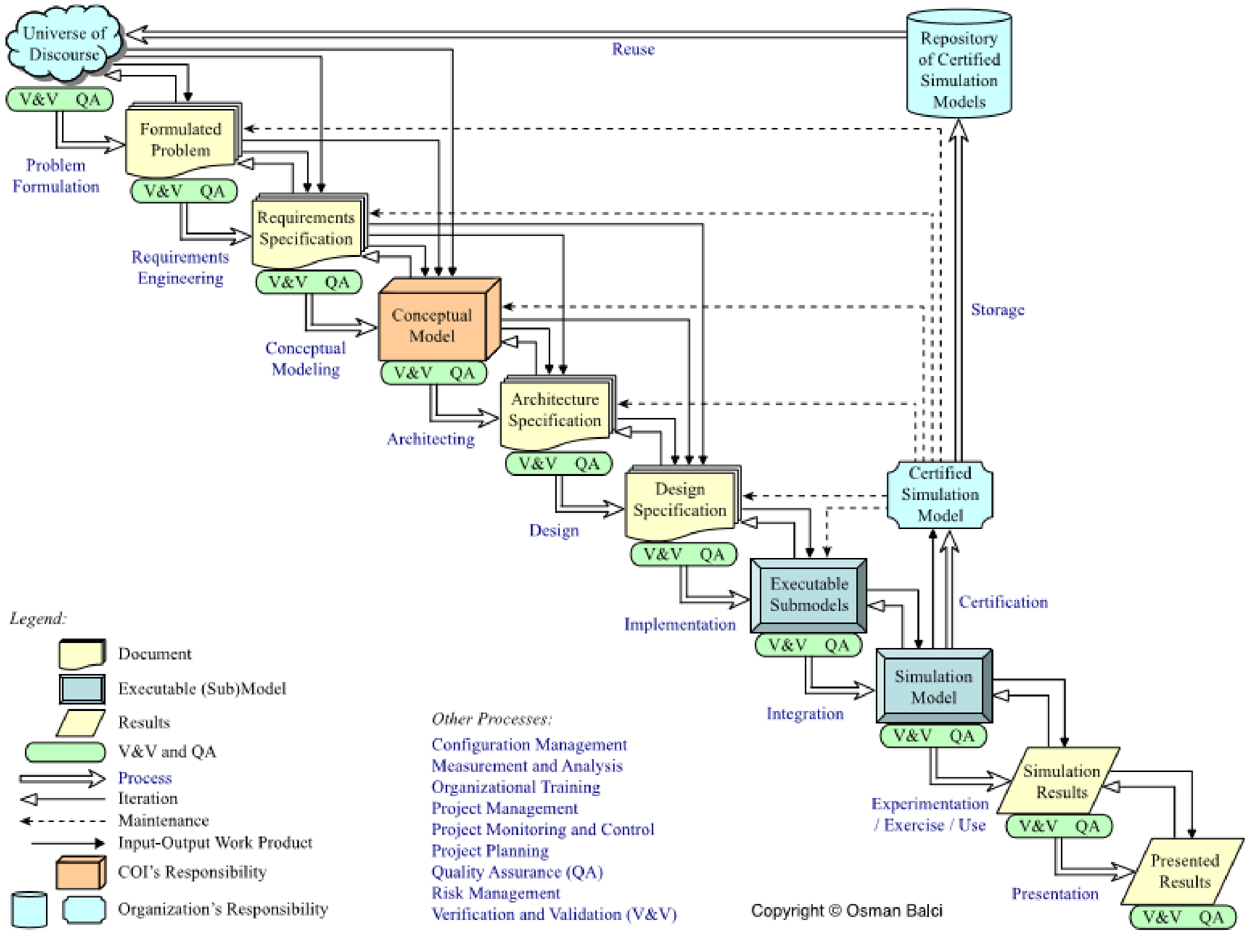

Figure 41: Osman Balci (2012), "A Life Cycle for Modeling and Simulation," S*imulation: Transactions of the Society for Modeling and Simulation International 88,* **7, 870–883.**

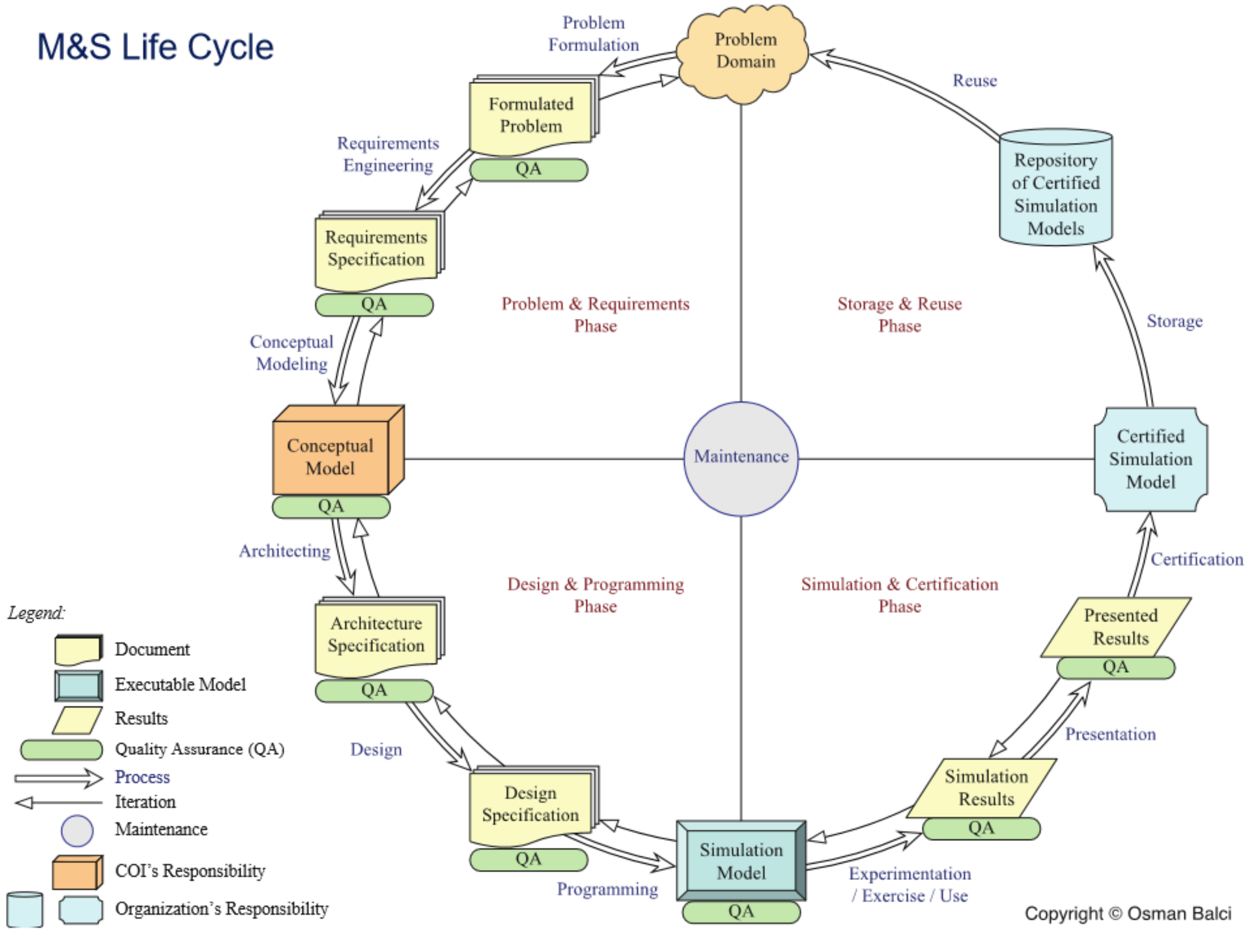

Figure 42: based on Osman Balci (2012), "A Life Cycle for Modeling and Simulation," S*imulation: Transactions of the Society for Modeling and Simulation International 88,* 7, 870–883.

Appendix B: Computer Model Algorithms flowcharts

Only the most important methods are presented in this appendix, to explain the logic of the most critical interactions between areas of the plant, or the concepts which we added to the model and that are not there in reality, e.g., the crane synchronisation.

In Figure 43, we present the release logic of blades production orders, which are stored in the form of Movable Units (entities) in a virtual buffer in the model.

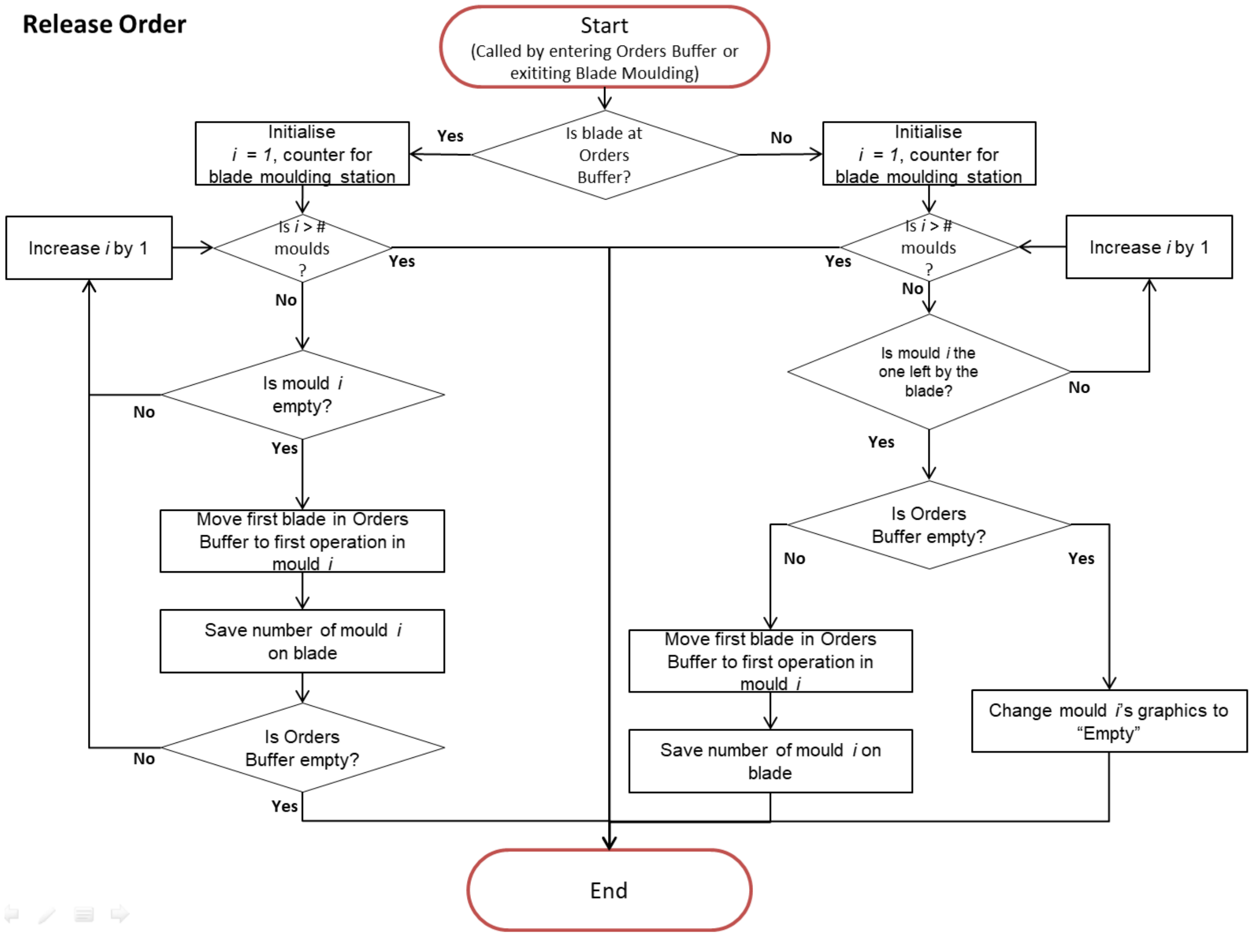

Figure 43: Method to start blade production.

Figure 44 presents the logic behind consumption of components. We only show the components' movements method as the materials' movements methods follows an identical logic.

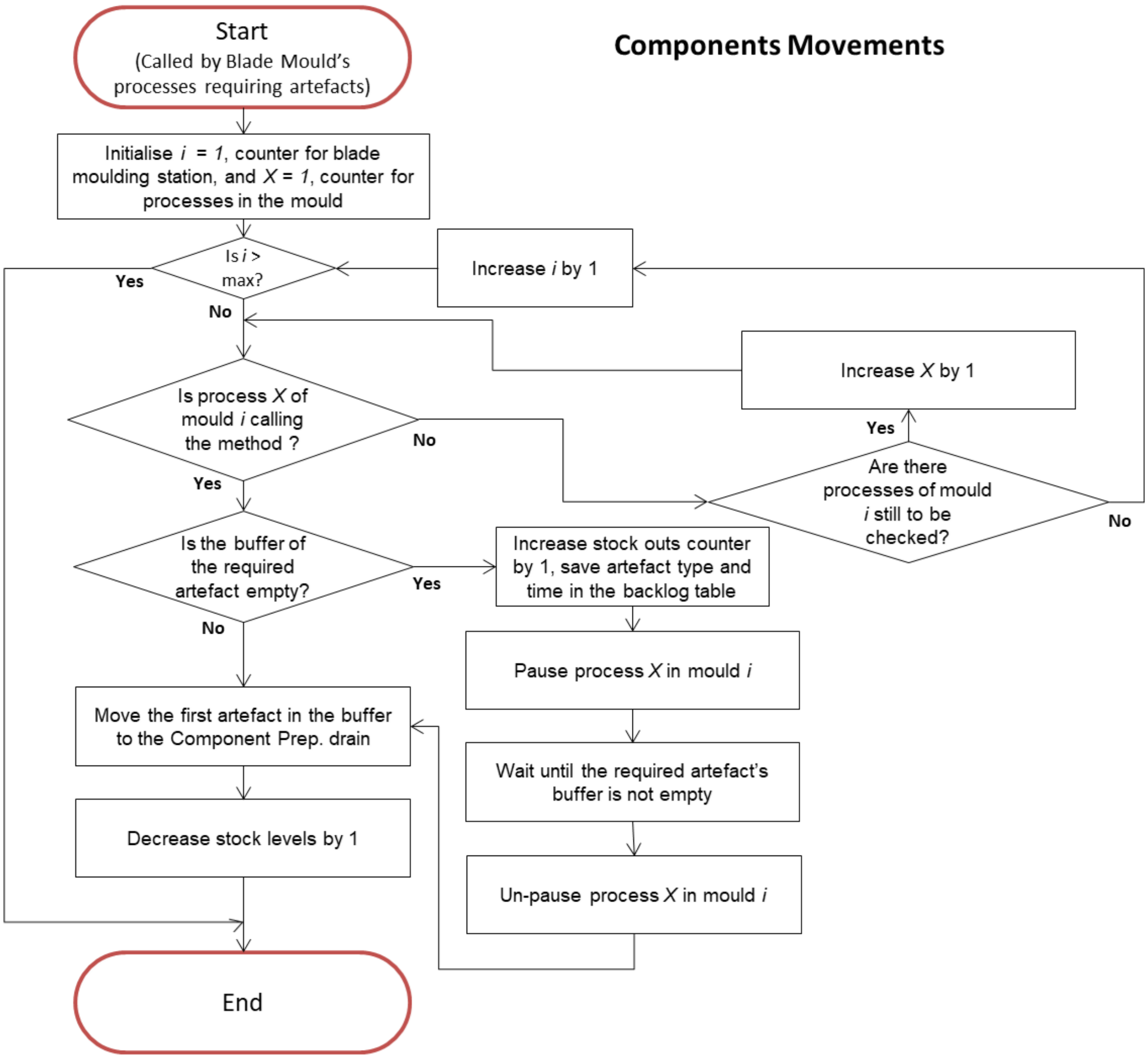

Figure 44: method to consume components requested by Blade Moulding.

In Figure 45, 46, 47, we display respectively the logic behind cranes synchronisation, crane requests and transportation, and crane movements to their default areas to prevent blocking production and collision.

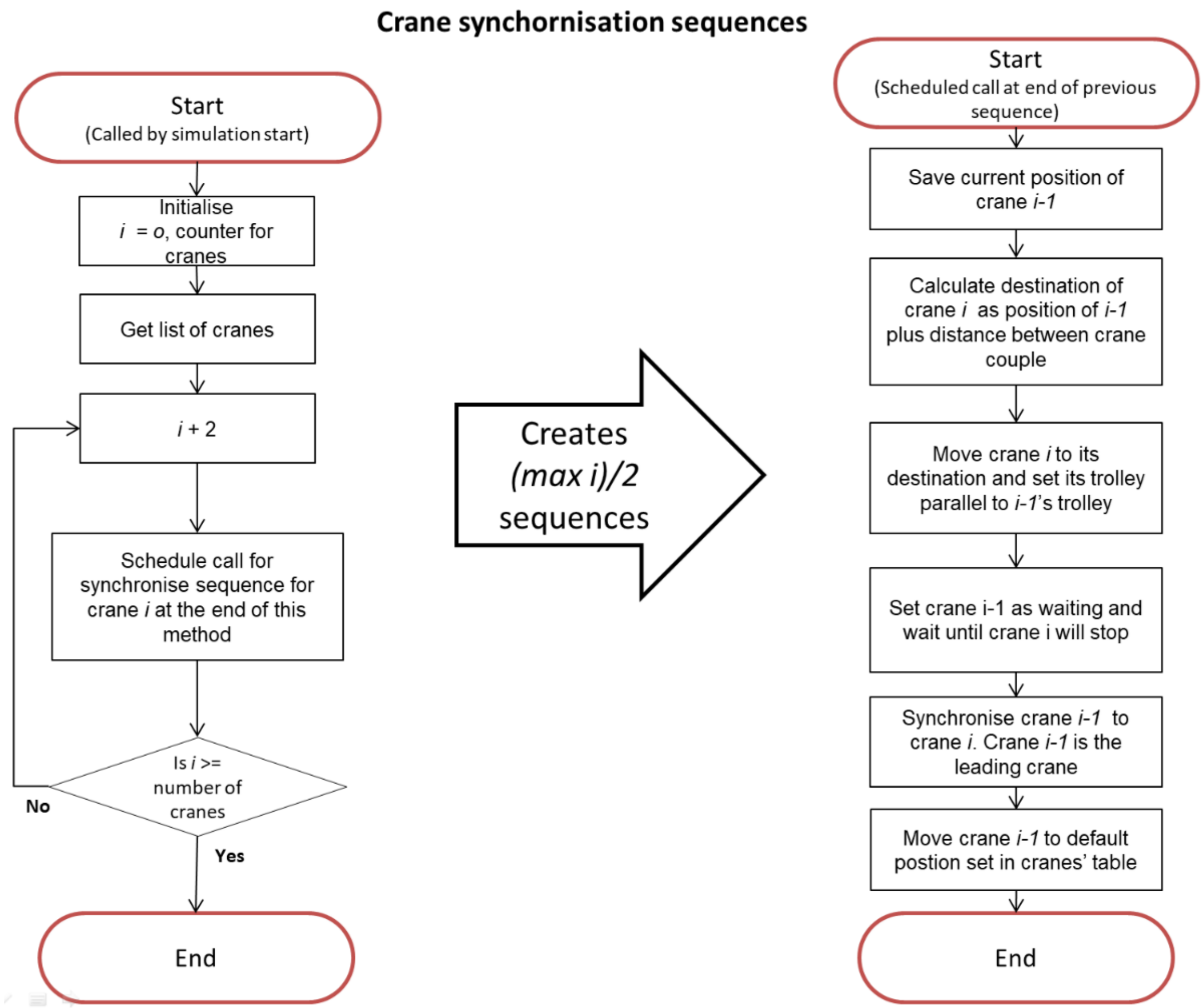

Figure 45: methods to initialise the crane couples and their default positions.

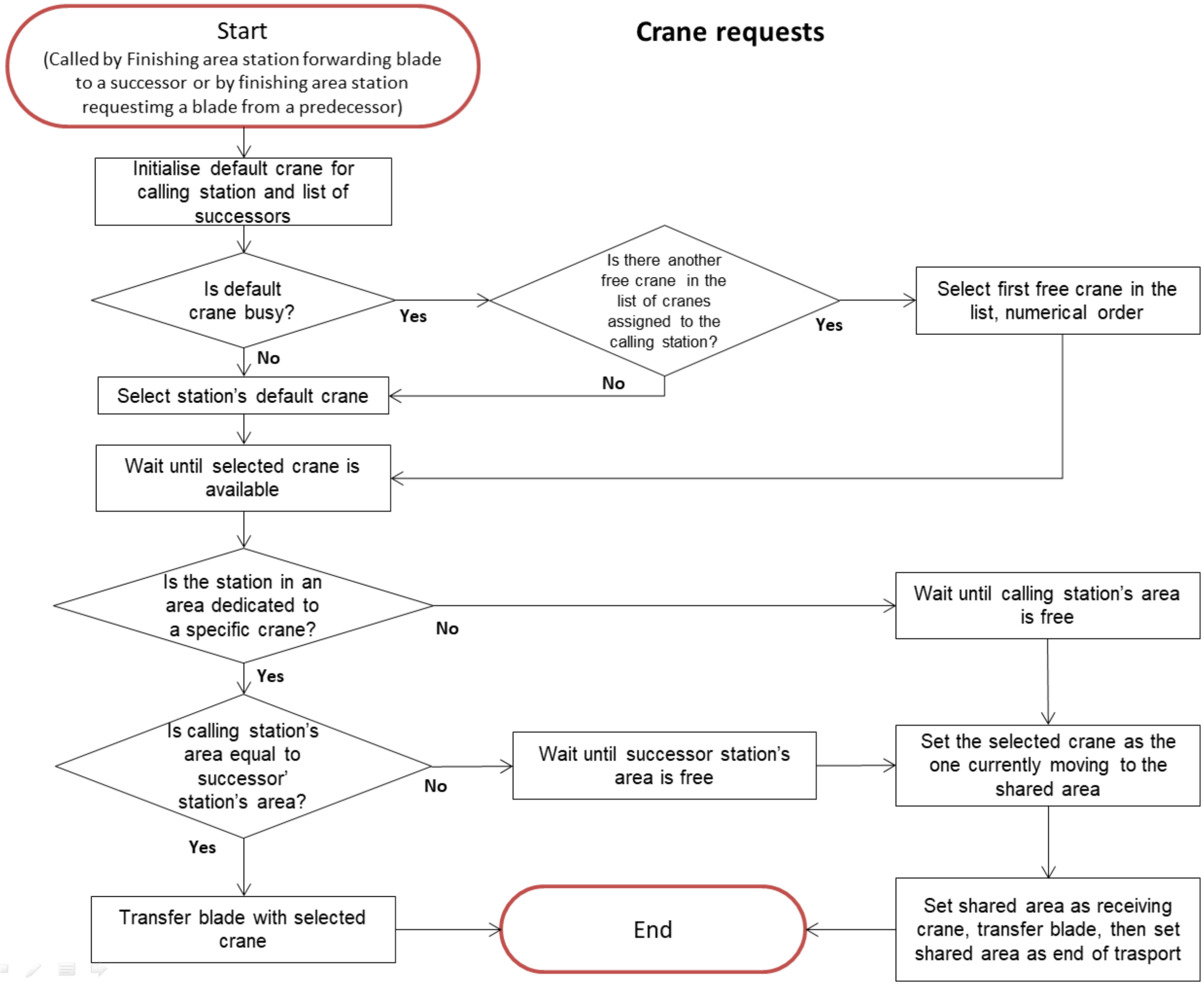

Figure 46: Method for requesting cranes and assign shared areas, to prevent collisions.

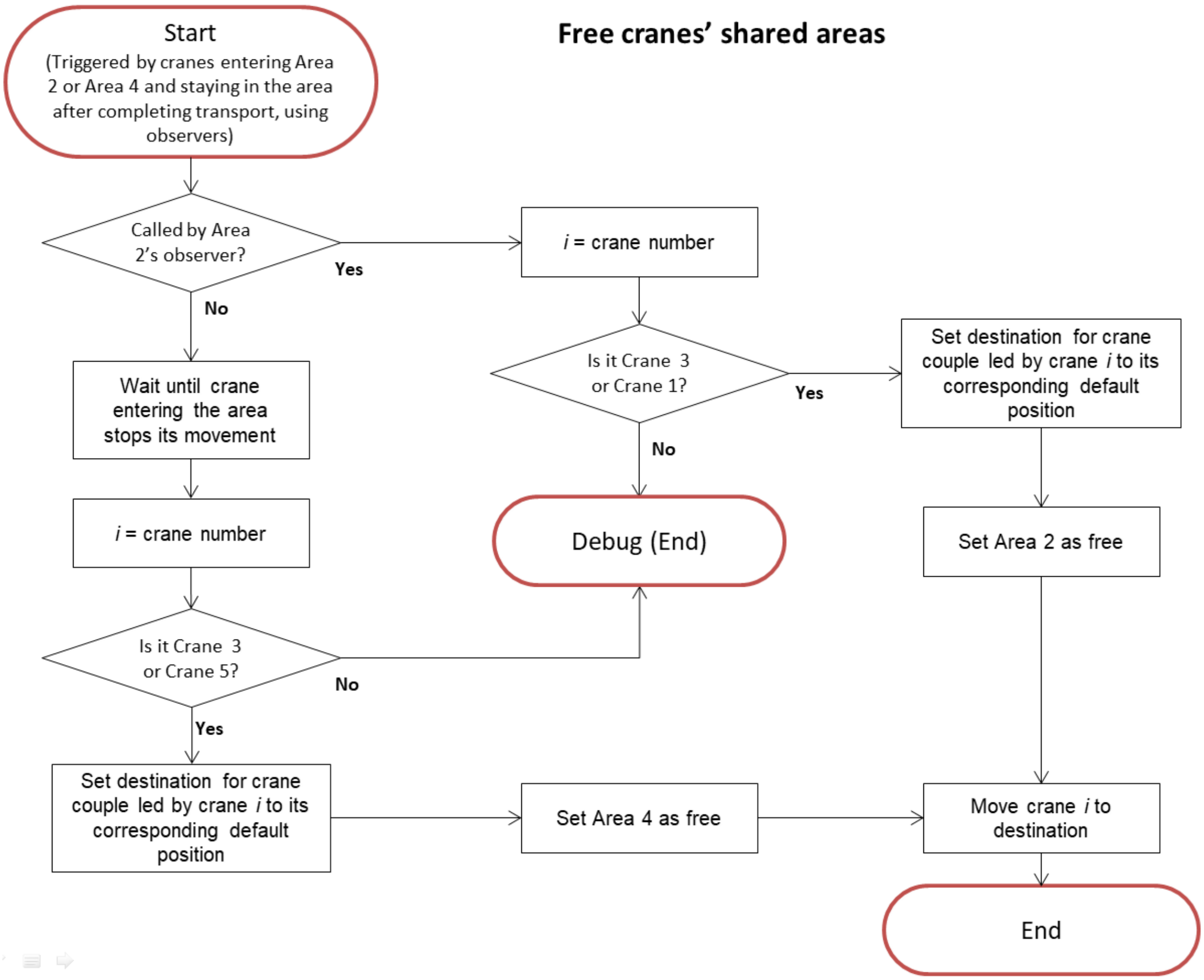

Figure 47: Method to free shared crane areas (area 2 and area 4) when cranes enter them for transportation and are not immediately called away to their default areas by blade requests.

Appendix C: Welch's graphical procedure

Here we present all the charts used for setting-up the warm-up period based on the procedure of Welch (1983). We graphically decided a data point and run the configurations models until the blade corresponding to the data point was reached, for multiple replications, then rounded to next integer and even number of days.

We refer again to Table 6 to display the settings of the procedure, where *n* is the number of replications, *m* is the run length for each configuration, and *w* is the window size of the moving average over which results have been smoothed.

Chosen data points per configuration:

- Configuration 2: blade number 44.
- Configuration 4: blade number 40.
- Configuration 18: blade number 110.
- Configuration 32: blade number 130.

Table 6: Warm-up estimations and parameters

Common settings	*w*	Configuration	Warm-up
n = 5 *m* = 288 days	5, 10, 25	2	48 days
	5, 10, 25	4	42 days
	5, 10, 25, 50	18	72 days
	5, 10, 25, 50	32	80 days

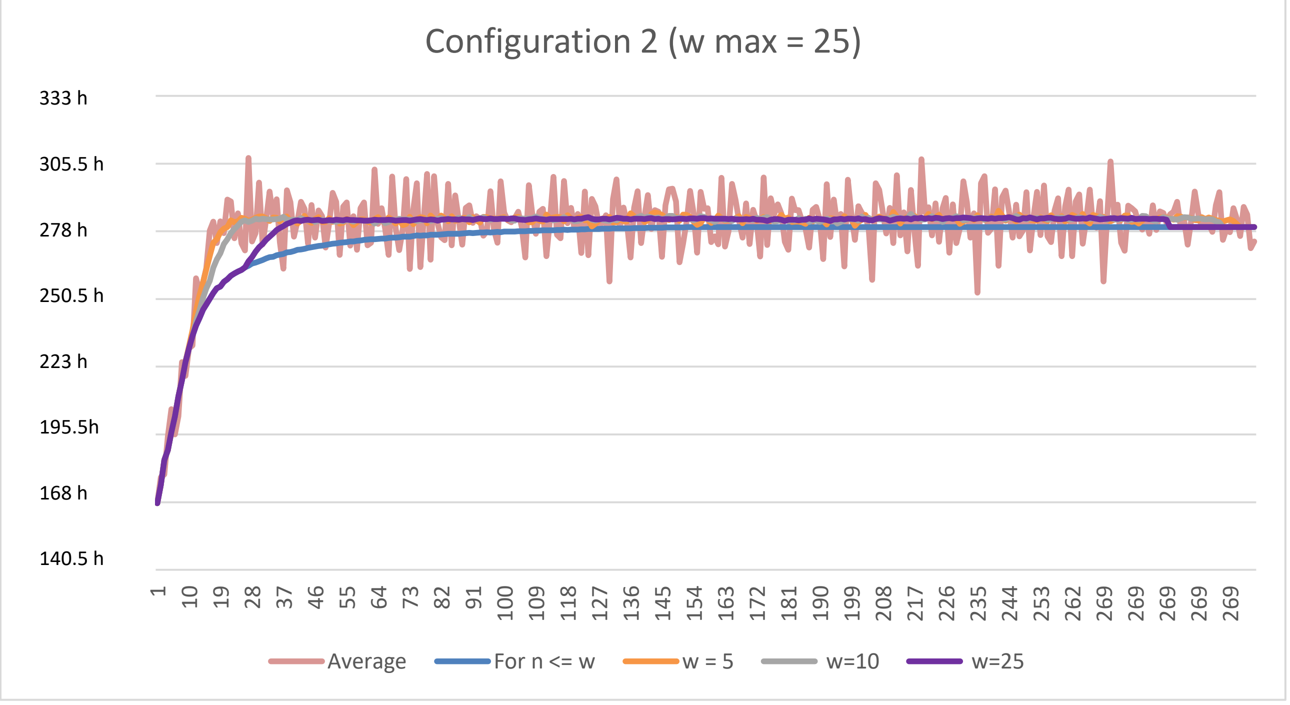

Figure 48: Welch procedure for 2D As Is model.

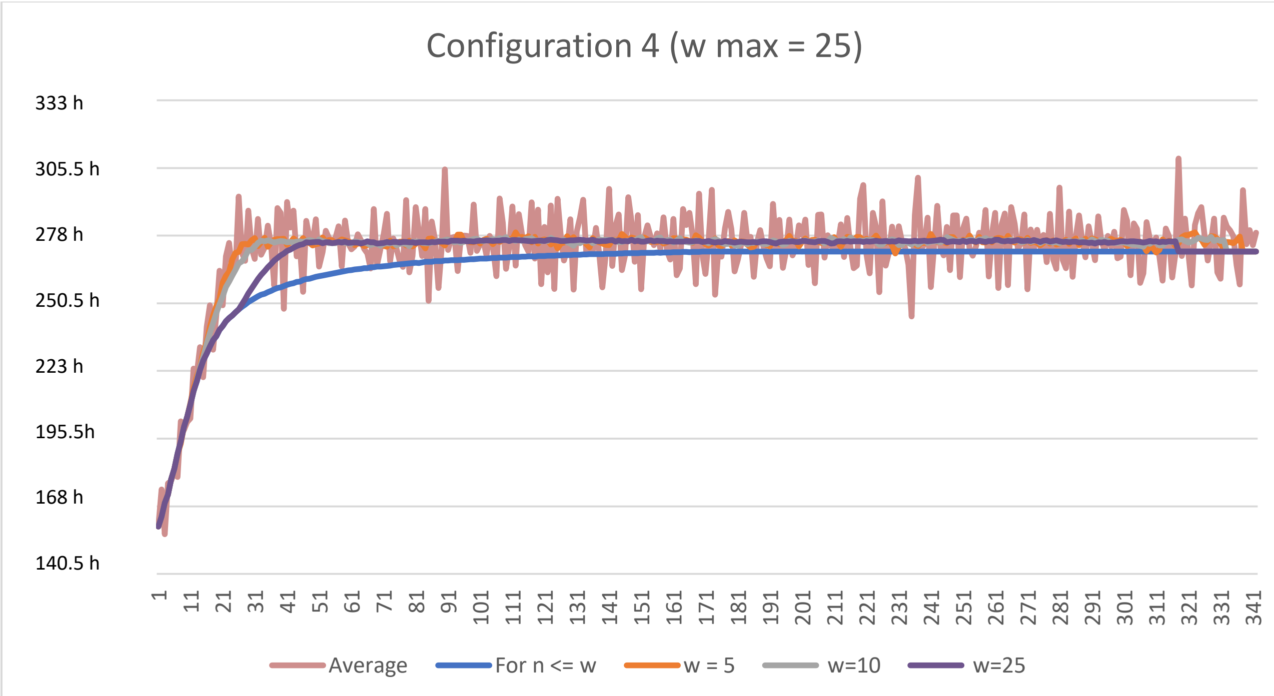

Figure 49: Welch procedure for 3D As Is model.

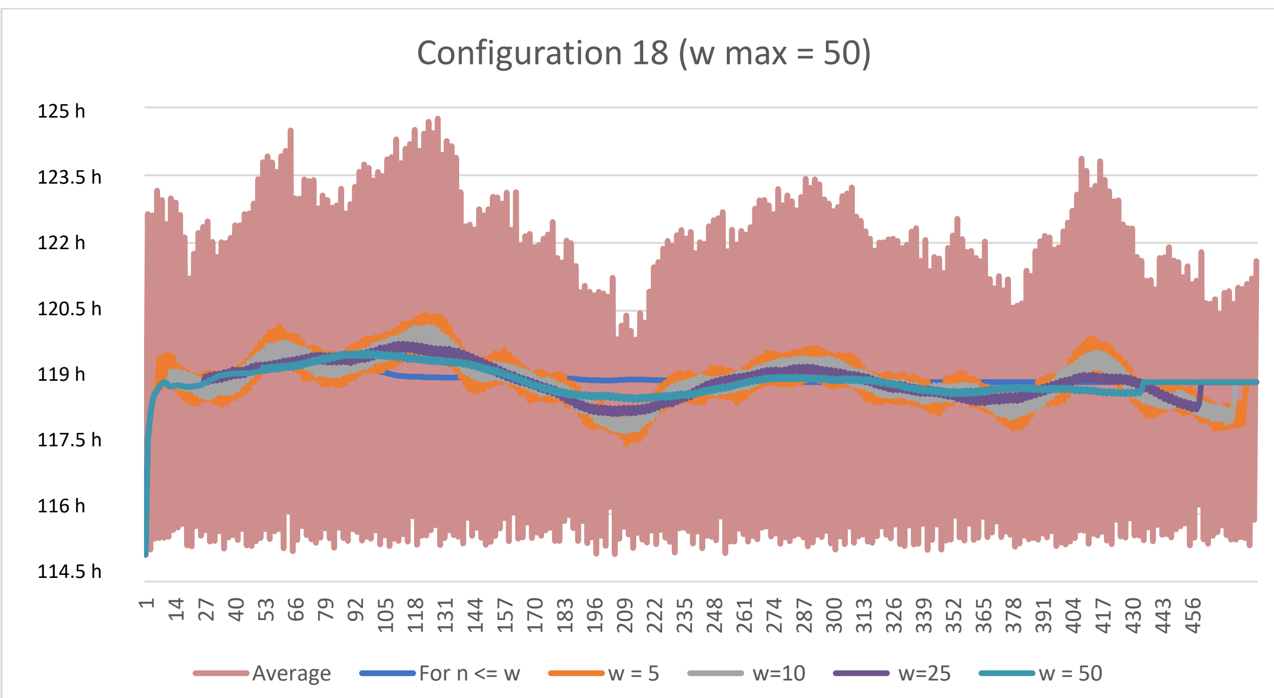

Figure 50: Welch procedure for 2D To Be model.

For Configuration 18, we add an extra chart, namely Figure 51, to show the behaviour of blade's Finishing Lead Time in detail, as it is not visible in Figure 50. There is a clear lead time drop between blade 70 and blade 110, then the FLT settles at a lower average value.

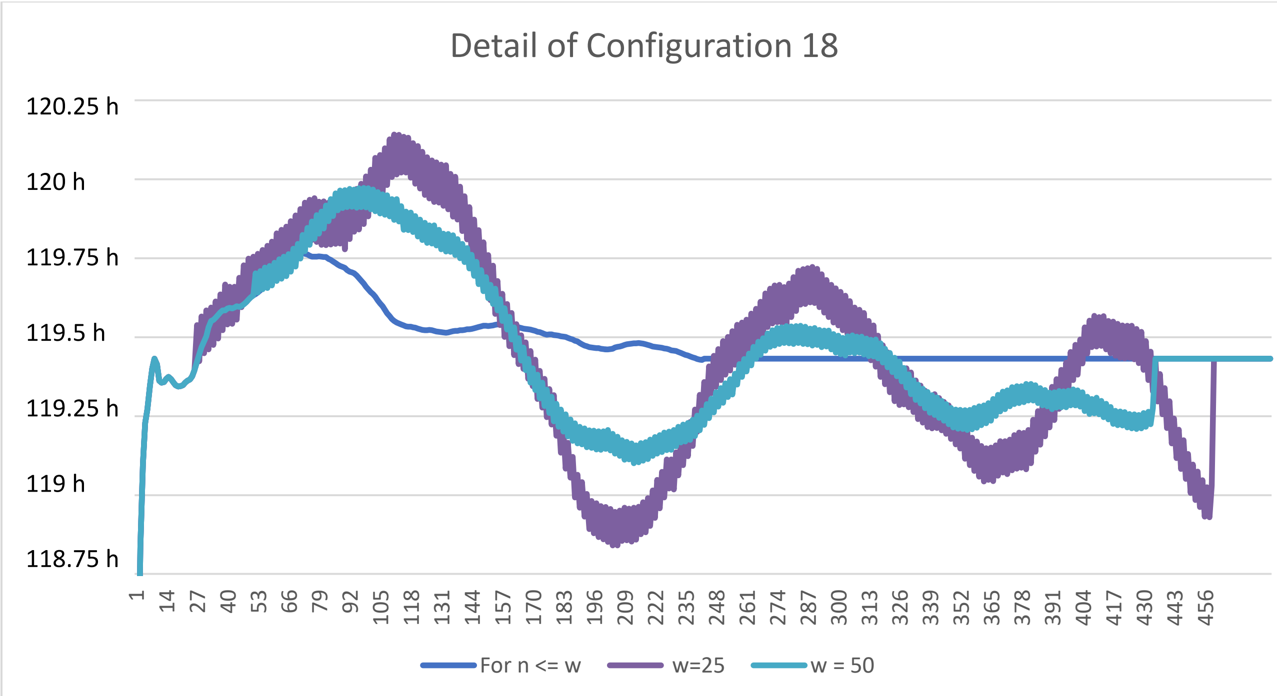

Figure 51: Detail of Welch procedure for 2D To Be model, Configuration 18.

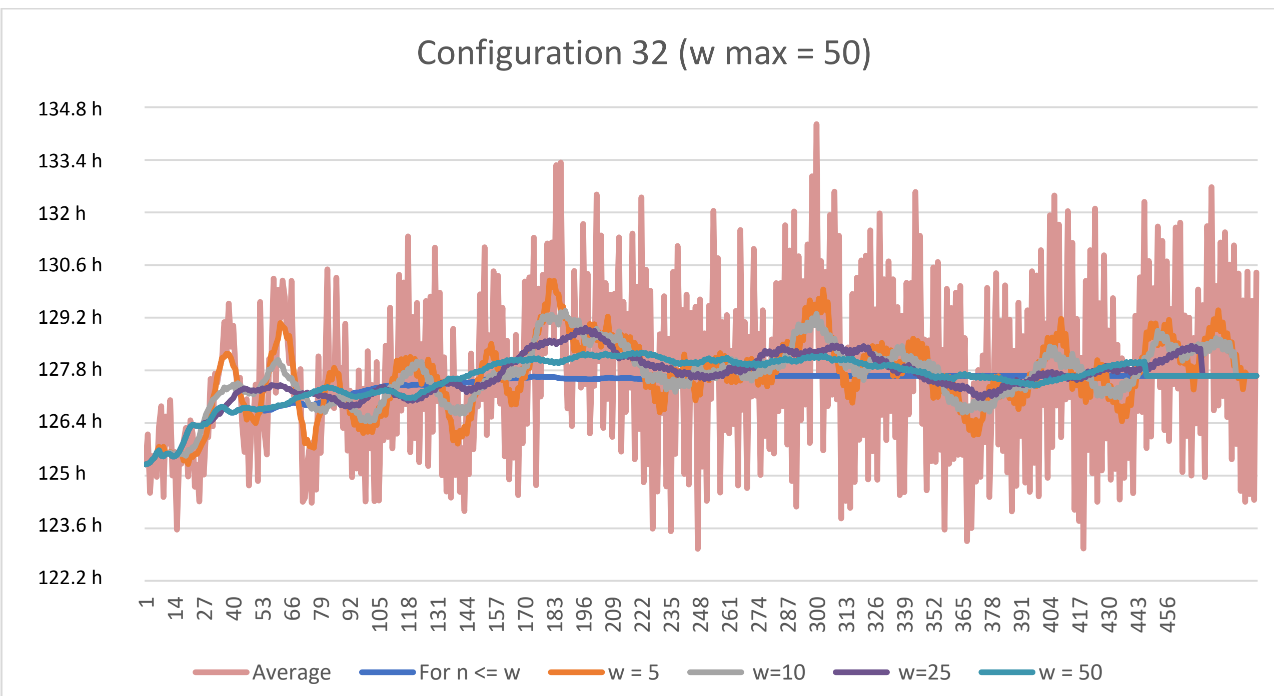

Figure 52: Welch procedure for 3D To Be model.

Appendix D: Analytic Hierarchy Process (AHP) details

Our quantitative simulation results focus on reducing lead times and improving the productivity of the plant, however we could not model important factors in the simulation, due to a lack of data and time constraints. The main factors we would like to add to our analysis are:

- The cost of new equipment to be bought, e.g., tools, machinery.
- The cost of salary for new employees or increased amount of working hours.
- The increased cost of materials, when required in larger amounts.
- The time of implementation, e.g., delivery and installation of newly bought equipment, time for layout modifications.
- The difficulties related to training the workforce, e.g., using a different tool for the same operation, performing a different task, changing completely a set of processes.
- The degree of rigidity, i.e., likelihood of problems arising when implementing the new intervention that cannot be solved at the plant but must be re-designed.

To include them, we use the AHP from Saaty (1990) and ask top management and senior engineers at SBT-NL to take part in the comparison process. They define the importance of one criteria over the other in a matrix, based on the current company situation. Then, we check the consistency of the contingent comparison matrix using the Consistency Ratio (CR). Lastly, we follow the approach of Biazzo et al. (2016): we evaluate the interventions against the factors in a second matrix, to obtain a degree of complexity for the interventions based on the level of importance of the criteria.

By including the listed factors in our comparison of the interventions, we can provide an implementation schedule based on expected benefits and a degree of complexity for the interventions. The expected benefits are validated through simulation and the complexity is analysed with qualitative and subjective opinions, partially bypassing the lack of data on the selected factors. This is a temporary solution using experts' opinion and will hopefully be replaced by more detailed simulation models, especially for factors related to costs. However, it is difficult to include all relevant factors in a simulation model, thus we expect this approach to change in the future – e.g., the number and type of factors – and be further integrated in a comparison with the simulation's results.

The contingent comparison matrix is shown in Figure 53. It displays the results of the first step in using the AHP, that is, the relative importance of each factor based on management and experts' opinion and the current goals of the company. The relative importance of each criteria is expressed with odd numbers ranging from 1 to 9 and their reciprocal; the former are used to express a higher importance of one criterion over another and the latter are used to express a lower importance. A consistency check is performed to ensure the relationships between criteria are assigned following a logic and will lead to consistent results. While a perfect decision maker would achieve a CR of 0, a certain degree of inconsistency is considered acceptable and is guaranteed to arise when the number of criteria increases. A comparison matrix whose CR is equal or lower than 0.1 is considered to be consistent and acceptable. The parameters resulting from the consistency check are shown beneath the matrix.

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.

Contingent comparison matrix														
	Operational Performances						*Normalized Column*							
Operational Performances	Cost of Equipment	Cost of material	Cost of salary	Time to implement	Workforce training	Rigidity of intervention							Absolute Weight	***Weight %***
Cost of Equipment	1.00	7.00	5.00	9.00	9.00	3.00	*0.53*	*0.60*	*0.73*	*0.28*	*0.28*	*0.29*	2.71	**45.16%**
Cost of material	0.14	1.00	0.33	7.00	7.00	3.00	*0.07*	*0.09*	*0.05*	*0.22*	*0.22*	*0.29*	0.93	**15.57%**
Cost of salary	0.20	3.00	1.00	9.00	9.00	3.00	*0.11*	*0.26*	*0.15*	*0.28*	*0.28*	*0.29*	1.36	**22.68%**
Time to implement	0.11	0.14	0.11	1.00	1.00	0.20	*0.06*	*0.01*	*0.02*	*0.03*	*0.03*	*0.02*	0.17	**2.80%**
Workforce training	0.11	0.14	0.11	1.00	1.00	0.20	*0.06*	*0.01*	*0.02*	*0.03*	*0.03*	*0.02*	0.17	**2.80%**
Rigidity of intervention	0.33	0.33	0.33	5.00	5.00	1.00	*0.17*	*0.03*	*0.05*	*0.16*	*0.16*	*0.10*	0.66	**10.99%**
Total	1.9	11.6	6.9	32.0	32.0	10.4	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	6.00	100.00%

$\lambda_{max} = 6.65146$ $\quad CI = 0.13$ $\quad CR = 0.1$

Figure 53: Contingent comparison matrix

The parameter λ_{max} is the principal eigenvector of the symmetric comparison matrix. The CR is calculated as the Consistency Index (CI) divided by a Random Index (RI). RI depends on the number of criteria used, as shown in Table 20, and is equal to 1.24 with six criteria; CI is defined in the formula below:

$$CR = \frac{CI}{RI}, with\ \ CI = \frac{\lambda_{max} \ - \#\ of\ criteria}{\#\ of\ criteria - 1}$$

Table 200: Random Index values based on the number of criteria

# of criteria	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Following the methodology of Biazzo et al. (2016), the stakeholders involved in the AHP procedure assigned a correlation value between each intervention and the six factors in the contingent comparison matrix, as shown in Figure 54. The correlation values are 0, 1, 3, and 9, meaning zero, weak, average, and strong correlation respectively. Negative correlations are not considered. The resulting complexity matrix allows us to calculate the total degree of complexity of an intervention; to do so, we multiply each correlation value to the absolute weight of the corresponding factor then the resulting values are summed to obtain the total complexity.

Possible Values: 0 = no correlation; 1 = weak correlation; 3 = average correlation; 9 = strong correlation;	Complexity matrix				
		Interventions			
	Operational Performances Weight	Rescheduling & Balancing	Reduction of intervention backlog	Operation optimisation	
Cost of Equipment	2.71		9.00	3.00	
Cost of material	0.93	9.00	1.00		
Cost of salary	1.36		9.00	9.00	
Time to implement	0.17	1.00	1.00	3.00	
Workforce training	0.17		1.00	9.00	
Rigidity of intervention	0.66	1.00	3.00	9.00	
Total		9.2	39.9	28.3	

Figure 54: Complexity matrix with absolute weight for criteria and total scores of complexity

Figure 55 shows the contingent intervention assessment chart, where the interventions are plotted against their degree of complexity. Then, the median of the degrees of complexity is used as a threshold to classify interventions as involving a high level of complexity, above the threshold, or a low level of complexity, below the threshold.

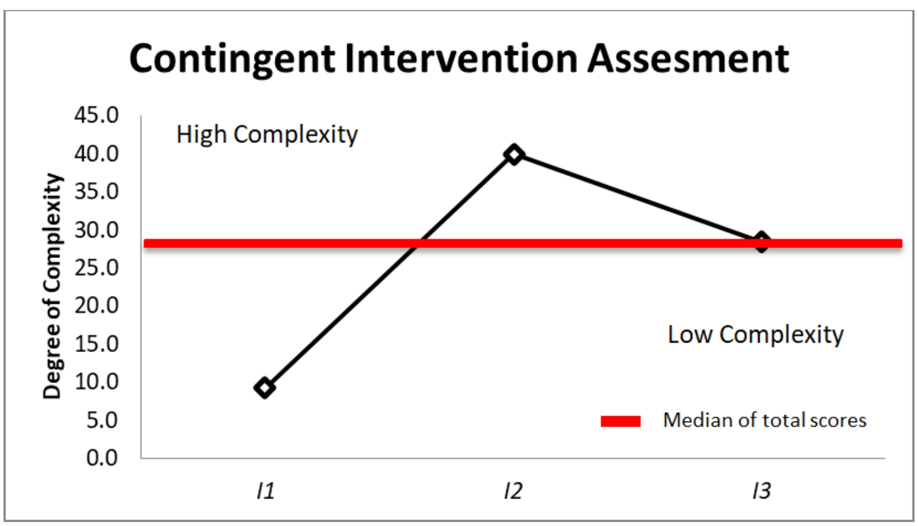

Figure 55: Contingent Intervention assessment with threshold for low or high complexity interventions

Middle managers at SBT-NL can decide to prioritise interventions with low complexity when resources are scarce and quick-wins are required, to show results and obtain more budget in the future. Vice versa, high complexity interventions can be prioritised when there is plenty of resources and their expected performances are better than for other interventions. Obviously, there is no need to prioritise high complexity interventions over low complexity ones, when the latter have better expected performances and there is no mandatory action to take.

Intervention 1, namely Rescheduling & Balancing, performs best on a quantitative level and has the lowest degree of complexity, thus we confirm its implementation to be first in the schedule. Intervention 2 and 3, respectively the backlog reduction and the Operation Optimisation, have higher degrees of complexity and their order of implementation could be argued to deeper detail. On a long term perspective, the backlog reduction would perform better quantitatively and ease the overall design process, leading to intangible benefits. However, Suzlon is currently undergoing a re-organisation phase and would profit from prioritising lower complexity projects, thus placing the Operation Optimisation intervention as second in order of implementation. The final choice is up to the decision makers in SBT-NL.

Through simulation, we obtained quantitative results and a detail perspective on the manufacturing process of wind turbine blade at the Ratlam plant. On the other hand, simulation doesn't provide direct choices or preferences and it must be complemented with decision-making tools or a criterion to obtain a final proposal. We applied the AHP to include additional factors in our analysis and showed how to follow-up on simulation results with a simple example, allowing the company to change the suggested implementation schedule from Section 6.2 based on their contingent availability of resources.